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Evaluation of kinetic coefficients using membrane bioreactor and active sludge process treating textile wastewater

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ABSTRACT

A long-term experiment with two pilot plants, one of Membrane Bioreactor (MBR) and the other of activated sludge (AS) process, was carried out in order to treat textile wastewater. Based upon theoretical inference and experimental data analysis, the kinetic properties of the MBR and AS, were comprehensively studied. Consequently, kinetic constants including true yield coefficient *(Y)*, endogenous decay coefficient *(k_d)*, maximum specific substrate utilization rate *(k)*, as well as the half-velocity constant (K_s) were calculated for the two process. The kinetic constants for MBR's biomass founding in the pilot plant, were $Y = 0.39$ mgMLSS/mgTOC·d, $k_d = 0.01$ d^{-1}, $k = 0.47$ d^{-1} and $K_s = 584$ mgTOC/L. And for AS biomass in pilot plant were $Y = 0.67$ mgMLSS/mgTOC·d, $k_d = 0.03$ d^{-1}, $k = 0.09$ d^{-1} and $K_s = 108$ mgTOC/L. These results demonstrate that the MBR process is more attractive to treat textile wastewater than a conventional process of active sludge, due the less production of sludge, accept high organic concentrations, and has higher substrate utilization rate.

Keywords: Textile waste water; Active sludge process; Membrane bioreactor; Kinetic constants

1. Introduction

The textile industry consumes large amounts of water, energy and auxiliary chemicals. The textile effluents are usually highly colored with pollutants like organics, toxic and inhibitory compounds, surfactants, chlorinated compounds, and salts with colored dyes are the most troublesome constituents of this wastewater. Previous studies have shown that many of the dyes are carcinogenic, mutagenic, and detrimental to the environment [1]. The most employed process to treat textile wastewaters is the biological [2], this is a process that involves a biological mass of microorganism, most of them bacteria which consume the biodegradable substrate. The most common biological process to treat textile wastewaters, is the activated sludge process (AS) [3]. This process involves the production and maintenance of microbial population in aerobic conditions. These microorganisms consume the biodegradable substrate, and solid separation is carried out by a secondary clarifier. The principal problems of the active sludge process are bulking sludge, and *Nocardia* foam [4], further more this process has several difficulties to remove slowly and non biodegradable substrate and virus and bacteria [5].

Environmental laws and the new technology available, make necessary the study of new processes to

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improve the removal of slowly and non biodegradable constituents, colloidal suspended solids, virus and bacteria, and allow reuse or recycle of the effluent. Actually they are a numerous modifications of the activated sludge process, is possible said that the MBR is an evolution of the activated sludge process, several authors [6–10], suggest that the membrane bioreactor (MBR) is revolutionize the waste water treatment, because is a process that involve two systems in one, the biological reactor (bioreactor) and the solids separation using micro filtration (MF) or ultra filtration (UF) membranes [11,12]. The principal advantages of this process in respect to traditional activated sludge processes are: better control of biological activity, longer sludge retention time independent of the hydraulic retention time (HRT), complete removal of solids and nearly complete removal of effluent microorganisms, smaller footprint, high removal ratios for most contaminants, reduced sludge production and rapid start-up of biological process [13–15]. However, important parts of this process need to be investigated, for example in the area of textile waste water.

The study of the kinetic phenomena involved in biological process, can helps to compare the efficiency between of MBR and AS process. They are two kinds of processes involved: microbial kinetic metabolism, this behavior depends of the substrate compounds. The microbial growth kinetic in municipal waste waters, has been deeply evaluated [3], however little has been reported on the kinetic properties of the MBR and AS plant treating textile wastewaters [15–17].

The aim of this experimental work was to study the kinetic properties of an MBR system, as well as the activated sludge process, applied to textile wastewaters, and evaluate the efficiency of the biological process in both, under similar operational conditions, growth kinetics and utilization of substrate [16]. The maximum specific substrate utilization rate (k), maximum specific bacterial growth rate ($_m$), half-velocity constant ($K_{s,}$), true yield coefficient (Y), as well as endogenous decay coefficient (k_d), are coefficients that helps to explain the microbial.

2. Materials and methods

2.1. Textile effluent

The wastewater treated was elaborated in laboratory conditions in order to reproduce the effluent of the industry of dyeing and finishing of cotton knit, ones of the most pollutants textile waste water [18].

2.2. MBR

The MBR used in this study was a pilot plant, composed of an aerobic reactor connected to an external tank with submerged UF membranes. The aerobic reactor had a working volume of 50 L. The affluent pumped directly from a raw wastewater tank, mixed completely with activated sludge and purified by a series of metabolic reactions of microorganism. The submerged UF membranes were connected to a suction pump, effluent passed through the membrane separation unit whit a flow velocity of 0.7–0.4 L/h, and *trans*-membrane pressure (TMP) of −0.1 bar. The reactor was aerated by a membrane diffuser in the bioreactor's base, the dissolved oxygen rate in the aerobic reactor was higher than 2 mgO_2/l. The reactor was coupled to an ultra filtration module of (POLYMEM – France) with submerged hollow fibers. The MBR pilot plant used in this work is shown in Fig. 1.

The polysufone tubular membrane (POLYMEM, France) employed in this pilot scale study had a filter area of 0.2 m^2, and a pore diameter of 0.2 μm and its initial permeability 8 L/(h m^2 kPa). After 60 min of operation, when the TMP went beyond 75 kPa, the membrane was cleaned. The cleaning procedure for surface fouling was a back wash with filtered effluent and cleaning solution.

2.3. AS unit

The AS unit used in this study was a pilot plant, composed for an aerobic reactor connected to sedimentation tank. The flux diagram is shown in Fig. 2.

2.4. Batch reactor

In order to obtain the kinetic constants, was employed batch reactor's with inoculums adapted from the MBR and sludge active pilot plant. The diagram of batch reactor is in Fig. 3.

2.5. Analyses

2.5.1. Physical analysis

Temperature, Mixed Liquor Suspended Solids (MLSS), turbidity, pH, conductivity, dissolved oxygen, Nitrogen (Kjendahl), phosphorus, chlorides, fats and oils, detergents, The protocol was the prescribe in the Standard Methods 20th ed. As well as color was measured by determining the spectral absorption coefficient of 0.45 μm filtered samples at 490 nm using a SHIMADZU UV spectrometer (Standard Methods 20th ed 2121 C).

2.5.2. Biochemical analysis

BOD_5, COD, TOC were determined as prescribed in Standard Methods 20th edition. Biodegradability test

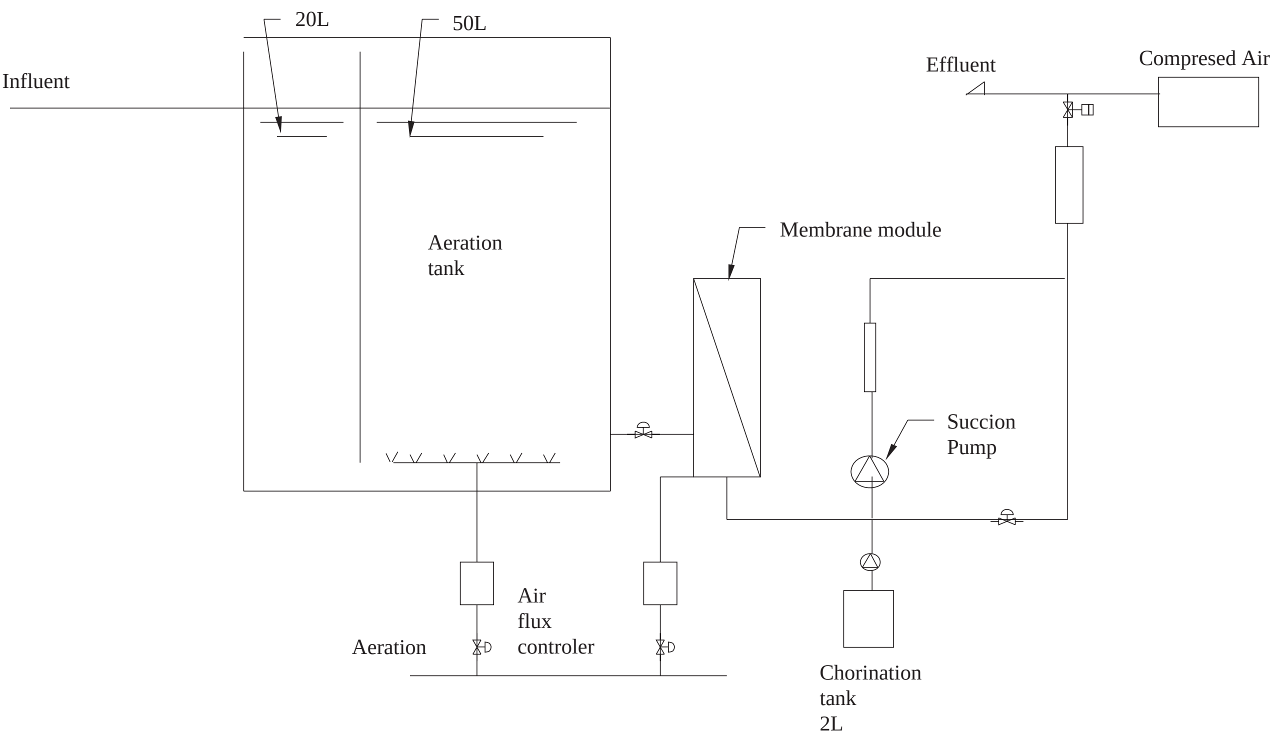

Fig. 1. Flux diagram. MBR pilot plant.

were performed according to the Electrolytic Respirometer Bioscience manual, using an Electrolytic Respirómeter (BI – 1000, Bioscience Inc).

2.6. Operation variables

Three experiments were conducted. The operation variables during the long-term pilot experiment are listed in. The COD influent, and the relation F/M was constant for the three experiments during 165 days of evaluation (Table 1).

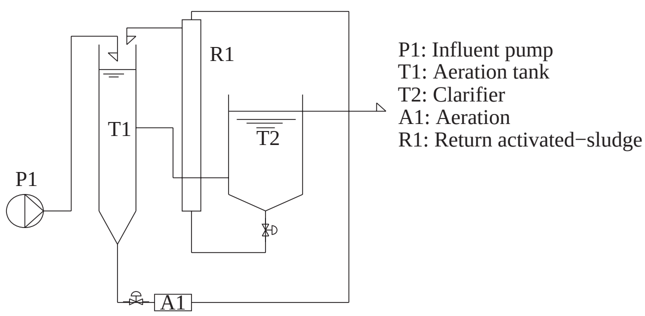

Fig. 2. Flux diagram. Active sludge pilot plant.

3. Results and discussion

3.1. Case description

The case study was performed at the Institut de Investigaciò Textil i Cooperaciò Industrial de Terrassa (Barcelona, Spain). The document ''*Reference Document of Best Available Techniques for the Textile Industry*'' [18], classify the sector of dyeing and finishing of cotton knit as a big consumer of water, and their effluent has a high COD. Furthermore produce the 50% of

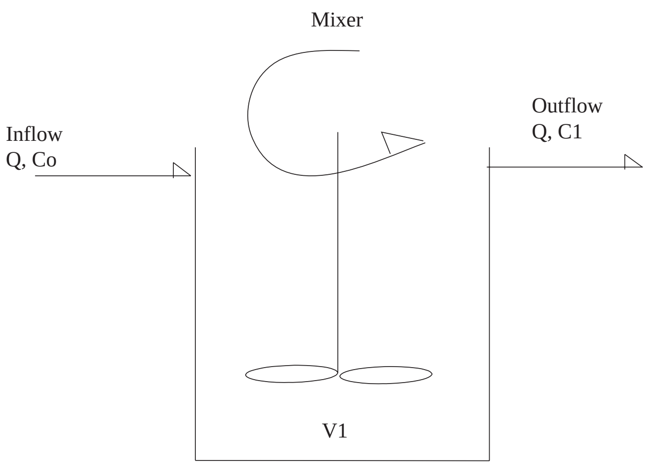

Fig. 3. Diagram batch reactor.

Table 1
Operation variables

Items	Process	
	AS	MBR
COD (mg/L)	1,500	1,500
MLSS (mg/L)	3,401	840
Qe (L/d)	2	6
HRT (d)	2	9
V (L)	4	40
F/M (kgCOD/kgMLSS.d)	0.2	0.2
Membrane flux (L/m^2.h)	–	3.5

the production and exportations of Spanish textile industry [19].

The effluent of this industry is composed by a series of effluents of wet processing: Scouring and desizing, dyeing, rinsing, washing and softening. The most contaminant wet process is the scouring and desizing whit a 50–70% of the COD [20]. Table 2, shows the bath relations for 1 kg of process matter.

Each effluent representative of the different cotton processes was elaborated in the laboratory except the desizing and scouring that come from a textile mill. The characteristics of each effluent of a wet process and the final textile effluent it is shown in Table 3.

3.2. Variation of COD and sludge concentration with time

The variations of COD with time during the three experiments are illustrated in Fig. 4. The influent COD remained at about 1,500 mg/L, the average effluent COD OF ACTIVATED SLUDGE PROCESS (effluent A.S.) was 532 mg/L, fluctuated from 60 to 1,269 mg/L, standar deviation was 365 mg/L, the average efficiency in COD removal was of 71%. The COD from the aerobic reactor in MBR (effluent MBR1 COD) was in average 416 mg/L, fluctuated from 181 to 617 mg/L, standard deviation 165 mg/L, the efficiency was 78%.

The effluent of BRM (effluent MBR2 COD) was in average 158 mg/L fluctuated from 60 to 280 mg/L, and a standard deviation of 50 mg/L, the efficiency was 91%. As it shows in Fig. 4, the activated sludge process has a high variability and lower efficiency, the MBR biological process is 7% more efficient and stable than an activated sludge process, the MBR process is 20% more efficiency than the active sludge process at similar operative parameters. It can be concluded that the removal efficiency of organic pollutants was high and stable when the MBR was applied to textile wastewater treatment.

Table 2
Bath relations 1 kg process matter

Process	R/b	Volume
Desizing and scouring	1/10	10
Dyeing	1/10	10
Bleaching	3/10	30
Washing	3/10	30
Softening	1/10	10
Efluent		90

The formation of sludge during the experiment is shown in Fig. 5. The behavior of the sludge concentration in active sludge process could be describe in three stages, at first they are an increasing rate, then they are a decreasing rate of the sludge concentration produced by a formation of a cake layer in the sedimentation tank, called *bulking* [3–4,21], after the *bulking* they are an increased tend again. Meanwhile the behavior of the sludge concentration in MBR, is stable in all the three studies, and they are not an increasing or decreasing rates. The kinetic analysis can help to explain this behavior.

3.3. Kinetic constants Y, K_d, K_s, k, $u_{\max}$ evaluation

According to the basic theory of activated sludge process, the five constants Y, K_d, K_s, k and $u_{\max}$ are generally adopted to describe the dynamic behavior. Y and K_d refer to microorganism growth and K_s and $u_{\max}$, to substrate degradation. These kinetic constants are significant in guiding scientific research and engineering design. The actual values of the four constants were investigated for the activated sludge and MBR processes applied to the textile wastewater treatment.

3.4. Kinetic evaluation for activated sludge process

The variables K_s and k can be obtained by the Eq. (1):
In which

$$k = \frac{u_{\max}}{Y} \tag{1}$$

The variables Y and K_d, can be obtained by the Eq. (2):

$$\frac{1}{SRT} = -Y\frac{r_{su}}{X} - k_d \tag{2}$$

Sludge from the MBR and activated sludge pilot plant was inoculate in batch reactors operated at different HRTs and sludge retention times (SRT).

Table 4, shows the operative parameters of a batch reactor whit sludge adapted from the sludge active pilot plant.

Table 3
Characteristic of each effluent of wet process and the final textile effluent

Parameter	Unit	Dyeing	Desizing and scouring	Washing	Softening	Total textile effluent
pH		11	11	8	8	8
Cond.	mS/m	701	684	155	154	1,382
T	°C	20	20	20	20	20
TOC	mg/L	154	3,563	28	160	617
COD	mg/L	511	13,812	24	40	1,500
BOD_5	mg/L	3	4,281	7	23	464
MLSS	mg/L	197	415	18	69	119
Color	Hazen	10,000	625	0	0	2,842
Phosphorus	mg/L	–	–	–	–	1.6
Nitrogen (Kjendahl)	mg/L	0	402	0	0	24
Biodegradability	%	0	31	30	27	31

Based upon Eq. (1) and the data in Table 4, were selected the abscissa and ordinate respectively, a linear regression of X·TRH/(S_0–S) against 1/S was carried out (Fig. 6). The inter-relationship coefficient was $R^2 = 0.9882$

The inter-relationship coefficient was $R^2 = 0.9882$. The intersection point whit the abscissa in the linear equation shows the 1/k value, and the slope represents the value of K_s/k. The respective value of k and K_s are:

$1/k = 10.1$ d
$k = 0.09$ d^{-1}
$K_s/k = 1091$
$K_s = 108$ mgTOC/L

Based upon Eq. (2) and the data in Table 4, were selected the abscissa and ordinate respectively, a linear regression of 1/SRT against (S_0–S)/(X·HRT) was carried out (Fig. 7).

The inter-relationship coefficient was $R^2 = 0.9937$. The intersection point with the abscissa in the linear equation shows the $-k_d$ value, and the slope represent the Y value. The value of Y and k_d for the activated sludge biomass, are: $Y = 0.67$ mgMLSS/mgTOC, $k_d = 0.03$ d^{-1} and $u_{\max} = 0.06$ d^{-1}.

3.5. Kinetic evaluation for MBR

The same procedure was followed in order to obtain the kinetic constants for the biomass of MBR process. The operational parameters of a batch reactor with MBR microorganisms as inoculums it shows in Table 5.

Based upon Table 5, were selected the abscissa and ordinate respectively, a linear regression of X·TRH/(S_0–S) against 1/S was carried out, Fig. 8.

The respective value of k and K_s are: $k = 0.47$ d^{-1} and $K_s = 584$ mgTOC/L. The linear regression of 1/SRT against (S_0–S)/(X·TRH) was carried out (Fig. 9), in order to obtain the Y and k_d values.

The inter-relationship coefficient was $R^2 = 0.9989$. The intersection point whit the abscissa in the linear equation shows the $-k_d$ value, and the slope represent the Y value. The value of Y and k_d for the biomass membrane bioreactor, are: $Y = 0.39$ mgLMSS/mgTOC, $k_d = 0.01$ d^{-1} and $u_{\max} = 0.16$ d^{-1}.

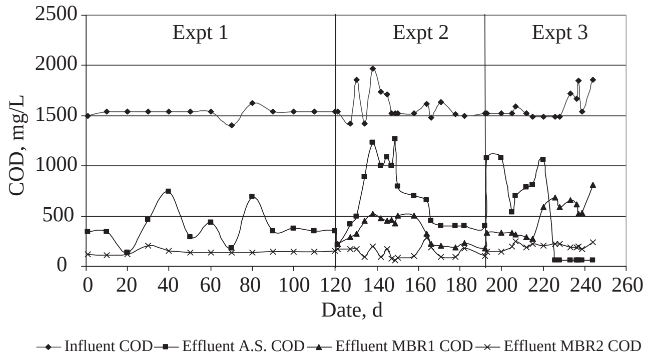

Fig. 4. Variation of COD whit time.

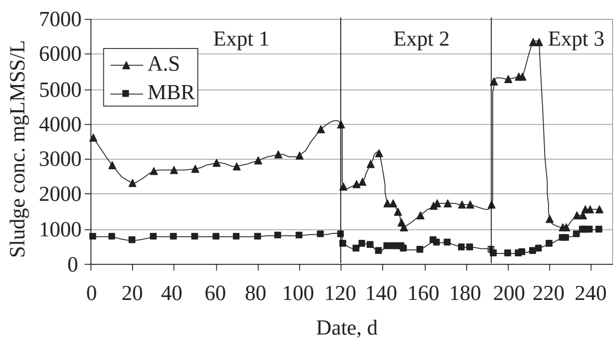

Fig. 5. The variation of sludge concentration with time.

Table 4
Operative parameters and analysis in batch reactor with inoculum from activated sludge

S_0, mgTOC/L	S_e, mgTOC/L	TRH, D	X, mgMLSS/L	X·TRH/(So–S), mgMLSS·d/mgTOC	1/S, (mgTOC/L)$^{-1}$	1/SRT, d^{-1}	(So–S)/X·TRH, mgTOC/mgMLSS·d
650	200	10	700	15.6	0.0050	0.016	0.064
650	250	9	650	14.6	0.0040	0.019	0.068
650	300	8	600	13.7	0.0033	0.023	0.073
650	350	6	530	10.6	0.0029	0.034	0.094
650	400	5	441	8.8	0.0025	0.050	0.113

The value of the maximum specific substrate utilization rate (k) was solved for a biomass of BRM as 0.47 d^{-1} and for the biomass of AS was solved as 0.09 d^{-1}, it can be concluded that the MBR process employed more efficiently the organic matter than a AS process. The value of the half-velocity constant, for the biomass of a AS was of 108 mgTOC/L and for BRM was of 584 mgTOC/L, it can be concluded that the MBR process accept higher organic concentrations than AS process.

The true yield coefficient (Y) for MBR process is 0.39 mgMLSS/mgTOC·d, meanwhile for AS is of 0.67 mgMLSS/mgTOC·d, probe that the sludge production in an AS is a 42% higher than in a MBR process, this is important parameter because reduce the production of residual sludge, cost of treatment and construction area, Xing et al. [22], said that the cost of sludge treatment, accounting of up to 60% of the total operating cost in a wastewater treatment plant. Analyzing the k and Y values for BRM we can explain this mode operation in terms of the maintenance concept as described by Pirt (1975). The maintenance concept describes operation where all incoming substrate is used for cell maintenance rather than growth, such that no excess sludge is produced.

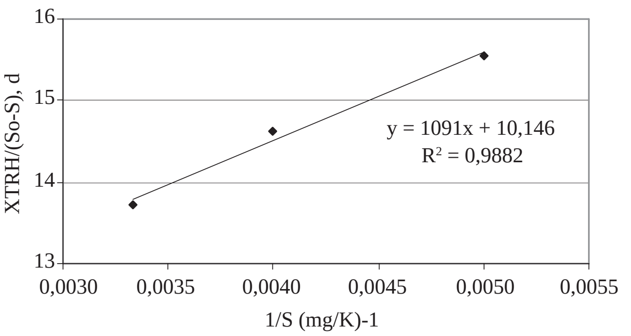

Fig. 6. Solving for K_s and k, for inoculum's activated sludge.

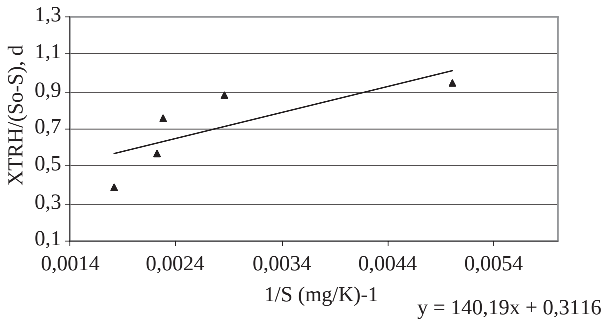

Fig. 8. Solving for K_s and k, for inoculum's MBR.

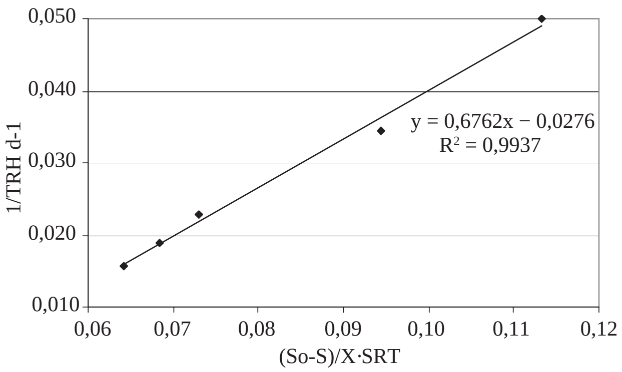

Fig. 7. Solving for Y and K_d.

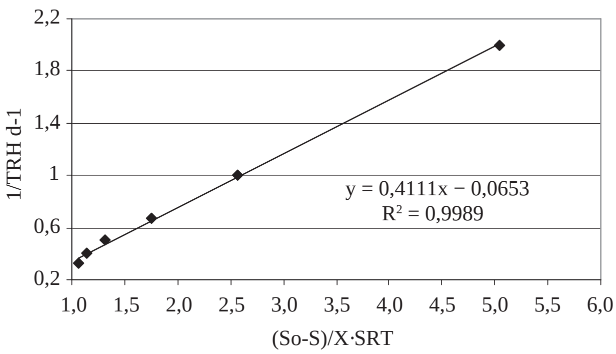

Fig. 9. Solving for Y and K_d.

Table 5
Operative parameters and analysis in batch reactor with inoculum from membrane bioreactor process (MBR)

S_0, mgTOC/L	S_e, mgTOC/L	TRH, D	X, mg MLSS/L	X·TRH/(So–S), mgMLSS·d/mgTOC	1/S, $(mgTOC/L)^{-1}$	1/SRT, d^{-1}	(So–S)/X·TRH, mgTOC/mgMLSS·d
200	1300	1230	0.95	0.0050	1.06	0.33	3.17
350	1150	1013	0.88	0.0029	1.14	0.40	2.84
440	1060	804	0.76	0.0023	1.32	0.50	2.64
449	1051	600	0.57	0.0022	1.75	0.67	2.63
550	950	370	0.39	0.0018	2.57	1.00	2.57
580	920	183	0.20	0.0017	5.04	2.00	2.52

The endogenous decay coefficient (k_d) for MBR was of 0.01 d^{-1} meanwhile for AS was of 0.03 d^{-1}, this coefficient 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. Thus the formation of the cake layer in the top of the secondary clarification tank in A. S. process, improve the bulking phenomena and the increase of biodegradable matter in the process.

4. Conclusions

The MBR process is a very good treatment to textile waste water, even better than an Active Sludge process, just the biological system of a MBR is 8% more efficient and stable than an activated sludge process, by the way the MBR process is an 20% more efficient and stable than a AS, It can be concluded that the removal efficiency of organic pollutants was high and stable when the MBR applied to textile wastewater treatment.

One of the principal factors to affect the efficiency the removal COD, in the AS process, was due to the bulking sludge phenomena produce by the filamentous bacteria (*Nocardia amarae*), results in a evacuation of biomass in the secondary settle thank, affecting the stability and efficiency of the process. Mean while the close box configuration of the MBR process make that all the biomass be in the biological thank, offer stability to the process.

The high values of the maximum specific substrate utilization rate (k) in MBR process prove that the biomass employed more efficiently the organic matter than an AS process. High values of the half-velocity constant (K) demonstrate that the MBR accept higher concentrations than AS. As well as low true yield coefficient (Y) in MBR show a down sludge production than AS. And the high value of the endogenous decay coefficient for AS. confirms the capacity of cell death one of the characteristics of the bulking phenomena.

Thus an MBR is better than an active sludge process to treat textile waste water, the constructive and operational cost could be equalize due the problems of conventional process like the *bulking*, higher sludge production and higher foot print.

Nomenclature

MBR	Membrane bioreactor
AS	Activated Sludge process
BOD	biological oxygen demand (mg O_2/L)
COD	chemical oxygen demand (mg O_2/L)
TOC	total organic carbon (mg/L)
MLSS	mixed liquor solid suspended
Qe	effluent flux
V	volume of the biological reactor
k	maximun specific substrate utilization rate (d^{-1})
μ_{max}	maximun spepcific bacterial growth rate (d^{-1})
K_s	half velocity constant (mg TOC/L)
k_d	endogenous decay coefficent d^{-1}
Y	true yield coefficient mg MLSS/mg TOCd^{-1}
Effluent MBR1 COD	effluent of the biological process in MBR
Effluent MBR2 COD	effluent of all the MBR process

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