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Innovative hybrid-upflow sludge blanket filtration (H-USBF) combined bioreactor for municipal wastewater treatment using response surface methodology

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ABSTRACT

In this study, the performance of the hybrid-upflow sludge blanket filtration bioreactor was studied for municipal wastewater treatment. The response surface methodology was used with three levels in order to investigate the effect of chemical oxygen demand (COD), biomass concentration, hydraulic retention time (HRT), and determining the optimal conditions. A ring-form moving bed packing was used in the bioreactor with a 50% filling ratio. The results showed that the concentration of COD, biomass concentration, and HRT were considerably more than other parameters and biomass concentration had the most effect on the performance of the system. Interaction among the factors was not significant. In addition, the results revealed that increasing of COD concentration led to decrease in the removal rate of COD and the removal percentage increased as the biomass concentration increased. Likewise, HRT had a direct correlation with the removal rate. Optimal levels for the removal of COD were obtained: about 98% for COD concentration levels 200 mg/L, a biomass concentration of 9,800 mg/L, and HRT 12 h.

Keywords: Wastewater treatment; Municipal wastewater; Hybrid growth; USBF; Response surface methodology

1. Introduction

Most conventional wastewater treatments are biological processes which are used at low biomass concentrations. The performance of the wastewater treatment plants can be improved by increasing the biomass concentration and hydraulic retention time (HRT) in biological systems [1]. Increasing the HRT in these systems make an increase in size of tanks, but it is not considered economically. So the best solution is the increase of biomass concentration in the system [2]. Nowadays, the use of the moving and fix media is increasing due to their small size and high surface area and the increase of wastewater treatment efficiency [3,4]. By adding the media in to the systems, the biomass concentrations is raised, hence an increase in the organic loading rate (OLR) [5].

The upflow sludge blanket filtration (USBF) bioreactors are a novel technology. The USBF process is configuration that incorporates an anoxic selector

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zone, an aeration unit, and an USBF clarifier in an integrated bioreactor [6,7]. In the USBF plant, wastewater enters the anoxic compartment where it mixes with the recycled activated sludge from the bottom of the clarifier. The mixed liquor eventually underflows into the aerobic compartment. After aeration, a stream of the mixed liquor enters the bottom of a prism or cone-shaped clarifier and, as it rises, upward velocity decreases until the flocs of cells become stationary. Then, the sludge flocs are separated from the liquid by USBF and the clear effluent overflows into a collection through and is discharged from the system [7,8].

Mahvi et al. [9], investigated the conventional USBF efficiency in a synthetic municipal wastewater treatment at the aeration times of 2, 4, and 6 h. The system's maximum removal efficiencies for BOD_5, TKN, and TP at the aeration time of 6 h were 82.25, 82.8, and 55%, respectively [9]. Mesdaghinia et al. [10], evaluated the system's performance in terms of chemical oxygen demand (COD) removal with a synthetic wastewater about 86% at HRT of 6 h [10]. Khorsandi et al. [11], designed a novel laboratory scale anaerobic/USBF combined bioreactor. The anaerobic/USBF technique was developed by adding an anaerobic reactor. The combined bioreactor performed a total nitrogen removal efficiency of 96.6% with the sludge age of 25 d, total HRT of 24 h, and optimum "COD/nitrogen/phosphorus" ratio of 100:5:1 [11].

In this study, the performance of a USBF bioreactor by adding moving media in the anoxic and aeration section was investigated for COD removal by using response surface methodology.

2. Material and methods

2.1. Wastewater characterization

Inlet wastewater, which was injected into the bioreactor, was provided for the raw wastewater and wastewater after settling tanks of South Isfahan WWTP. Characteristics of wastewater, which was used in this study, are shown in Table 1.

2.2. Description of the experimental setup

Fig. 1 shows a schematic of the bioreactor that was used in this study. In this study, a tank was applied with the capacity of 500 L, consisted of anoxic 100 L, aeration 300 L, and sedimentation tank 100 L. The sedimentation tank was formed cone-shaped in the middle of the tank bioreactor. The required air in the aerobic section was supplied by installation of the aeration stones in the bottom tank that was returned to the anoxic section, and disposal of excess sludge in a sedimentation tank were carried out by the airlift system, which was designed in the tank.

Table 1
Characteristics of the inlet wastewater

Parameter	Value		
COD (mg/L)	200 ± 20	400 ± 50	600 ± 80
BOD_5 (mg/L)	110 ± 10	245 ± 48	332 ± 68
pH	7.2–7.7	7.4–7.8	7.4–7.78
TSS_{in} (mg/L)	130 ± 15	235 ± 26	308 ± 38
VSS/TSS	0.79	0.81	0.88

The ring form type media is used in the pilot. The media specifications are summarized in Table 2. The ring form *type media's* with a filling reactor volume ratio of 50% is utilized in the anoxic and aeration sections.

2.3. Start-up and operation

The factors and their selected levels are presented in Table 3.

In order to start up, the bioreactor was used on the excess activated sludge in the secondary sedimentation tank of south Isfahan wastewater treatment plant for inoculation. pH was adjusted between 7.3 and 7.8. The anoxic and the aeration sections dissolved oxygen are maintained less than 0.5 and set between 3.6 mg/L and 5.1 mg/L, respectively. The sampling was carried out from the bioreactor inlet and outlet. The experiments are performed according to standard methods for examination of water and wastewater [12]. The initial feed, with OLR 0.2 kg COD/m^3 d, was injected in order to compatibility of micro-organisms with contaminants and the biofilm formation on the media. The media is placed in a different tank for biofilm formation and is inserted to the anoxic and aeration sections after about 40 d. Then the bioreactor performance was studied after compatibility of micro-organisms, biofilm formation on the media, and adjusting the suspended biomass concentration of 3,000 mg/L. Due to slight changes in the attached biomass concentration after the biofilm formation, performance of bioreactor was studied by changing the suspended biomass concentration at three levels. Attached biomass concentration was in the range of 3,150–3,600 mg/L. This way, the performance of the bioreactor was examined by COD concentration of 200 ± 20 mg/L at biomass concentration of 6,000 mg/L (suspended biomass concentration at 3,000 mg/L) at three levels of HRT of 6, 9, and 12 h. Then the biomass concentration was increased to 8,000 and 10,000 as mg/L, at the same HRT, and the system performance was evaluated for the removal of COD.

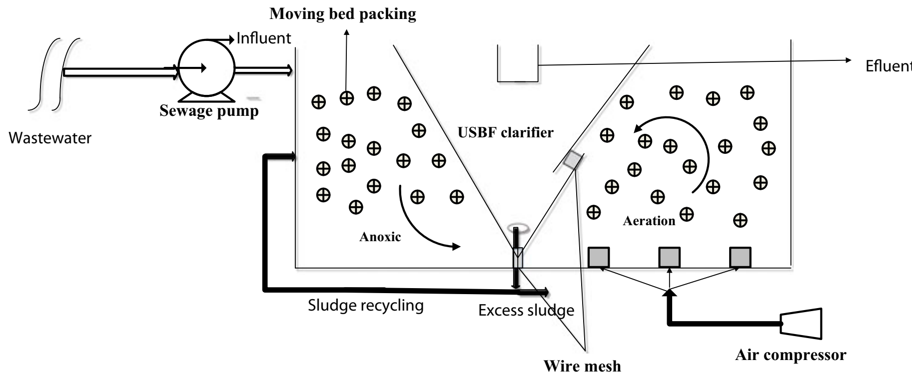

Fig. 1. Schematic view of the H-USBF system used in this study.

Table 2
The media specifications

Manufacturer	Density (g/cm^3)	Media weight of per liter (g)	Number of media per liter	Specific surface area (m^2/m^3)	Material
NPGH-CO (Iran)	0.98	63	160	375	Special polymers with biological adsorbent

Table 3
Factors and selected parameters

Factor	Level		
COD (mg/L)	200	400	600
Biomass concentration (mg/L)	6,000	8,000	10,000
HRT_{total} (h)	6	9	12

In the next step, all the previous sections were done except the COD concentration of entering into the bioreactor (400 ± 50 and 600 ± 80 mg/L) that was changed compared to before section.

The gravimetric method is used to measure the attached biomass concentration [13,14].

2.4. Experimental design

The response surface methodology is an effective method for response optimization. In this method, Box–Behnken design is adopted to optimize the responses [15,16]. This design includes three trihedral factors, and presents 15 experiment runs to conduct. The Design Expert software 8.0.1 was used for this design and for the statistical analysis of the results. The confidence level was taken as 95%. Experimental results were in compliance with the proposed model with the coefficient of determination and residuals plot were expressed. A second order polynomial is presented by the design approach to fit the experimental data as [15–18]:

$$Y = b_0 + b_1X_1 + b_2X_2 + b_3X_3 + b_{11}X_1^2 + b_{22}X_2^2 + b_{33}X_3^2 + b_{12}X_1X_2 + b_{13}X_1X_3 + b_{23}X_2X_3$$

where X_1, X_2, X_3 represent the coded levels of the independent variables and b_0, b_i, b_{ij} (i,j = 1, 2, 3) are the coefficient estimates, and b_0 is the interception, b_i is the linear terms, b_{ii} is the quadric terms, and b_{ij} is the interaction terms.

In this study, the purpose is maximizing COD removal percentage that is considered as response.

3. Results and discussion

Input parameters COD, biomass concentration, and HRT to evaluate the performance of hybrid-upflow sludge blanket filtration (H-USBF) bioreactor was studied. The experimental design based on the Box–Behnken method and the measured COD removal efficiencies are presented in Table 4.

The significant factors are the ones in which their amount of p-value is less than 0.05 and in the confident level of 95%. The factors with the higher F-ratio have greater effect on the system performance.

3.1. Effect of factors (COD, Biomass concentration, and HRT)

The analysis of variance (ANOVA) is presented in Table 5. According to the results presented in Table 5, *p*-value of COD, biomass concentration, and HRT was less than 0.05. Whenever the *F*-ratio is higher, the effect of that factor will be greater on the response. Therefore, the factors of COD, biomass concentration, and HRT had more effect on the response, respectively. Interaction between other factors is not important.

3.1.1. Effect of COD

The contour plots in Figs. 2–4 show the COD removal rate at varying levels of COD, biomass concentration, and HRT. The results of Figs. 2 and 3 indicate that by increasing the concentration of COD the removal efficiency decreased. Increasing of OLR led to decreasing efficiency. When the OLR increased, the ability of Micro-organisms can decrease in consumption of organic materials as food and subsequently, the efficiency of the system in the COD removal decreases. The results which are presented in Table 4 indicate that maximum response is seen in the COD equal to 200 mg/L.

3.1.2. Effect of biomass concentration

According to Figs. 2 and 4, the COD removal efficiency increases as the biomass concentration increases. In this case, increasing efficiency was due to the increasing population of micro-organisms in the biological systems, which by increasing of these organic materials was consumed further by micro-organisms and thus reduce the effluent COD concentration.

3.1.3. Effect of HRT

Figs. 3 and 4 show that the COD removal rate has direct correlation with the HRT. Thus, the COD removal efficiency increases by increasing HRT. Increasing of removal efficiency was due to the reduction ratio of food per micro-organisms (*F*/*M*) in the system. According to ANOVA table, the interaction of other factors was not also significant.

3.2. Contribution factors

The factors that their *F*-ratio is less than one should be deleted from the ANOVA table and added to their contribution to the error. The value of *F*-ratio for *AB*, *AC*, and C^2 interactions is less than one. These factors should be deleted from ANOVA table and its contribution should be added to error. After deleting these factors, the contribution percentage calculated for other factors was expressed through Eq. (1) as follows [15,17]:

$$\text{Contribution percentage}\,(\%) = \frac{\text{SS}_\text{i}}{\text{SS}_\text{total}}\left(\frac{F_\text{i}-1}{F_\text{i}}\right)\times 100 \tag{1}$$

Fig. 5 shows the contribution percentage factors for COD removal.

Table 4
Box–Behnken method results

Experiment No.	COD (mg/L)	Biomass concentration (mg/L)	HRT_total (h)	COD removal percentage
1	600	6,000	9	89.7
2	600	8,000	6	91.2
3	400	8,000	9	94.9
4	600	10,000	9	93.8
5	200	8,000	6	94.6
6	400	6,000	6	89.8
7	200	8,000	12	96.3
8	400	8,000	9	94.1
9	400	10,000	12	97.2
10	400	8,000	9	95.2
11	200	10,000	9	97.6
12	200	6,000	9	92.8
13	400	6,000	12	93.3
14	600	8,000	12	93.7
15	400	10,000	6	95

Table 5
ANOVA for COD removal rate

Model terms	Sum of the error squares (SS)	Mean square error (MS)	Degree of freedom	F-ratio	p-value	Status
Model	77.66	78.69	9	41.92	0.0004	Significant
A: COD	21.32	21.32	1	103.56	0.0002	Significant
B: Biomass concentration	40.59	40.59	1	197.16	<0.0001	Significant
C: HRT	12.10	12.10	1	58.79	0.0006	Significant
B × A	0.15	0.15	1	0.74	0.4293	Not significant
C × A	0.19	0.19	1	0.94	0.3767	Not significant
C × B	0.45	0.45	1	2.18	0.1998	Not significant
A × A	1.23	1.23	1	6.00	0.0580	Not significant
B × B	1.77	1.77	1	8.62	0.0324	Significant
C × C	0.17	0.17	1	0.82	0.4077	Not significant
Lack of fit	0.13	0.38	3	0.39	0.7735	Not significant
Pure error	0.32	0.65	2	–	–	–
Total	78.69	–	14	–	–	–

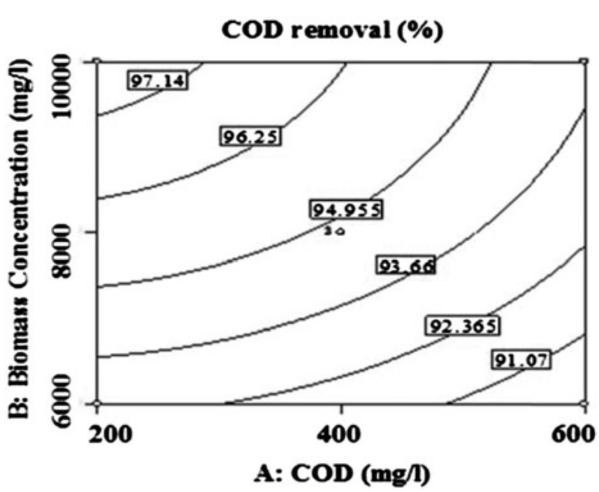

Fig. 2. Contour plots of the COD removal efficiency: the effect of COD and biomass concentrations on the removal efficiency of COD at constant HRT.

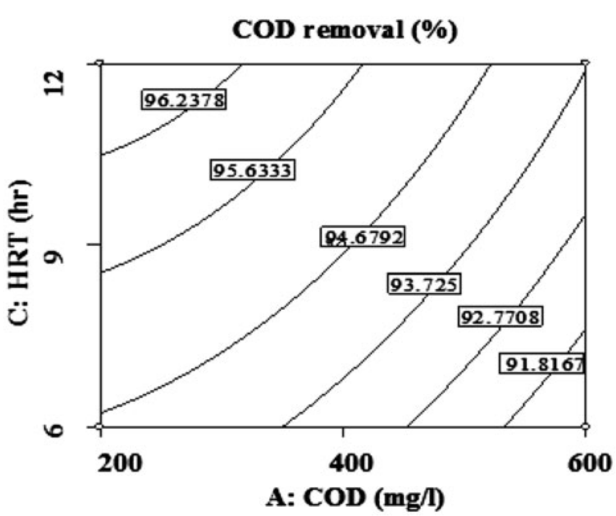

Fig. 3. The effect of COD and HRT on the removal efficiency at constant biomass concentration.

3.3. Model

The mathematical model based on actual values for COD removal percentages are expressed through Eq. (2) as follows:

$$R_1(\%) = 94.74 - 1.6325A + 2.2525B + 1.23C - 0.195AB + 0.22AC - 0.335BC - 0.5783A^2 - 0.6933 \times B^2 - 0.2133 \times C^2 \tag{2}$$

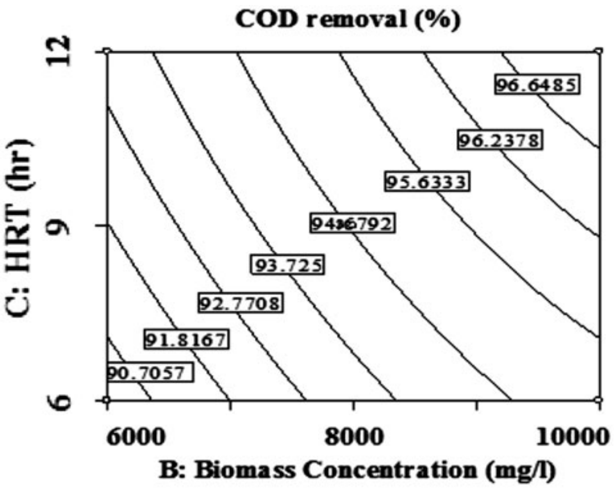

Fig. 4. The effect of HRT and biomass concentration on the removal efficiency at COD constant.

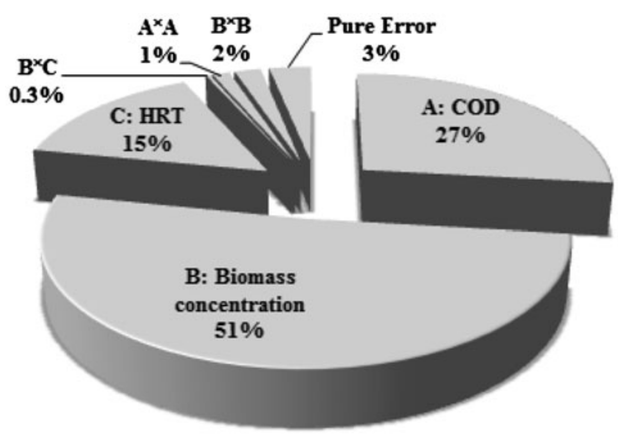

Fig. 5. The contribution percentage factors for COD removal.

The validation of quadratic polynomial model was confirmed by diagnostic plots such as the predicted vs. experimental values. The data points on this plot lie reasonably close to the straight line and indicate a high correspondence between the data obtained from the model and the actual data. The regression parameter R^2 is applied to determine the agreement in comparison of the experimental responses to the ones estimated by Box–Behnken method. The R^2 value for Eq. (3) is found to be 0.9869. Since the R^2 values are close to unity it indicates that there is a good correlation between the experimental and predicted removal efficiency from this model and the model can be considered as a good fit. Fig. 6 shows actual plot vs. predicted plot for COD removal.

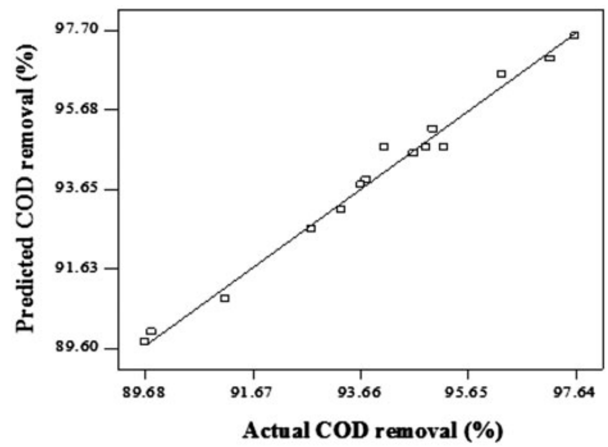

Fig. 6. Actual plot vs. predicted plot for COD removal.

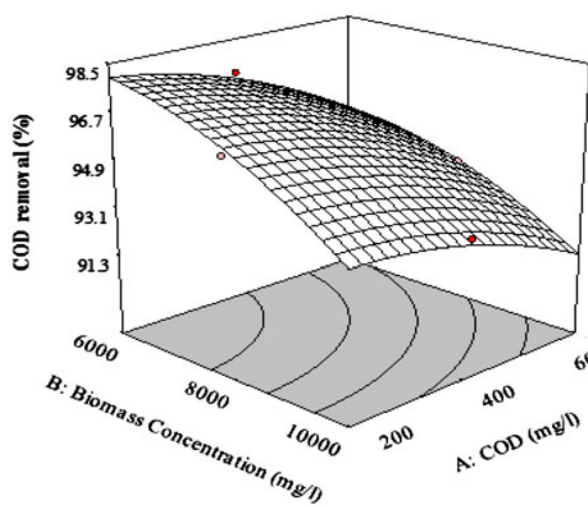

Fig. 7. The 3D plot at optimum condition for COD removal.

3.4. Optimizing process

The optimum conditions for removing COD from municipal wastewater on the basis of Box–Behnken method are estimated at the maximum efficiency of 97.98% and in the COD level about 200 mg/L, biomass concentration of 9,800 mg/L, and total HRT about 12 h that has a reasonably good agreement with the experimental results. Fig. 7 shows the 3D plot at optimum condition for COD removal.

4. Conclusion

The results indicate that H-USBF bioreactor had a suitable approach in the removal of COD. According to tests that were designed in the effect of COD, biomass concentration, and HRT were significant and the biomass concentration had the highest effect on response. Increase of COD concentration led to decreasing of COD removal efficiency and removal efficiency increased by increasing biomass concentration and HRT. Interaction between factors was not significant. The optimum condition for COD removal efficiency was obtained about 98%. The presented model for COD removal was a polynomial model and had a high accordance with experimental results. According to analysis of results, with using of response surface method, it was obtained as the optimum condition and suitable for increasing efficiency of H-USBF.

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