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A Comparative Study on Performance of Two Aerobic Sequencing Batch Reactors with Flocculated and Granulated Sludge Treating an Industrial Estate Wastewater: Process Analysis and Modeling

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ABSTRACT

In this study, the performance of two aerobic sequencing batch reactors (SBR) in removing carbon and nutrient (N & P) from Faraman's industrial estate wastewater (FIW) with flocculated and granulated sludge was compared. The comparison study was performed by varying two significant independent variables (aeration time and mixed liquor volatile suspended solids (MLVSS)). The experiments were conducted based on a central composite design (CCD) and analyzed using response surface methodology (RSM). The region of exploration for the process was taken as the area enclosed by aeration time (6-24 h) and MLVSS (2000-7000 mg/L) boundaries. The results showed that the granulated sludge system was more efficient than the flocculated sludge system in removing the non-biodegradable COD (nbCOD), total nitrogen (TN), total phosphorus (TP) and other sludge studied characteristics. The performance of both systems was almost the same for COD removal in FIW with a maximum removal of about 70 %.

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NOMENCLATURE

AS	Activated sludge	*PAOs*	Phosphorus accumulating organisms
AFFFBR	Anaerobic fixed film fixed bed reactor	*PCOD*	Particulate COD
BOD_5/COD	Biochemical oxygen demand to chemical oxygen demand ratio	*PTA*	Purified terephthalic acid
CNP	Carbon, nitrogen and phosphorous	*PNP*	Para-nitro phenol
CSTR	Continuously stirred tank reactor	*PHB*	Poly hydroxy butyrate
DO	Dissolved oxygen	*RBC*	Rotating biological contactor
FIW	Faraman's industrial estate wastewater	*SBR*	Sequencing batch reactor
FSS	Flocculated sludge	*SCOD*	Soluble COD
F/M	Food to microorganism ratio	*SND*	Simultaneous nitrification–denitrification
GSS	Granulated sludge	*TN*	Total nitrogen
nbCOD	Non biodegradable COD	*TP*	Total phosphorus
PAOs	Phosphorus accumulating organisms	*TCOD*	Total COD
PCOD	Particulate COD	*UAASB*	Up-flow aerobic anoxic sludge bed
PTA	Purified terephthalic acid	*UASB*	Up-flow anaerobic sludge bed

1. INTRODUCTION

Industrial wastewater causes severe hazards to receiving water bodies and indirectly threatens human health. Therefore, the release of such wastewaters is firmly regulated, and companies are responsible to ensure the discharge quality is environmental friendly manner. Selection of a suitable treatment process for an industrial wastewater is totally depended on the wastewater characteristics. The composition of industrial effluents is characterized by its high structural diversity of constituents and concentration level [1].

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Table 1 shows a summary of types of reactors used for biological treatment on various types of industrial wastewaters [2-13]. From Table 1, it can be concluded that despite applying two bioreactors, the COD removal efficiencies are still low except for the food industrial effluents, implying remarkable inhibiting impact of non-biodegradable COD (nbCOD) on the process performance.

Nutrient removal from wastewater is of vital importance as the discharge standards have been more stringent. Many physico-chemical and biological methods are used to remove nitrogen compounds; however biological methods are of more attention because of their lower cost and reliability. Basically, biological nitrogen removal (BNR) consists of nitrification and denitrification processes.

Simultaneous nitrification–denitrification (SND) is usually performed in a single reactor for deletion of nitrogen compounds from wastewater with smaller reactor volume, lower energy consumption and easier operation [14-16].

Phosphorus can be removed in biological treatment by repetitive operation of anaerobic and aerobic steps by polyphosphate accumulating bacteria (PAOs) in the form of poly-p. Accordingly, alternating oxygen conditions are needed to remove nitrogen and phosphorus simultaneously with traditional activated sludge. However, the integrated N and P removal in single aeration basins can occurr in the presence of anaerobic zone in dense aerobic activated sludge [14].

Aerobic granule technology has been investigated for over 10 years for wastewater treatment. It is noted that biogranules can not occur naturally, and they must be cultivated in specific conditions with strong selective pressure. Many have reported that aerobic granules can be typically achieved in sequencing batch reactors (SBR) [17-20]. In comparison with conventional activated sludge, aerobic granule has regular and compact physical structure, diversified microbial species, good settling property, high biomass retention, and great ability to withstand shock load or shock of toxic compounds. Therefore, aerobic granule is becoming a promising technology for wastewater treatment [23-26].

The role of microbial aggregations form (flocculated and granulated structure) in an aerobic treatment system removing nbCOD and nutrients from an industrial estate's wastewater with low BOD/COD ratio has not been studied up to this date. Therefore, this study was aimed to compare the performance of granulated and flocculated sludge in CNP removal from FIW in two parallel SBRs.

In addition to the process analysis, a general factorial design was employed to describe and model eight significant responses as a function of two independent variables, aeration time and mixed liquor volatile suspended solids (MLVSS). The process responses selected are total COD (TCOD) removal, BOD removal, nbCOD removal, total nitrogen (TN) removal, total phosphorus (TP) removal, sludge volume index (SVI), settling velocity and effluent turbidity.

TABLE 1. Biological treatment of different industrial wastewaters in various treatment systems.

No.	Type of Wastewater	Type of Reactor	COD Removal, %	HRT, h	Ref.
1	Wool acid dying	UASB + CSTR	51-84	17	[2]
2	Pulp and paper industry	UASB + CSTR	85	12	[3]
3	Green olive debittering	CSTR + AS	73	120	[4]
4	Cotton textile mill	UASB + CSTR	40-85	120	[5]
5	PNP effluent	SBR	49	8	[6]
6	Food solid waste leachate	2 UASBs + CSTR	96–98	138	[7]
7	PTA effluent	AFFFBR +AS	96.4	23–27.2	[8]
8	Textile industry	Packed column reactor + AS	50–85	22–82	[9]
9	Food canning wastewater	RBC	93.7	40	[10]
10	petroleum refinery industry	CSTR	96	144	[11]
11	Industrial estate wastewater	UAASB	93	12	[12]
12	Palm oil mill effluent	UASFFB	na	24	[13]

UASB: upflow anaerobic sludge bed, CSTR: continuously stirred tank reactor, AS: activated sludge, RBC: rotating biological contactors, SBR: sequencing batch reactor, AFFFBR: anaerobic fixed film fixed bed reactor, PTA: purified terephthalic acid, PNP: Para-nitro phenol.

2. MATHEMATICAL MODEL

2. 1. Faraman's Industrial Estate Wastewater (FIW) Wastewater sample was taken from a working wastewater treatment plant in Faraman Industrial estate, Kermanshah, Iran. The samples were stored in a cold room at 4 °C. This storage technique had no observable effect on its composition. The FIW characteristics are shown in Table 2. COD:N:P ratio of the FIW was almost 100:15:2.

2. 2. Granule Cultivation The original biomass aggregation collected from Faraman's industrial estate wastewater treatment plant was in the form of conventional flocs. A bubble column type reactor with a working volume of 2L was used for granule cultivation. The reactor was inoculated with activated sludge taken from the industrial wastewater treatment plant. The reactor was initially operated in 4-h cycles with 30 min settling time and 210 min aeration time. The settling time was stepwisely shortened to 5 min during the granule cultivation. At the beginning of every cycle, a certain amount of synthetic wastewater (about 1.5 L) was added from the top of the reactor, and the effluent was drawn at the bottom of the reactor and the volumetric exchange ratio increased from 55 to 77% during the granule cultivation. In order to enhance granule formation, a synthetic wastewater was used in this stage. The composition of the synthetic wastewater used was as follows: acetate, 500 mg/L; sugar, 500 mg/L; $MgSO_4.7H_2O$, 200 mg/L; $CaCl_2.2H_2O$, 10 mg/L. The cultivation phase lasted for 40 days.

2. 3. Bioreactor Configuration and Operation The schematic diagram of two identical SBR systems is shown in Figure 1. These systems were designed in the form of column for a working volume of 2 L with internal diameter of 8.5 cm and total height of 36 cm. Air was supplied into the reactors by blower and two fine air bubble diffusers from the bottom of the columns. The dissolved oxygen (DO) concentration was maintained at about 7 mg/L. The difference between the two systems was the type of sludge in the system as shown in Figure 1. So, one system was operated with granulated sludge (GSS) and another system was operated with flocculated sludge (FSS). The industrial wastewater was introduced from the top of the reactors.

The following conditions were applied to the SBRs:

a. Filling time of 10 min
b. Mixing without aeration for 40 min, in order to develop anaerobic condition
c. Aeration time (6-24 h)
d. Settling and drawing for 40 min and 10 min, respectively

In each cycle, after settling, about 1.5 L of the supernatant was taken for analysis, and the volume was substituted with fresh wastewater. Anaerobic condition was continuously ensured by monitoring the DO level after 20 min (about 40 min under anaerobic condition). In order to control the DO level in the reactors, an air flow meter and a flow adjustment valve were used for each reactor. The intermittent aeration was supplied by installing a timer on the blower. The process was also operated with safety factor, whereby the solids retention time per cycle time was greater than 40. The volatile fraction of biomass content was determined by measuring VSS. The ratio of MLVSS to MLSS obtained about 0.7 in average.

TABLE 2. Characteristics of Faraman's industrial estate wastewater

Parameters	Unit	Amount
TCOD	(mg/L)	945-1145
SCOD	(mg/L)	478-604
PCOD	(mg/L)	341-601
BOD_U	(mg/L)	388-460
BOD_5	(mg/L)	170-180
nbCOD	(mg/L)	557-682
TN	(mg/L)	135-222
TP	(mg/L)	16-26
TSS	(mg/L)	120-360
pH	-	5.5-7

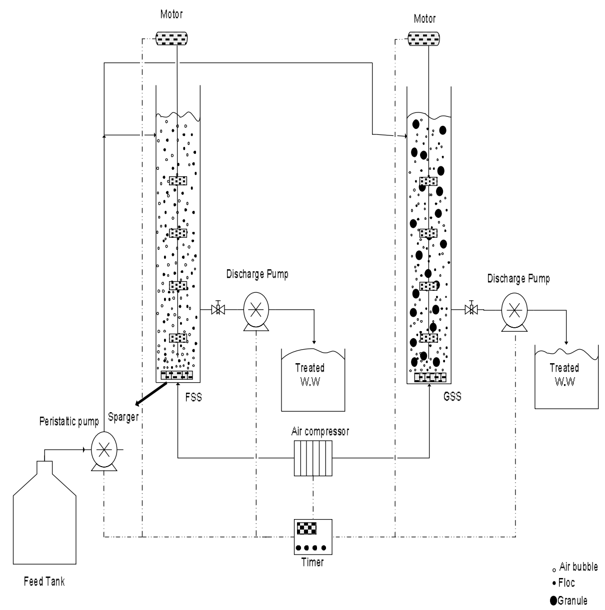


Figure 1. Exprimental setup

2. 4. Experimental Design and Mathematical Model Statistical design of experiments and data analysis was carried out by Design Expert Software (version 7.0). Two independent effective variables, aeration time and MLVSS concentration, were selected in the experiment design. The range and levels of the variables in coded and actual units are given in Table 3. The two operating variables were considered at five levels based on α=0.45.The CCD alpha (α) value is the distance that the star points are located from the center of the design space. It provides two additional experimental points between or beyond the studied range. The allowed range is 0.1 to 6.0. In the basis of the factorial design, 13 experiments (including 4 factorial points, 4 axial points, 1 center point and 4 replications of the center point) were designed. TCOD removal, BOD removal, nbCOD removal, TN removal, TP removal, final turbidity, SVI and settling velocity were measured or calculated as responses. The experimental conditions and results obtained are shown in Table 4.

TABLE 3. Experimental range and levels of the independent variables

	Range and levels				
Variables	-1	-α	0	+α	+1
Aeration time, h	6	11	15	19	24
MLVSS, mg/L	2000	3400	4500	5600	7000

TABLE 4. Experimental conditions and results

Type of system	Variables			Responses							
	Run	Factor1: A:MLVSS mg/L	Factor2 B:Aeratio time, h	TCOD removal, %	rb COD removal, %	BOD removal, %	TN removal, %	TP removal, %	Effluent Turbidity, NTU	SVI mL/g	Settling velocity m/h
	1	2000	6	31.54	19.11	53.63	14.87	36.47	74.4	65	2.54
	2	2000	24	52.66	36.83	80.55	20.99	44.16	50.6	65	2.34
	3	3400	15	43.56	38.29	55.28	28.19	62.21	66	38	2.28
	4	4500	11	53.53	37.57	71.52	26.04	61.82	51.4	41	1.7
	5	4500	15	61.83	44.41	81.49	28.08	84.13	52.7	41	1.74
GSS	6	4500	19	75.19	79.14	68.46	34.04	91.94	55.4	43	1.32
	7	5600	15	58.31	49.87	77.07	30.15	11.4	59.5	40	0.84
	8	7000	6	52.66	28.08	91.11	45.44	2.38	17.5	48	0.43
	9	7000	24	57.28	37.62	88.03	50.38	3.96	18.6	50	0.4
	10	4500	15	64.14	62.97	65.31	35.38	80.1	53	43	1.68
	11	4500	15	50.32	51.56	70.17	30.91	82.21	52.1	42	1.51
	12	4500	15	62.98	60.35	84.65	33.69	81.47	50	40	1.95
	13	4500	15	65.42	55.62	62.56	27.56	78.45	52.6	45	1.61
			6								
	1	2000	24	33.01	21.76	53	7.72	32.67	131	68	2.26
	2	2000	15	40.15	27.47	62.69	16.26	51.57	95.9	72	1.64
	3	3400	11	33.23	13.08	78.09	24.58	72.3	47.7	60	1.52
	4	4500	15	47.04	28.11	68.39	21.65	52.39	41.1	106	0.08
	5	4500	19	53.70	27.55	83.18	23.50	61.01	31	106	0.08
	6	4500	15	64.1	63.71	64.77	20.75	36.56	8.08	113	0.05
FSS	7	5600	6	56.16	40.89	90.15	24.97	56.25	13.1	110	0.04
	8	7000	24	74.64	63.39	92.25	12.76	7.84	11.6	94	0.04
	9	7000	15	68.08	55.12	88.36	38.47	3.56	14.6	94	0.04
	10	4500	15	57.72	35	62.11	23.69	55.41	32.6	108	0.07
	11	4500	15	54.11	38.12	65.25	22.98	45.23	30	100	1.00
	12	4500	15	60.26	32.56	63.5	24.51	50.69	20.45	110	0.06
	13	4500	6	62.13	30.56	70.56	23.92	52.71	33.21	92	0.06

The experimental data obtained was used to determine the coefficients of the polynomial model (Eq. (1)) [27]:

$$Y = \beta_0 + \beta_i X_i + \beta_j X_j + \beta_{ii} X_i^2 + \beta_{jj} X_j^2 + \beta_{ij} X_i X_j + ... \quad (1)$$

where, i and j are the linear and quadratic coefficients respectively, and ß is the regression coefficient. P value with 95 % confidence level was considered to evaluate the effectiveness of the model terms.

2. 5. Analytical Methods The concentrations of chemical oxygen demand (COD), biological oxygen demand (BOD), total Kjeldahl nitrogen (TKN), nitrate, TN, phosphate, MLSS, mixed liquor volatile suspended solid (MLVSS),SVI and settling velocity were determined using standard methods [28]. In this study, the nbCOD was calculated as TCOD-BOD.

A colorimetric method with closed reflux method was developed for COD. Spectrophotometer (DR 5000, Hach, Jenway, USA) at 600 nm was used to measure the absorbance of COD samples.

TKN was determined by TKN meter Gerhardt model (Vapodest 10, Germany). The DO concentration in wastewater was determined using a DO probe. DO meter was supplied by WTW DO Cell OX 330, electro DO probe, Germany. Turbidity was measured by a turbidity meter model 2100 P (HachCo,USA).

3. RESULTS AND DISCUSSION

3. 1. Microbial Granulation The original biomass aggregation collected from Faraman's industrial estate wastewater treatment plant was in the form of conventional flocs. Figure 2 represents the biomass appearance in the duration of the granulation process. Figures 2a and b show the flocculated sludge.
As it is observed in Figure 2, by progressing time the number of integrated flocs formed as pinpoint increased along with the enlargement in their sizes. Scanning electron microscopy (SEM) images of the granules grown after 60 days are presented in Figure 3. From the SEMs, majority of the microbial population in the granule is Coccus with spherical shape which is related to the type of substrate used for cultivation.

Previous reports confirm the findings obtained in this study, dominating non-filamentous and very compact bacteria in the granules grown on acetate [29].

3. 2. Process Performance

3. 2. 1. Carbon removal:

-*TCOD removal:* The ANOVA values for TCOD removal efficiency are shown in Table 5. The experimental data were fitted to two reduce quadratic models for GSS and FSS systems. In GSS, MLVSS content (A), aeration time (B) and A^2 were significant model terms, whereas, A and B were significant model terms in FSS. From the regression models, it is clear that MLVSS content affects more on FSS compared to GSS. Figure 4a and 4b show the simultaneous effect of MLVSS content and the aeration time on the TCOD removal in GSS and FSS, respectively. The maximum value of TCOD removal efficiency in GSS was 68.19 % and 73.89 % in FSS at MLVSS concentration of about 5600 mg/L and aeration time of 24 h, and 7000 mg/L of MLVSS and aeration time of 24 h, respectively. This study showed that the performance of both systems was almost similar in terms of TCOD removal for FIW. A similar result has been reported by Sanchez et al. and Gao et al [30-31]. The efficiency was relatively low because of particulates and non biodegradable residues which account for about 25 and 50 % fraction of TCOD content in FIW.

In order to evaluate the process kinetics, specific substrate utilization rates (U) for GSS and FSS in different conditions were calculated (Table 6). The maximum of U (corresponding to maximum treatment capacity) for GSS and FSS were obtained to be 0.446 and 0.48 $gCOD_{rem}$/L.d, respectively at MLVSS of 2000 mg/L and aeration time of 6h.

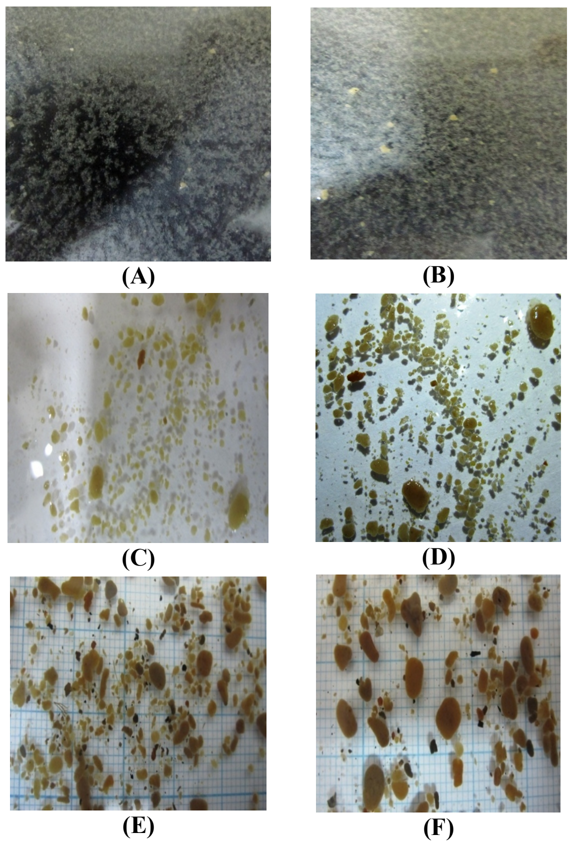
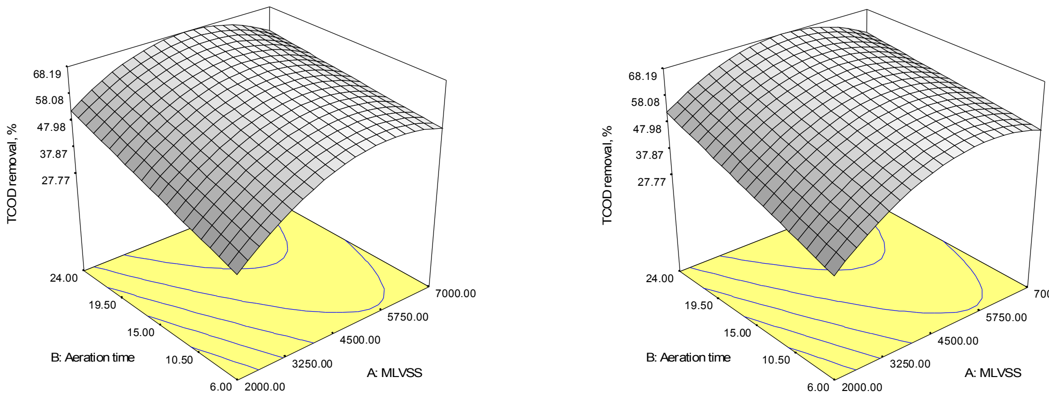


Figure 2. Sequence of aerobic bio-granule formation in the SBR, (A) after 10 days, (B) after 15 days, (C) after 25 days, (D) after 40 days, (E) after 60 days and (F) after 70 days

TABLE 5. ANOVA results for the equations of the Design Expert 6.0.6 for studied responses

Type of System	Response	Modified equations with significant terms	Probability	R^2	Adj.R^2	Adeq. precision	S.D	CV	PRESS	Probability for lack of fit
GSS	COD removal	$59.84+7.43A+8.13B-12.5A^2$	<0.0326	0.6954	0.5431	7.759	7.41	13.32	7475.58	0.2558
	TN removal	$30.52+14.31A+1.03B+1.65A^2$	<0.0002	0.8704	0.8272	14.252	3.88	12.48	541.32	0.2099
	TP removal	$68.30-22.21A+5.06B-49.20A^2$	<0.0375	0.6878	0.5838	6.830	20.77	40.18	6222.41	0.5273
	SVI	$40.84-7.09A+15.97B^2$	<0.0001	0.9172	0.9006	19.3	2.82	6.11	120.46	0.1593
	Settling velocity	$1.51-1.07A$	<0.0001	0.9335	0.9282	26.941	0.18	11.83	0.58	0.2588
	Effluent turbidity	$57.08-20.92A-16.84B^2$	<0.0002	0.8196	0.7835	12.787	7.64	14.87	1448.95	0.2087
FSS	COD removal	$53.92+18.03A+1.93B$	<0.0011	0.7451	0.6942	11.832	7.03	13.03	810	0.0722
	TN removal	$22.94+6.15A+7.88B-4.83B^2+4.25AB$	<0.0003	0.9086	0.8629	16.884	2.68	12.58	2044.88	0.0027
	TP removal	$50.57-18.24A-27.44B^2$	<0.0001	0.8556	0.6778	9.988	11.19	27.10	2096.53	0.4520
	SVI	$102.98+14.95A-21.83A^2$	<0.0019	0.7995	0.7594	11.271	14.11	18.85	2734.07	1.14
	Settling velocity	$0.28-1.02A+0.75A^2$	<0.0003	0.8080	0.7696	11.403	0.38	70.77	2.35	0.6685
	Effluent turbidity	$27.13-49.22A+35.79A^2-10.63B+9.53AB$	<0.0001	0.9656	0.9484	23.809	8.12	20.71	14252.40	0.1208



(A) **(B)**

Figure 4. Response surface plots for TCOD removal efficiency: (A) GSS, (B) FSS.

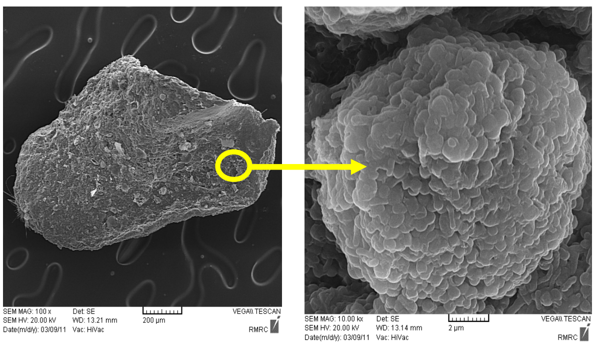


Figure 3. SEM images of aerobic bio-granule after 60 days

-BOD and nbCOD removal The major problem associated with the biological treatment of industrial wastewater is non biodegradable fraction of COD (nbCOD) which inhibits the treatment performance of the bioreactors. In order to investigate the bioreactors performance removing nbCOD, the nbCOD and BOD concentrations at influent and effluent were monitored throughout the experiments. BOD/COD ratio constitutes a good measure of the biodegradability of a wastewater and contaminants. BOD_5/COD ratio of ≥0.4 is generally accepted as biodegradable [32]. Literatures stated that BOD/COD ratio for industrial estate wastewaters is varied from 0.17 to 0.74 [33]. The ratio for FIW was in the range of 0.31-0.5.

Figure 5a and 5b represent the BOD and nbCOD removal efficiencies at different conditions for the GSS and FSS systems, respectively. The figures have been drawn accordingly using the data presented in Table 4. In overall, the GSS showed to be more efficient in removing nbCOD (20-80 % versus 20-60 %). This was owing to the synergistic relationship among the various species in the microbial aggregations in the form of granule which led to a higher decomposition of nbCOD contents [29]. Whereas in the FSS, as the microorganisms are directly subjected to the substrate, the biodegradable fraction of COD are preferred to be consumed [34].

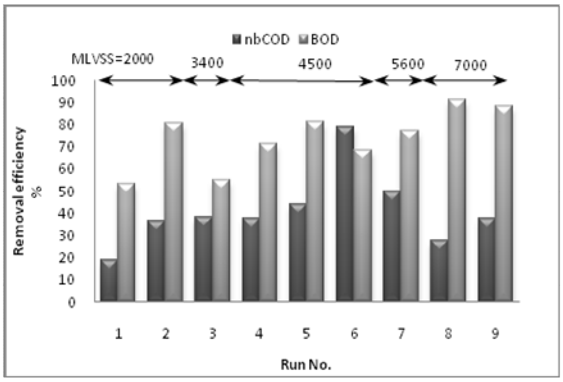
Maximum nbCOD removal efficiency of 80 % was achieved at a condition with MLVSS and aeration time of 4500 mg/L and 19 h, respectively (no. 6). Lower efficiencies were obtained at the higher MLVSS concentrations (5600 and 7000 mg/L). This might be the cause of higher extracellular polymeric substances (EPS) consumption in the GSS compared to the FSS [18, 35].Moreover, at lower MLVSS concentrations (2000 and 3400 mg/L) and high F/M ratio (about 0.4 gCOD/gVSS) caused a decrease in the response. For FSS, MLVSS concentration showed a positive effect on nbCOD removal, resulting in a lower F/M ratio. Furthermore, from Figure 5a and 5b it was noticed that an increase in aeration time caused an increase in nbCOD removal efficiency and also, a slight decrease in BOD removal at high nbCOD removal (no. 6). This is mainly due to less BOD consumption rate compared to nbCOD to bCOD conversion rate [36].

3. 1. 2. Nitrogen Removal The ANOVA results for TN removal efficiency in the GSS and FSS are presented in Table 5. Two reduced quadratic models describe the variation of the TN removal in the studied systems. A, B and A^2 were significant model terms for the GSS while in the FSS, the significant model terms were determined to be A, B, B^2 and AB.

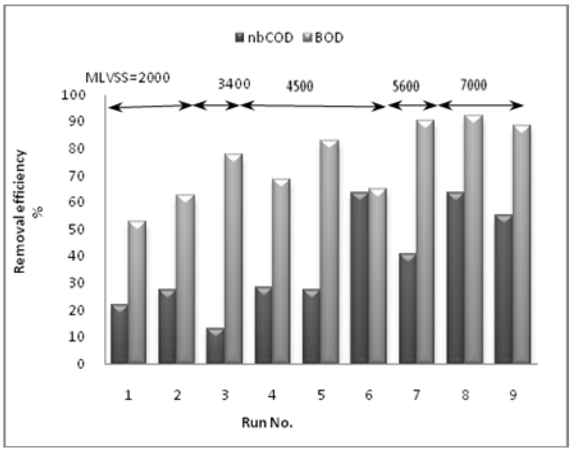
Figures 6a and 6b show the interactive effects of the variables on the response. From this figures it was observed that the maximum values of TN removal efficiency were found to be 47.50 % and 36.39 % for the GSS and FSS, respectively. Figure 6a depicts an increase in the response as a result of an increase in MLVSS concentration. This was due to an anoxic zone development inside the granules resulted from limitation in O_2 transfer to the biomass aggregations [37]. In the FSS (Figure 6b), simultaneous increase in the factors caused an increase in the response, emphasizing that with addition of MLVSS concentration and aeration time, a remarkable impact was observed on the response. There is an established matter about inverse relationship between MLVSS and O_2 concentrations, which is again confirmed in this work [38]. It should be highlighted that the O_2 level in the systems at the late hours was more comparative with conditions with higher organic loads (with a difference about 2-3 mg/L).

TABLE 6. Specific COD utilization rate (U) in different operating conditions

Run	Factor2 B:Aeration time (h)	Factor1 A:MLVSS (mg/L)	Specific substrate utilization rate (U), g/l.d GSS	FSS
1	6	2000	0.446	0.48
2	24	2000	0.199	0.154
3	15	3400	0.144	0.111
4	11	4500	0.209	0.165
5	15	4500	0.197	0.152
6	19	4500	0.191	0.161
7	15	5600	0.159	0.147
8	6	7000	0.242	0.395
9	24	7000	0.057	0.071



(A)



(B)

Figure 5. Removal efficiency of BOD and nbCOD at different operational conditions studied for (A) GSS, and (B) FSS

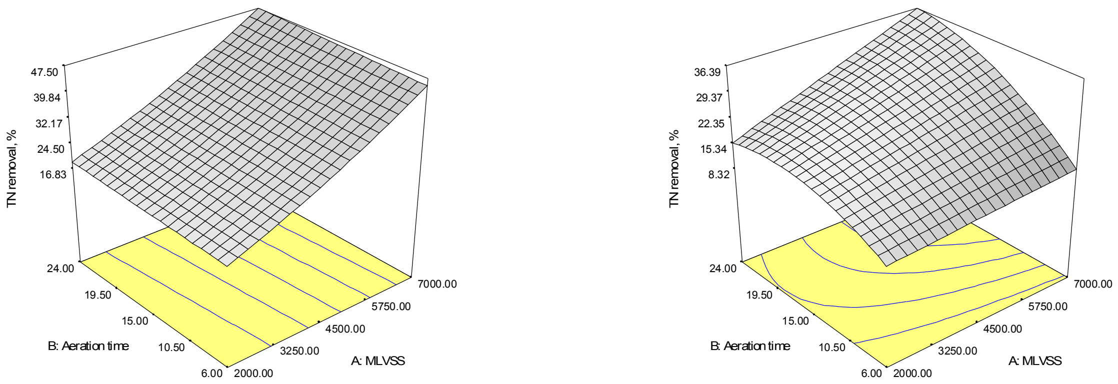
Furthermore, it must be noted that about 30-35 % of the TN removal was related to the cell growth. As it was expected, TN removal in the GSS was higher than the values obtained in this study. The low performance of the GSS could be convinced by two reasons; (1) high dissolved oxygen supplied (about 7 mg/L) and (2) small size of the granules formed (< 0.5 mm). Kreuk et al. (2005) proved that TN removal efficiency in the GSS is strongly depended on the granules diameter [19].

This type of observation was prominently found for GSS in real industrial wastewater, where the granules were gradually disintegrated. However, for GSS fed with synthetic wastewater (acetate and fructose) the granules growth was considerably better.

3. 1. 3. Phosphorus Removal As a granular sludge process was used in the present work, TP removal in the aerobic GSS is probably expected. Therefore, TP removal was determined as a response in this study. Two modified quadratic models described the response variations as a function of the variables in both systems. From the ANOVA results presented in Table 5, A, B and A^2 were the significant model terms for the GSS while for FSS, A and B^2 were the significant model terms.

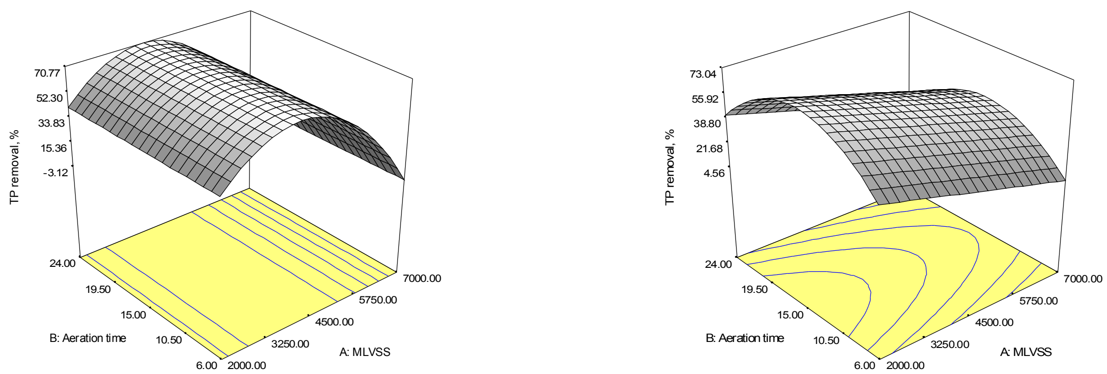
Figures 7a and 7b demonstrate the response versus the variables. In the GSS, as MLVSS increased from 2000 to 4500 mg/L, TP removal efficiency was increased. Further increase in the MLVSS resulted in a decrease in TP removal. It seems that low BOD loading was the cause of decrease in TP removal [39]. Figure 7a shows that for GSS, the aeration time had almost no impact on the response. 6 hours of aeration time was sufficient to achieve highest TP removal percentage. In the FSS, by increasing the aeration time from 6 to 15 h the TP removal efficiency was also higher and this was due to an increase in phosphorus uptake at a longer aeration time [40]. On the other hand, at aeration times longer than 15 h, the trend was inversed. This was owing to deactivation of PAOs originated from inadequate poly hydroxy butyrate (PHB).

The maximum values of TP removal efficiency were found to be 70.77 % and 73.04 % for GSS and FSS, respectively. The relatively high efficiency of TP removal for both systems could be attributed to the low initial phosphorus concentration (about 20 mg/L).



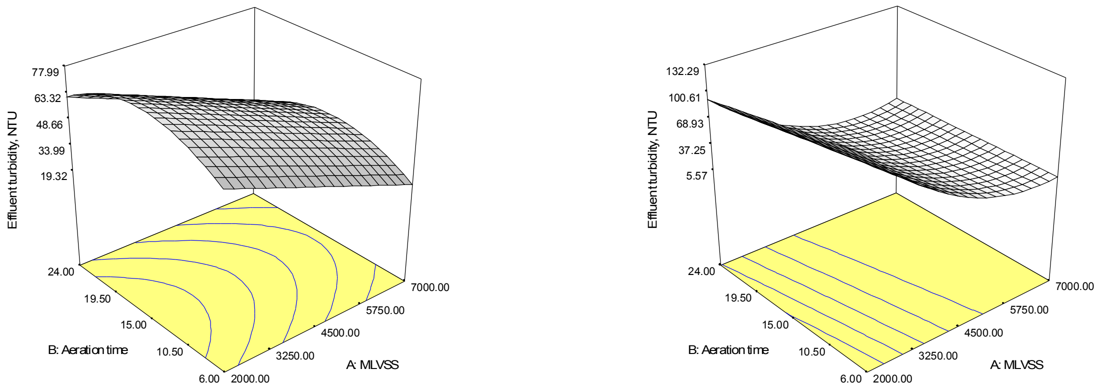
(A) **(B)**

Figure 6. Response surface plots for TN removal efficiency; (A) GSS and (B) FSS



(A) **(B)**

Figure 7. Response surface plots for TP removal efficiency; (A) GSS and (B) FSS



(A) (B)

Figure 8. Response surface plots for effluent turbidity; (A) GSS and (B) FSS

3. 1. 4. Effluent Turbidity Turbidity as a process control parameter indicates the system performance as well as sludge characteristics. From the modified quadratic model presented in Table 5, the MLVSS concentration was found to be the most significant variable. The effects of the variables on the response for the GSS and FSS are shown in Figures 8a and 8b, respectively. As noted in the figures, aeration time had no significant impact on the response. A slight increase on the response in GSS for aeration time in the range of 6 h to 15 h was due to a decrease in F/M ratio which stimulates the growth of filamentous microorganisms. Similar findings were reported in the literature [41]. Figure 8a and 8b demonstrate a lower turbidity reading with an increase in MLVSS and a lesser intensity for GSS. The range of the effluent turbidity obtained for GSS and FSS were 19.32 to 63.32 NTU and 5.57 to 100.61 NTU, respectively. FSS showed a better effluent clarification at MLVSS>2000 mg/L. It is known that at the higher MLVSS the fraction of suspended solids in the sludge cannot be trapped by the granules. As a result, the performance of the GSS in settling the suspended solids at high MLVSS has not been as efficient as obtained in the FSS, implying ascendancy of sweeping mechanism at higher levels of MLVSS in the form of floc [42]. A similar finding was reported by Yilmaz et al. [43].

3. 1. 5. Sludge Volume Index (SVI) From the ANOVA results for SVI presented in Table 5, A and B^2 were observed as significant model terms for the GSS, while for the FSS, A is the only significant term with the first and second order effects. Figure 9a and 9b represent the variation of SVI as a function of the variables in the systems. The results showed that the SVI for the granular sludge was more stable compared to the flocculated one. As observed in the figures, SVI values obtained in GSS (33-63 mL/g) were smaller than those in FSS (66-105 mL/g), indicating a smaller reactor volume required for the GSS compared to FSS. Aeration time showed an inverse impact on SVI in the GSS. Increasing the factor from 6 to 15 h led to a decrease in the response that yield more compact and denser aerobic granules [20-21]. Further increase in the aeration time (15 to 24 h) showed an increase in the response. This might be the cause of deficiency in the biodegradable substrate in this condition, which lead the granules to disintegrate [22]. Minimum amount of SVI (33 mL/g) was obtained at the aeration time and MLVSS of about 15 h and 7000 mg/L respectively. In FSS (Figure 9b), SVI increased with an increase in MLVSS concentration from 2000 to 5000 mg/L. It indicates decreasing impact of high biomass concentration on the flocs compactness caused by low F/M ratio [38].

3. 1. 6. Settling Velocity Observations on the interface of the settling region at different MLSS concentrations showed that the rate of water transfer above the sludge was enhanced by microbial granulation. From the models in Table 5, the significant model terms for GSS were A and A^2 for FSS, indicating that aeration time in the studied range had no impact on the systems for settling velocity.

Figures 9c and 9d demonstrate simultaneous effects of the variables on the response for both systems. The trend represented in both figures, confirms the typical relationship between gravitational solid flux and suspended solids concentration [42]. The data showed that at the same suspended solid concentration, the settling velocity for the granulated sludge is larger than the flocculated sludge. It implies that the structural characteristics of microbial aggregation have a significant effect on the settling properties.

3. 2. Improving Strategies for the Process Performance In order to improve the process performance removing nutrients as well as minimizing the energy consumption, two solutions were derived from this study. One; operating the systems with a lower DO level by reducing the rate of aeration and the other one; operating the systems with intermittent aeration regime. Therefore, to validate the performance additional experiments were conducted.

In this section, the GSS and FSS treating the FIW were examined at 4500 mg/L of MLVSS and 15 h of aeration time and with different aeration strategies (extended aeration with DO≈3 mg/L, and intermittent aeration with 40 min/h). In order to analyze and compare the process performance of the systems, the responses were measured and tabulated in Table 7.

From Table 7, it can be deduced that reduction in the oxygen level from 7 to 3 mg/L with extended aeration mode resulted in decrease in TCOD, nbCOD and BOD removal efficiencies for both systems. This was because of the less oxidation. However, this level of DO did not show any significant impact on TN removal.

The amount of phosphate uptake normally depends on the concentration of DO in the granulated sludge because DO provides an anoxic zone rather than aerobic zone at low concentration. The experimental results showed that the TP removal decreased from 84 % to 22 %. The same trends were reported in the literature [19, 44]. The oxygen concentration had diminutive effect on TP removal in the FSS.

The effluent turbidity and SVI were considerably improved in low O_2 concentration in GSS, implying more favorable condition compared to high DO concentration [22]. In the second step, the intermittent aeration applied (40 min/h) led to a decrease in TCOD, nbCOD, TP removal, effluent turbidity and SVI and an increase in BOD and TN removal efficiency in the both systems. It is concluded that by optimizing the operation conditions (cycle time and aeration time) under intermittent aeration, the process performance of the SBR removing CNP from the FIW can be improved.

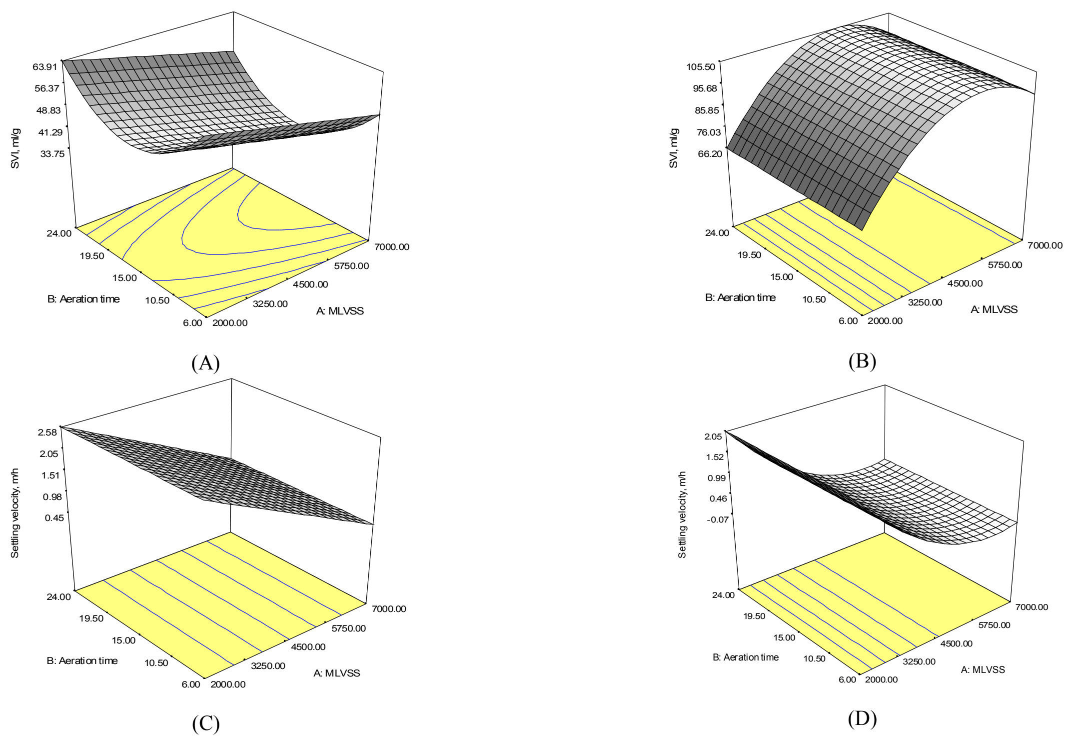


Figure. 9. Response surface plots for SVI; (A) GSS and (B) FSS; for settling velocity (C) GSS and (D) FSS

TABLE 7. The performance of the bioreactors at different aeration strategies

		Responses						
Type of system	**Experimental conditions**	**TCOD removal, %**	**nbCOD removal, %**	**BOD removal, %**	**TN removal, %**	**TP removal, %**	**Effluent turbidity NTU**	**SVI mL/g**
GSS	Extended aeration, 7 mg/L	61	44	81	28	84	52.7	41
	Extended aeration, 3 mg/L	22	1	47	30	22	5	33
	Intermittent aeration	51	23	85	75	48	35	33
FSS	Extended aeration, 7 mg/L	53	27	83	23	61	31	106
	Extended aeration, 3 mg/L	24	1	50	22	62	24	110
	Intermittent aeration	43	9	84	33	35	39.3	100

Decrease in TCOD and nbCOD removal efficiencies was because of low biodegradability of the raw wastewater which needs longer aeration time. Whereas, decrease in TP was owing to denitrification prior to PHB accumulation by PAOs [39], proved by increase in TN removal efficiency.

4. CONCLUSIONS

The experimental work, along with the data analysis, led to the following conclusions. The results showed that GSS was more efficient compared to FSS in removing nbCOD, TN, and TP. GSS gave a better sludge characteristic. The performance of both systems treating FIW in terms of COD removal was almost similar (maximum in both system was approximately 70%). The maximum values of TN removal efficiency were found to be 47.5 % and 36.39 % for the GSS and FSS, respectively. The FSS showed a better effluent clarification except at the low MLVSS (2000 mg/L) compared with the GSS system. DO reduction in the systems (especially for the GSS) improved TN removal. As a conclusion, by intermittent aeration, the BOD and TN removal from FIW in the SBR could be improved.

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A Comparative Study on Performance of Two Aerobic Sequencing Batch Reactors with Flocculated and Granulated Sludge Treating an Industrial Estate Wastewater: Process Analysis and Modeling

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چکیده

در این مطالعه، عملکرد دو واکنشگاه زیستی ناپیوسته منقطع با لجن های لخته ای و گرانولی به منظور حذف کربن و مواد مغذی از فاضلاب شهرک صنعتی فرامان مقایسه شده اند. این مطالعه مقایسه ای با تغییر دادن دو متغیر موثر مستقل (زمان هوادهی و غلظت لجنموجود) انجام شد. آزمایشات بر اساس طراحی ترکیب مرکزی (CCD) سازمان دهی و سپس با استفاده از روش پاسخ سطحی (RSM) ، تحلیل شدند. دامنه تغییرات غلظت لجنموجود و زمان هوادهی به ترتیب ۷۰۰۰-۲۰۰۰ میلی گرم بر لیتر و ۲٤-٦ ساعت می باشند. نتایج نشان می دهند که سیستم لجن گرانولی عملکرد بهتری درحذف CODهای غیر قابل تجزیه پذیری بیولوژیکی(nbCOD) ، کل نیتروژن(TN)، کل فسفر(TP) و سایر ویژگی های لجن مطالعه شده دارد. راندمان حذف COD در هر دو سیستم تقریبا مشابه بوده و بیشترین مقدار حدود ٪۷۰ گزارش شده است.

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