REDUCING OF EXCESS SLUDGE PRODUCTION IN WASTEWATER TREATMENT USING COMBINED ANAEROBIC/AEROBIC SUBMERGED BIOLOGICAL FILTERS

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ABSTRACT
In this research, possibility of reducing excess sludge production in wastewater treatment was investigated using a combined anaerobic and aerobic submerged biological filter in a pilot scale. The physical model designed, erected and operated consisted of two pipes of PVC type with 147mm and 237mm diameter used as aerobic and anaerobic filters, respectively. The effective height of porous media in these filters was 70cm. Two filters were connected to eachother in a series form and the resulted system was loaded using synthetic wastewater based on sucrose in the range of 1.91 to 30.61 kg/m^3 for anaerobic filter and 1.133 to 53.017 kg/m^3 for aerobic filter. For similar loadings, the aerobic filter showed efficiency of 1.8 times that of anaerobic filter in removal of soluble COD. Return of 100% flow from the aerobic filter to the anaerobic filter for 30kg/m^3.d of organic loading increased the efficiencies of the anaerobic filter, the aerobic filter and the combined system as 17%, 14% and 15%, respectively and the effect of the return of the flow was more pronounced in smaller hydraulic retention times and larger loadings. 100% return of the flow reduced the yield coefficient for the whole system to 0.037 for 53 kg/m^3 loading which is a suitable value with regard to the scheme and no use of chemical materials such as chlorine and ozone. This coefficient reached a value as small as 0.007 in common loadings (7.5kg/m^3) for 100% return of the flow which is very close to zero. So, this method could be considered as a complete biological treatment with low excess sludge and could be assessed in full scale.

Key words: Excess sludge reduction; Sludge minimization; Biological aerated filter; Submerged anaerobic filter; Yield coefficient

INTRODUCTION
Currently, the activated sludge process (ASP) dominates the biological treatment of municipal wastewater (Eckenfelder and Grau, 1998). The major objective of ASP is to reduce organic contaminants (Metcalf and Eddy, 2003). It is estimated that about two thirds of the organic load is removed by ASP, approximately half of which is converted to excess sludge (Speece, 1981). Such excess sludge has to be properly treated prior to final dispoal, even though the cost of sludge treatment is extremely high, accounting for up to 60% of the total operating cost in a wastewater treatment plant (Canales, 1994). As a result, excess sludge disposal has been a significant challenge and has attracted a great deal of attention in both academic and engineering fields.

It has been suggested that within the framework of sustainable developmant, the disposal problem may be solved by minimizing excess sludge production and decreasing of yield coefficint (Y) at the source (Roeleveld *et al*., 1997). In this way,

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increase of oxygen concentration in activated sludge flocs, with *Y* of 0.2 (Abbasi *et al*., 2000), two – stage membrane–assisted bioreactor, *Y* of 0.35 to 0.45 (Ghyoot *et al*., 2000), ozone induced biodegradation, *Y* of 0 to 0.3 (Kamiya *et al*., 1998; Sakai *et al*., 1997; Song *et al*., 2003; Yasui *et al*., 1996), growth of controllable predators, *Y* of 0.01–0.23 mg biomass/mg COD (Lee and Welander, 1996; Rensink and Rulkens, 1997), uncoupling of metabolism with paranitrophenol, *Y* of 0.25 (Low *et al*., 2000) and intermittent chlorination method, *Y* of 0.16 to 0.48 (Takdastan *et al*., 2009) have been tested at either laboratory or pilot scale. Results have shown that although yield factor and "excess sludge production" (*ESP*) can be significantly reduced, the quality of final effluent often deteriorates due to the inherent limitations of conventional gravity clarifiers.

In general, high biomass concentration can be attained in a reactor through cell immobilization by attachment to a surface (Metcalf and Eddy, 2003). One of the most recent attached growth systems (biofilm reactors) used in wastewater treatment is the submerged filter in different forms including upflow and downflow types under aerobic and anaerobic conditions.

The advantages of attached microbial film compared to suspended microorganisms in the degradation of fluid pollutants are high biomass concentration, higher metabolic activity, greater resistance to toxicity, and better sludge properties (Yariv, 2001).

Biological aerated filter (BAF), due to the nature of the treatment scheme have been avaluable help in soluble COD removal (Baghapour and Jabbari, 2007); however, with regard to the fact that in aerated treatment systems including BAF, the sludge yield is generally high and it is the case for biological aerated filters as well, research on the rate of suspended sludge production as excess sludge in this kind of filters looks necessary.

From the view point of the excess sludge production, effluent biomass of BAF can be digested by an anaerobic biofilter in serial condition. The main objective of this study was to develop a hybrid system for the reduction of excess sludge production in biological wastewater treatment process. So, in the present study, using a physical model in a pilot scale, the effect of sludge recirculation from BAF to a downflow anaerobic filter (DAnF) in various hydraulic retention times (HRT) on soluble COD removal effeiciency and the amount of the suspended sludge production in this kind of hybrid system were evaluated.

Theoritical development

Sludge concentration in activated sludge process (ASP) and submerged biological filters (in general) could be obtained using the following equation:

$$X_t = \frac{SRT.\ Y(C_i - C_e)}{(1 + k_d\ .\ SRT)\ HRT} \tag{1}$$

In this equation X_t is the biomass concentration in the reactor in kg VSS/m^3; *SRT* is the sludge retention time, 1/day; *Y* is the maximum yield coefficient in kg VSS/kg SCOD; C_i and C_e are the concentrations of soluble substrate in the bioreactor in the inflow and outflow, respectively, in kg SCOD/m^3 and k_d is the endogenous decay coeeficient, 1/day.

As it was already mentioned, for reducing and minimizing the amount of suspended sludge in submerged filters, the microbial storage capacity and the *SRT* should be increased as much as possible. So, the problem could be kept on by increasing the SRT to the very high values and then equation 1 could be written as:

$$X_t = \lim_{SRT \to \infty} \frac{SRT.\ Y(C_i - C_e)}{(1 + k_d\ .\ SRT)\ HRT} \tag{2}$$

If the limit of equation 2 is computed, the following equation would be obtained.

$$X_t = \frac{(C_i - C_e)\ Y}{k_d\ .\ HRT} \tag{3}$$

X_t includes the attached biomass (X_a) and the suspended biomass (X_S) as:

$$X_t = X_a + X_s \tag{4}$$

In the steady state,

$$X_s = X_e \tag{5}$$

In which X_e is the suspended or effluent VSS (g/m^3); on the other hand, we know that

$$X_a = L_f\, S_s\, \rho_{tn} \tag{6}$$

In which, L_f is the thickness of biofilm (m); S_S is the specific surface area of filter media (m^2/m^3) and ρ_{bm} is the biomass density (g biomass/m^3 biofilm). Also, the hydraulic retention time (*HRT*) and *SRT* may be defined as follows:

$$HRT = \frac{V_v}{Q} \tag{7}$$

$$SRT = \frac{V_v X_t}{Q\, X_e} \tag{8}$$

Where V_V is void volume of filter (m^3). By Substitution of X_t, *HRT* and *SRT* from Eqs. (4), (7) and (8) in Eq. (1), X_e would be obtained:
Hence, the excess sludge production in submerged filter (ESP_{SBAF}) may be obtained from the following equation:

$$X_e = \frac{\frac{V_v X_t}{Q\, X_e} Y\,(C_i - C_e)}{(1 + k_d \frac{V_v X_t}{Q\, X_e}\,)\ \frac{V_v}{Q}} - X_a \tag{9}$$

$$ESP_{SBAF} = Q\, \frac{Y\,(C_i - C_e) - k_d\, HRT\, L_f\, S_s\, \rho_{tn}}{1 + k_d\, HRT} \tag{10}$$

It is seen that all eight parameters, i.e., Q, Y, (C_i – C_e), k_d, *HRT*, L_f, S_S, and ρ_{bm} are important to *ESP* in the submerged biological filters.

MATERIALS AND METHODS

Setup of biological filters

The experiments were performed in pilot scale. The physical model in this research was setup at the hydraulic laboratory of the School of Health at Shiraz University of Medical Sciences. A simplified flow-sheet of the pilot plant is shown in Fig. 1.

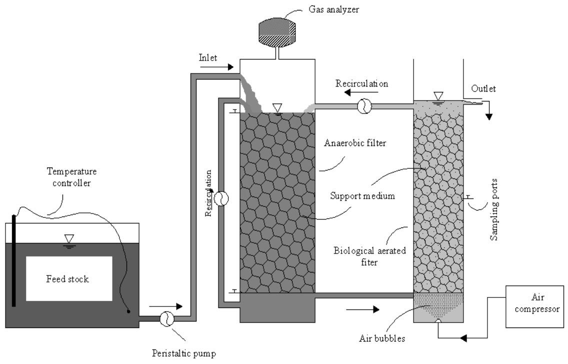

Fig 1: Schematic view of experimental system

The model consisted of 2 PVC pipes of 237mm and 147mm inside diameter as downflow anaerobic filter (DAnF) and biological aerated filter (BAF), respectively. The columns were connected to eachother with a pipe of 20mm in diameter. The effective height of two filters was 70cm. These columns were filled with immobilized biofilm support which were pieces of 32mm and 20mm PVC raschig rings with the same height and diameter. PVC raschig ring was used as biofilm support material because of its high porosity (up to 80%) and low price compared to the other synthetic packing media, such as pall rings, which can be supplied by the pipe manufacturing industries.
Physical specifications of the model are presented in Table 1.

Table 1: Physical specificatios of the reactors

Column	Diameter (mm)	Height (cm)	V_t (L)	V_v (L)	n (%)	S_S (m^2/m^3)
DAnF	237	70	30.9	26.958	87.33	175
BAF	147	70	11.9	9.853	82.8	295.7

In the model, at the heights of 35 and 70 cm from the bottom of the packing media sampling ports were considered. Aeration was done from the bottom of the BAF reactor by diffusers placed upside down. The amount of injected air was chosen such that oxygen would not be a limiting factor for biological growth.

Synthetic wastewater

For feeding the bioreactors, sucrose-based synthetic wastewater of 2000 mg/L COD was used which was prepared using beet sugar molasses (sucrose) as the main substrate and tap water. pH fluctuation were controlled using 0.5 normal sodium bicarbonate. Table 2 shows the composition of wastewater used as the feed of the pilot reactors during the test period.

Table 2: Chemical composition of synthetic wastewater

Chemical	Concentration (mg/L)
$NaHCO_3$	20
$FeSO_4.7H_2O$	0.2
KH_2PO_4	10
$CaCl_2.2H_2O$	10
$MgSO_4.7H_2O$	10
$ZnCl_2$	0.1
$CoCl_2$	0.1
$NiCl_2$	0.1
COD	2000

Synthetic wastewater was injected at the top of the anaerobic filter by a peristaltic pump and its temperature was controlled in the reservoir by an electric heater on 30±0.2 ^oC.

Startup and system operation

For operation of the system, the columns were filled with synthetic wastewater of 10000 mg/L. Seeding was provided by anaerobic and aerobic bacteria collected from the activated sludge system of the domestic wastewater treatment plant. Then, the air compressor was turned on and the reactors started to work in a batch condition.

The bacterial adaptation stage took about 35 days. During this time, the wastewater inside the reactors was changed four times and at the end of this period, thickness of biofilm in each reactor reached about 200 µm.

Measurement method of the biofilm thickness

For measurement of biofilm thickness formed on porous media of the columns, the difference between the initial volume and porous volume (V_V) was divided by specific surface of each filter.

It should be mentioned that at the end of each run, at the steady state, the reactors were washed using clear water in such a way that the outflow waste from the reactor would be clear and then the new porosity was measured and used in the computations.

It should also be noted that the water velocity for washing was kept low enough so that, the above-mentioned layer was not washed out.

Experiments

After the adaptation period, the continuous feeding was started. For the study of the effect of HRT on the efficiency of the filters, wastewater with strength of 2000 mg/L was injected by a peristaltic pump with flow controller to the anaerobic reactor with various discharges corresponding to different HRT_s and different volumetric organic loads (VOL_s) in both filters.

In the meantime, for the study of the effect of sludge recycling from BAF to DAnF on suspended sludge production rate in both filters, different fractions of flow were returned to anaerobic filter and each run was continued to reach the steady state.

Sampling at the sampling points was carried out regulary and when columns reached a steady state from the viewpoint of soluble COD and outflow volatile suspended solids (VSS), volume of biofilm was measured and the thickness of the biological layer was estimated in each column having the specific surface of filter media.

The measured parameters in this research were SCOD, VSS, pH, DO, CH_4, and temperature. The first two parameters, the filter efficiency in substrate removal and excess sludge production could be obtained in each run and with a specified HRT, pH and DO measurements were carried out randomly. These two parameters were included in the list for measurements just to be sure about proper operation of the system and stability of the reactors.

It should be noted that all the experiments were carried out based on the standard methods for the examination of water and wastewater (standard methods for the examination of water and wastewater, APHA, 1998).

In Table 3, the operational scheme of the system for 20 situations (Runs) using different discharges and recycling rates is presented.

Nonlinear regression model using the software of Curve Expert was applied for statistical analysis of the data.

RESULTS

The most important parameters monitored in the experiments were soluble COD (SCOD) and VSS (Table 4). It should be mentioned that the COD of the inflow wastewater in all situations was 2000 ± 25 mg/L. For brief and clearer explanation, the results of SCOD and VSS exiting from the employed biological filters, versus the HRT and recirculation rate (R%) are presented in Table 4.

Table 3: Operational scheme of the system

Run	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
Recirculation (%)	0	10	30	50	0	10	30	50	0	20	50	100	0	20	50	100	0	10	20	100
HRT_{DAnF} (h)	21.4				10.7				5.35				2.68				1.34			
VOL_{DAnF} (kg SCOD/m^3.d)	1.9138				3.826				7.6536				15.3056				30.6113			
HRT_{BAF} (h)	8				4				2				1				0.5			
VOL_{BAF} (kg SCOD/m^3.d)	1.133				3.040				7.691				20.746				53.017			

Table 4: SCOD and VSS exiting from the bioreactors in steady state at 30°C

Run	$SCOD_{in}$ (mg/L)	$SCOD_{out}$ DAnF (mg/L)	$SCOD_{out}$ BAF (mg/L)	VSS_{out} DAnF (mg/L)	VSS_{out} BAF (mg/L)	Run	$SCOD_{in}$ (mg/L)	$SCOD_{out}$ DAnF (mg/L)	$SCOD_{out}$ BAF (mg/L)	VSS_{out} DAnF (mg/L)	VSS_{out} BAF (mg/L)
1	2000 ± 25	456	23	0.2	8	11	2000 ± 25	625.5	63	10.3	17
2	2000 ± 25	562	25	1.7	8	12	2000 ± 25	571.7	42	8.6	14
3	2000 ± 25	494	20	5	7.2	13	2000 ± 25	1044	324	23.1	55
4	2000 ± 25	445	17	5.2	6.3	14	2000 ± 25	969	262	29.5	98.3
5	2000 ± 25	612	55	2.4	16	15	2000 ± 25	754	166	18.8	27.2
6	2000 ± 25	560	45	3.1	14.2	16	2000 ± 25	621.3	112	11.5	22.6
7	2000 ± 25	481	29	6.1	13.5	17	2000 ± 25	1334	587	29.2	126
8	2000 ± 25	402	22	7.2	10.1	18	2000 ± 25	1177	483	40.3	98
9	2000 ± 25	774	124	16.3	39	19	2000 ± 25	1007	373	36	112
10	2000 ± 25	723.6	100	14.6	51	20	2000 ± 25	974	292	29.4	64

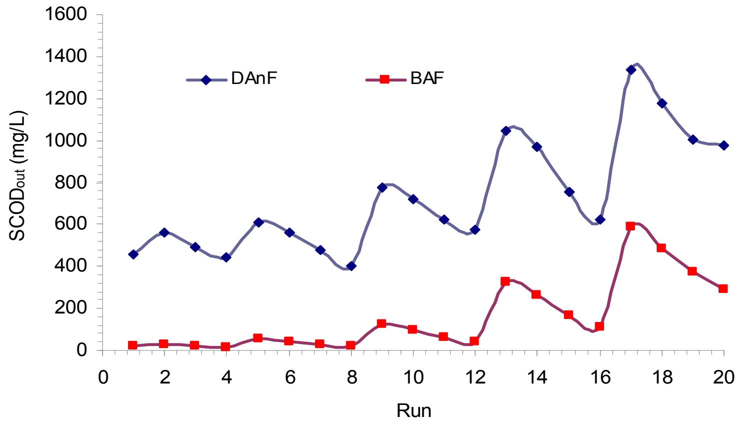

Fig 2: $SCOD_{out}$ variation in different operations (Runs) of the bioreactors

Table 5: SCOD removal efficiency for DAnF, BAF and the hybrid system (E), %

Run	1*	2	3	4	5*	6	7	8	9*	10	11	12	13*	14	15	16	17*	18	19	20
DAnF	77.2	71.9	75.3	77.8	69.4	72	76	79.9	61.3	63.8	68.7	71.4	47.8	51.6	62.3	68.9	33.3	41.2	49.7	51.3
BAF	95	95.6	96	96.2	91	92	94	94.5	84	86.2	89.9	92.7	69	73	78	82	56	59	63	70
overall	98.9	98.8	99	99.2	97.3	97.8	98.6	98.9	93.8	95	96.9	97.9	83.8	86.9	91.7	94.4	70.7	75.9	81.4	85.4

*: Operation without recirculation

Fig. 2 shows the variation of outflow soluble COD with different operations (Run) of system. In Table 5 the results of SCOD removal efficiency for DAnF, BAF and hybrid system (overall) are shown; also, in Figs. 3 and 4 the variations of SCOD removal efficiency with HRT and different recycling rate (Runs) are respectively shown .

In Fig. 4 the variation of SCOD removal efficiency during the different runs is shown.
It should be noted that almost in all references, among them (Rusten, 1984), it is confirmed that the criterion for submerged filters design is the rate of volumetric organic load (VOL) on the filter media.

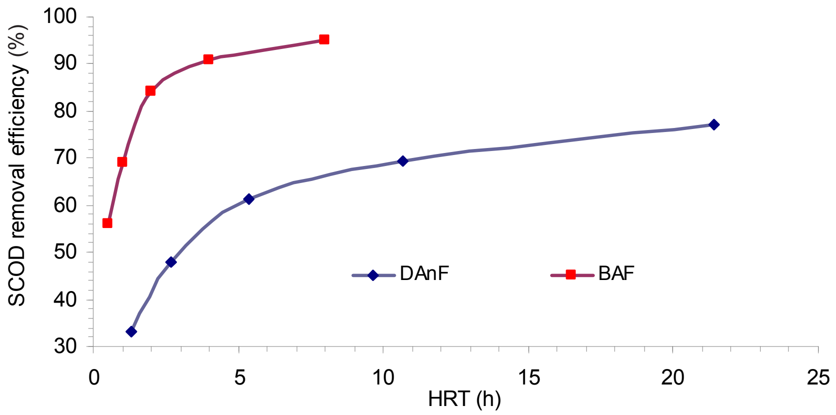

Fig 3: Variations of $SCOD_{out}$ percentage

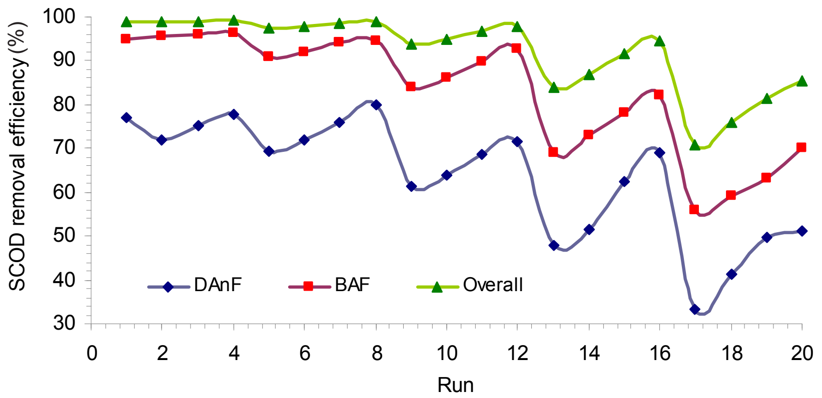

Fig 4: Variations of $SCOD_{out}$removal efficiency removal with HRT at 30°C with different runs at 30°C

The rate of substrate removal in aerobic and anaerobic filter is obtained from the Stover – Kincannon function (Stover, 1982; Borghei, 2008), such as Eq. 11:

$$r_{COD} = r_{max} \frac{B_{COD}}{k + B_{COD}} \quad (11)$$

r_{COD} is the rate of the substrate removal, r_{max} is the maximum rate of substrate removal, B_{COD} is the organic load per unit volume of the filter and k is the constant of half velocity. All the parameters are in kg SCOD/m^3.d.

Returning to Eq. 11, it can be rewritten in the form of:

$$\frac{1}{r_{COD}} = \frac{k}{r_{max}} \times \frac{1}{B_{COD}} + \frac{1}{r_{max}} \quad (12)$$

The values of B_{COD} and r_{COD} could be obtained from the following equations:

$$B_{COD} = \frac{Q}{V} C_i \quad (13)$$

$$r_{COD} = \frac{Q}{V} (C_i - C_e) \quad (14)$$

Using equations 13, 14 and Tables 1 and 4, values of B_{COD} and r_{COD} could be computed for various situations. The main values are presented in Table 6.

By taking Eq. 12 in a linear form, coefficients k and r_{max} could be extracted. Table 7 shows the values of these coefficients.

Table 6: Volumetric load and removal of SCOD in bioreactors at 30^{o}C

Run	DAnF B_{COD} (Kg SCOD/m^3.d)	DAnF r_{COD} (Kg SCOD/m^3.d)	BAF B_{COD} (Kg SCOD/m^3.d)	BAF r_{COD} (Kg SCOD/m^3.d)
0	0	0	0	0
1	1.9138	1.4775	1.133	1.076
5	3.826	2.6552	3.040	2.766
9	7.6536	4.6917	7.691	6.461
13	15.3056	7.3161	20.746	14.315
17	30.6113	10.1936	53.017	29.690

From substitution of the values in Table 7 into Eq. 11, diagrams in Fig. 5 are obtained. Moreover, each filter possess a limited ultimate strength of soluble substrate removal in volumetric loading which is independent from HRT. The values of these ultimate strengths, r_{max}, are presented in Table 7. Using the graphs in Fig. 5, submerged filters could be designed.

Table 7: Coefficients k and r_{max} of the bioreactors at 30^{o}C

Coefficient	DAnF	BAF
K (Kg SCOD/m^3.d	19.65	54.93
r_{max}(Kg SCOD/m^3.d	16.58	53.19

The results in Table 4 and the diagrams in Fig. 6 show the outflow VSS of the bioreactors. This outflow sludge (VSS_{out}), is in fact the excess sludge, which should be minimized in submerged filters.

Analysing these results, with a nonlinear regression model using the software Curve Expert, the best model with highest regression was selected. The Multiple Multiplicative Factor (MMF) model with a one variable nonlinear regression showed a good regression for the results in this table.

Structure of this model is shown in the form of the following equation:

$$y = (ab + cx^d)/(b + x^d) \quad (15)$$

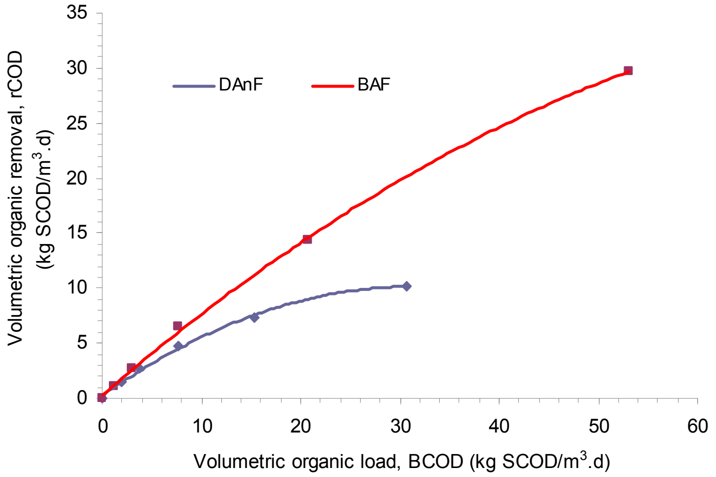

Fig 5: Organic loading of bioreactors at 30°C

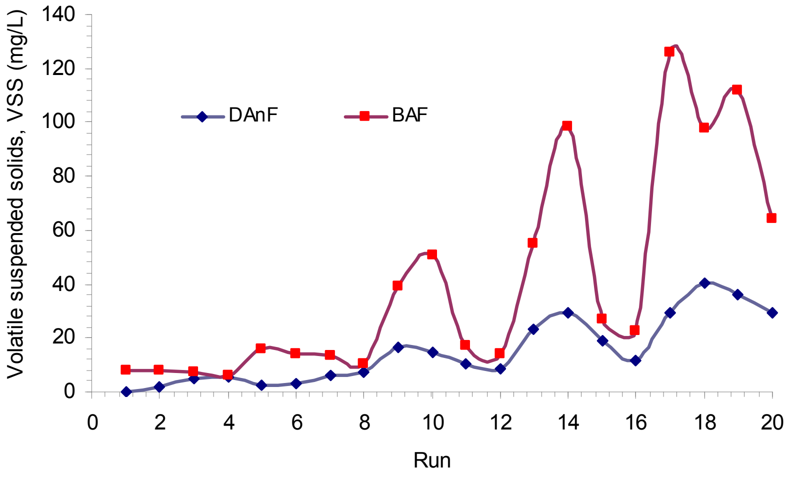

Fig 6: VSS_{out} variation in different operations (Run) of the bioreactors

In this equation, x is the volumetric organic removal, kg SCOD/m^3.d, and y is the outflow VSS from the reactor in gr/m^3. Also, a, b, c, and d are constants.

In Figs. 7 and 8, the regressions of this model on the results in Tables 4 and 5 are shown.

The values of a, b, c, and d of MMF model are presented in Table 8.

In Table 9 the results of observed yield coefficients (Y) for DAnF, BAF, and combined system (overall) are shown. Observed yield (Y) is equal to $(VSS_{out}-VSS_{in})/(SCOD_{in}-SCOD_{out})$.

As it is seen, the observed yield coefficients are negative values for all runs of anaerobic filter except for the runs without recirculation.

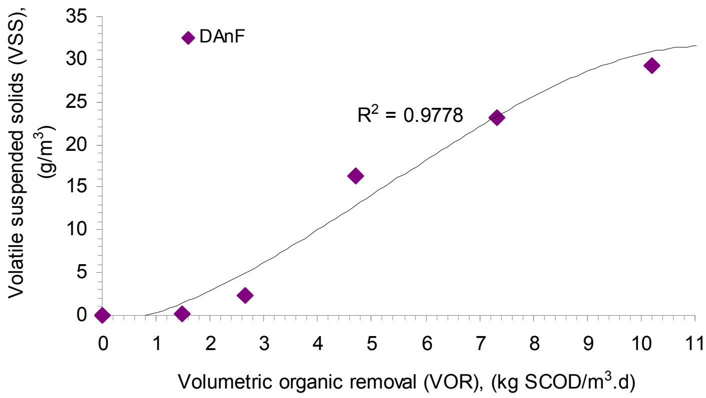

Fig 7: MMF model for outflow

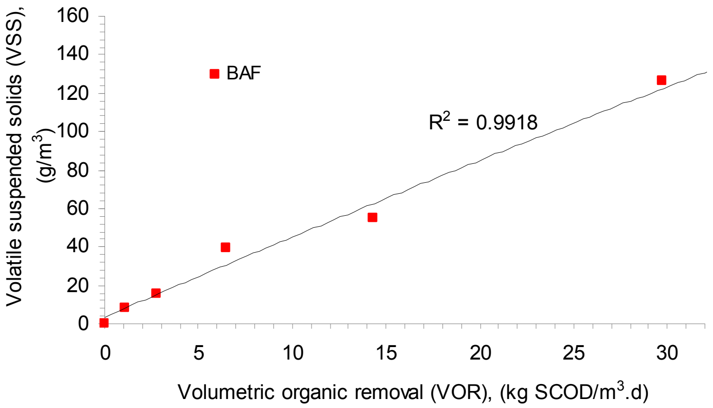

Fig 8: MMF model for outflow VSS from DAnF at 30°C VSS from BAF at 30°C

Table 8: Values of constants in the MMF model for outflow VSS at 30°C

	Constants			
Bioreactor	a	b	c	d
DAnF	-0.2945	218.8	29.97	3.51
BAF	1.556	28297968	1.495 E 10^8	0.926

These values are positive for all runs of aerated filter. The reason for decrement of Y in the overall system is the combination of DAnF and BAF in serial condition with recirculation of flow from BAF to DAnF.

The variations of Y_{DAnF}, Y_{BAF}, and $Y_{overall}$ are presented in Fig. 9.

Table 9: Observed yield coefficient (Y) for DAnF, BAF and hybrid system (overall), (kg VSS /kg SCOD)

Run	DAnF	BAF	Overall	Run	DAnF	BAF	Overall	Run	DAnF	BAF	Overall	Run	DAnF	BAF	Overall
1*	0.0001	0.018	0.004	6	-0.0077	0.0216	0.0073	11	-0.0049	0.0119	0.0088	16	-0.0081	0.0218	0.012
2	-0.0044	0.0117	0.0041	7	-0.0049	0.0164	0.0068	12	-0.0038	0.0102	0.0072	17*	0.0438	0.1296	0.0892
3	-0.0015	0.0046	0.0036	8	-0.0018	0.0076	0.0051	13*	0.0242	0.0443	0.0328	18	-0.0701	0.0831	0.0646
4	-0.0007	0.0026	0.0032	9*	0.0133	0.0349	0.0208	14	-0.0667	0.0973	0.0566	19	-0.0765	0.1199	0.0688
5*	0.0017	0.0244	0.0082	10	-0.0285	0.0584	0.0268	15	-0.0067	0.0143	0.0148	20	-0.0337	0.0507	0.0375

*: Operation without recirculation

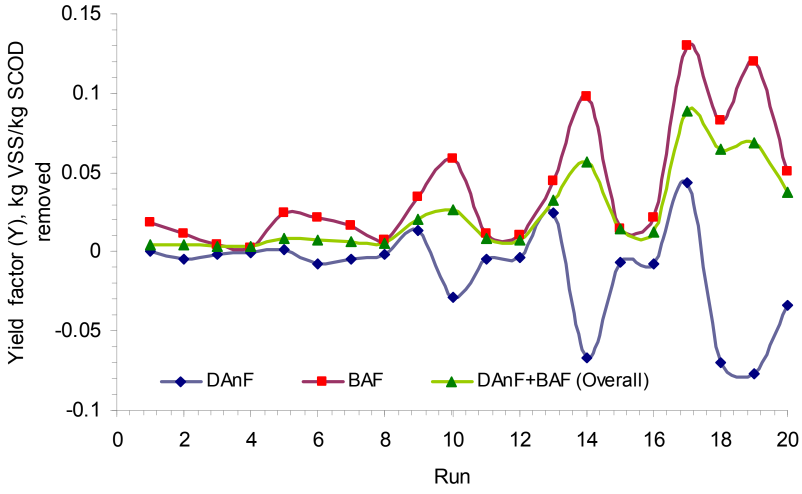

Fig 9: Variation of Yield factor in different operations (Run)

DISCUSSION

In this research, the effect of the return of the flow from an aerobic filter to an anaerobic filter for reduction of excess sludge in wastewater treatment was investigated using a physical model in pilot scale consisting of two filters of submerged aerobic and anaerobic types. These two filters were connected to eachother in a series form and were loaded by syntheetic wastewater based on sucrose.

Results (Fig. 3) showed that in both filters, the SCOD removal efficiency increases with HRT. As it was expected, with similar loadings, the aerobic filter showed a better efficiency of 1.8 times that of the anaerobic filter from the viewpoint of the removal of soluble organic matters.

Also, in both filters, and therefore in overall condition, the SCOD removal efficiency increases with recirculation rate. 100% return of the flow from the aerobic filter to the anaerobic filter for 30kg/m^3.d of organic loading increased the efficiencies of the aerated filter, the anaerobic filter and the combined system as 17%, 19% and 15%, respectively and the effect of the return of the flow was more pronounced in smaller hydraulic retention times and larger loadings.

From the viewpoint of excess sludge production, the yield factor, as a criterion in sludge production, in the aerobic filter was 3 to 14 times that of the anaerobic filter for different loadings. The yield factor of the whole system, however, was half of the yield factor of the aerobic filter for different loadings, from the viewpoint of the excess sludge production, for 100% return of the flow. For 53 kg/m^3 loading, the yield factor of the aerobic filter was 0.13 which is a suitable value compared to the other wastewater treatment schemes and with 100% return of the flow this value reduced to 0.05 which shows the extremely important role of the anaerobic filter in excess sludge reduction. The maximum of the observed yield factor was 0.04 for 30.61kg/m^3 which reduced to -0.03 for 100% return of the flow and removal of suspended organic matters. For maximum organic loading of 53 kg/m^3, the yield factor reached 0.037 for 100% return of the flow which is a suitable value with regard to the scheme and no use of chemical materials such as chlorine and ozone with yield factor of 0.16 and 0 to 0.3 (and Yasui *et al*., 1996; Sakai *et al*., 1997; Kamiya *et al*., 1998; Song *et al*., 2003; Takdastan *et al*., 2009) or increase of oxygen in activated sludge flocs with yield factor of 0.2 (Abbasi *et al*., 2000). Also, this factor reached a value as small as 0.007 in common loadings (7.5 kg/m^3) for 100% return of the flow which is very close to zero. So, this method could be considered as a complete biological treatment with low excess sludge and could be assessed in large scale.

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