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# Sensitivity study on moving bed hybrid bio-reactor (MBHBR) system treating composite chrome tannery wastewater

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An optimization study was conducted on Moving Bed Hybrid Bioreactor (MBHBR) system while treating composite chrome tannery wastewater. The aim of study was to explore the influence of important variables on performance of MBHBR. To do this a simplified solution of MBHBR Model is used, which depicts the correlation between influent COD (Chemical Oxygen Demand) concentration (So), effluent COD concentration (S), COD flux (J), bio-film density ($X_f$), specific surface area (a), hydraulic retention time ($\theta$) and solid retention time ($\theta_c$). The model used, evaluates the performance quickly and accurately for any known set of input variables. With a view to explore the sensitivity of the said model, crucial parameters like COD loading rate, HRT ($\theta$) and bio-carrier density (C) were varied suitably within their viable ranges. Ultimately, the values of COD removal efficiency were plotted with respect to the relevant input variables for investigating the optimum state under the steady operation. The optimization study reveals that COD loading rate, HRT and the bio-carrier density should be 6 kg/m$^3$/day, 8 h and 75 g/L respectively for the removal of 85% or more COD from chrome tannery wastewater in MBHBR system.

Keywords: MBHBR, mathematical model, simplified solution, optimization study, chrome tannery wastewater.

## Introduction

Moving Bed Hybrid Bioreactor (MBHBR) is the modified version of activated sludge process, in which attached-growth biomass grown on moving carrier particle can float freely in the whole reactor vessel[1].This hybrid technology ensures high biomass content within a reactor system so that desired treatment efficiency can be obtained in a limited volume[2]. Apart from that it has lot of benefits like simple maintenance, better sustainability, higher sludge retention time and capability to withstand toxicity as well as shock loading[3,4]. The modeling of biological process in MBHBR system is already accomplished by different researchers to evaluate its performance. However, interestingly most of them showed various limitations in respect of real-life application[5]. Earlier research studies on MBHBR model showed that computations are complex, lengthy and also not accurate for biofilm. Although pseudo-analytical solution[6] was found to be accurate in some cases, it appeared to be unsuitable for process design and optimization of MBHBR system[7] proposed a fixed bed hybrid bioreactor model, which could be used successfully for optimization of process parameter and treatment of wastewater containing toxic/inhibitory substances with low biodegradability.

In the recent years, many statistical models like factorial model, fraction factorial model, ANNOVA model, CCD-RSM model etc. using some computer aided software tools have been applied to evaluate the performance and to optimize the MBHBR system treating different domestic and industrial wastewater[8] tested CCD-RSM model to examine the effect of HRT, DO and media configuration on MBBR system for combined COD and nitrogen removal from municipal wastewater. Similar studies were reported by various researchers including[9] on anaerobic/anoxic/oxic ($A^2O$) MBBR system to find out the effect of influent COD, HRT and packing media concentration in case of combined removal of organic carbon and nutrients from the synthetically prepared wastewater. However, in most previous studies on statistical modelling, no definite correlation has been found between the output and input variables. Mainly the solution of these models derived some higher order polynomial equations of the input variables as a solution. The optimum condition can be calculated from the higher order polynomial equation using the value of its' partial derivatives equating to zero with respect to the input parameter. However, in most cases the application of statistical models in biological system, especially in biofilm environment appeared to be ineffective in order to describe the system behaviors more precisely.

Under this scenario, a simplified mechanistic model of MBHBR system has been used to predict the substrate concentration in effluent. The developed MBHBR model is based on three assumptions – (1) Substrate diffusion via liquid biofilm interface, (2) Simultaneous use of substrate by the biofilm and suspended biomass and (3) Biomass shear loss, which is the combination of hydraulic shear loss and loss due to inter-particle collision[5]. The analytical solution to this model was made employing FORTRAN program. With a view to establish the optimum condition in MHBHR system a series of simulation studies were carried out employing FORTRAN program. Therefore, the characteristics of composite chrome tannery wastewater and the design parameters like COD loading rate, hydraulic retention time ($\theta$) and bio-carrier concentration (C) were taken into consideration. The parameters were varied within their workable regime and the profiles of variation were shown with respect to effluent COD removal efficiency. Thus the optimum state of such crucial process variables is established from the graphs. This developed methodology will also help in the optimization of process design of a MBHBR system.

## Materials and methods

*(A) Simplified MBHBR model and solution procedure:*

A simplified mathematical model for MBHBR system has been developed using a FORTRAN program to determine the outputs like effluent COD concentration, COD flux, and biofilm thickness. The developed model is based on steady state substrate mass balance and biomass balance both under suspended and attached growth condition concurrently. Monod kinetics was used for substrate utilization for both the phases considering no inhibition. Average substrate flux into the bio-film was also used for calculating the effluent substrate concentration (S). The solution of MBHBR system i.e. steady state effluent substrate concentration (S) was determined as follows. Initially, the substrate mass balance equation was established combining suspended and the attached growth condition assuming suspended growth biomass removes a fraction of substrate and attached growth biomass removes residual fraction. Thereafter, in the combined substrate mass balance equation, the suspended biomass concentration (X) was replaced by the entity developed from biomass balance for the suspended growth. Obviously, the suspended biomass consists of hydraulic shear loss from biofilm and loss due to particle-particle collision. Substrate flux into the biofilm was calculated using the general solution of substrate mass balance into the bio-film. Finally, effluent substrate concentration was calculated replacing substrate flux value in the combined substrate mass balance equation using the iteration process. The schematic diagram of MBHBR system and the basic model equations are given below.

Steady state equation for suspended biomass can be written as:

$$f \times [Q(S_0 - S)] = p \times \left(\frac{k.X.S.V}{K_S + S}\right) \tag{1}$$

Steady state equation for attached biomass can be written as:

$$\{(1 - f) \times [Q\,(S_0 - S)]\} = a \times J' \times V \tag{2}$$

Now, adding the eqs. (1) and (2) the combined equation is derived as given below:

$$S = S_0 - \left[a \times J' \times \theta + \left(\frac{k.X.S.\theta}{K_S + S}\right)p\right] \tag{3}$$

The steady state biomass mass balance for MBHBR system is

$$Q \times (X_0 - X) + \left[V \times X \times \varphi \times \left\{\frac{Y \times K \times S}{K_S + S} - b_d\right\}\right] + \left[V \times \frac{b_s \times J'.a.Y}{b_t}\right] + [V \times R_{abr}] = 0 \tag{4}$$

Now, substituting the expression of 'X' in eq. (3) the final equation for substrate balance yields

$$S = S_0 - [a \times J'.\theta] - \left[\left(\frac{K.S.\theta}{K_S + S}\right) \times \left\{\frac{\frac{X_0}{\theta_c} + \left[\frac{b_c.I_r Y.a}{b_t.p}\right] + \frac{R_{abr}}{p}}{\left(\frac{1}{\theta_c} - \left\{\frac{y.k.s}{K_S + S} - bd\right\}\right)}\right\}\right].p - \tag{5}$$

Now, average substrate flux (J′) can be calculated using the general solution of biofilm as given below[10].

$$J_{avg} = \sum_{i=1}^{6}\sqrt{2\times k\times X_f\times D_f\times\left((Si - S_{min}) + K_s\times \ln\left(\frac{K_s + S_{min}}{K_s + S_i}\right)\right)} \quad (6)$$

Now the substrate balance eq. (5) can be reduced to

$$S = S_0 - [a\times J'\times\theta] - TEMP\times J' \quad (7)$$

where, TEMP =

$$\left[\left(\frac{K.S.\theta}{K_S + S}\right)\times\left\{\frac{\frac{X_0}{\theta_c} + \left[\frac{b_c.Y.a}{b_t.p}\right] + \frac{R_{abr}}{p}}{\left(\frac{1}{\theta_C} - \left\{\frac{y.k.s}{K_S + S} - bd\right\}\right)}\right\}\right].p$$

$$\text{or,}\quad J' = \frac{(S_0 - S)}{(a\times\theta + TEMP)} \quad (8)$$

Now, the eqs. (6) and (8), can be solved by using the iteration process in FORTRAN program. Thereafter, the effluent COD concentration (S) can be computed provided all the input parameters i.e. $\theta$, $\theta_c$, k, $K_s$, Y, $b_s$, $b_t$, $b_d$, $S_0$, $X_f$, a, p, $R_{abr}$ and $L_f$ are given.

*(B) Identifying variables for optimization:*

To optimize the performance of MBHBR system, a set of important input parameters viz. COD loading rates (OLRs), HRT ($\theta$) and bio-carrier concentration (C) were considered. Each relevant input parameter was varied within their realistic range. The influent COD concentration was between (1500±50) and (2500±50) mg/L. The hydraulic retention time was varied between 4 and 12 h at an interval of 2 h and the bio-carrier concentration (C) was changed between 25 and 100 g/L in the step of 25 g/L. Apart from that, following set of kinetic coefficients were considered, K = 3 $day^{-1}$, $K_s$ = 245 mg COD/L,Y = 0.48 mg/mg, $b_t$ = 0.13 $day^{-1}$, $b_s$ = 0.08 $day^{-1}$, $b_d$ = 0.05 $day^{-1}$, $D_f$ = 0.75 $cm^2$/day and $X_f$ = 25 mg/cc and steady state bio-film thickness ($L_f$) = 200 $\mu$m.

## Results and discussion

The effluent substrate concentrations (S) were calculated using FORTRAN program for the developed MBHBR model considering other parameters constant. As a result, % COD removal values were estimated and presented in respect of

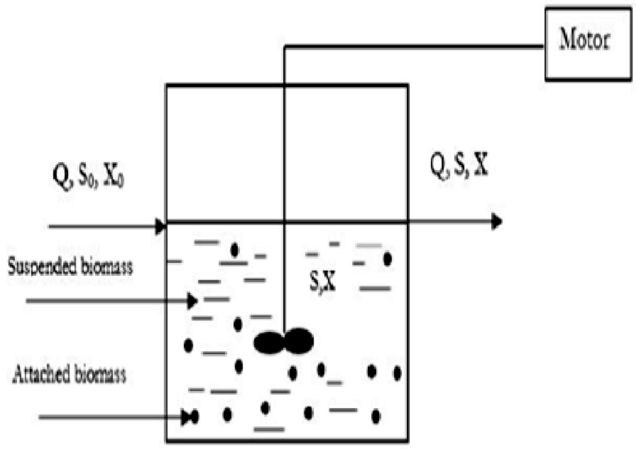


**Fig. 1.** Schematic arrangement of MBHBR system.

OLRs, HRTs and attached bio-carrier concentrations. The profile of % COD removal with respect to OLR is shown in Fig. 2a through Fig. 2d. Similarly, the % COD removal with respect to $\theta$ is presented in Fig. 3a through Fig. 3d. Again, the % COD removal in respect of bio-carrier concentration (C) was plotted in Fig. 4a through Fig. 4d.

The volumetric COD loading rate varied between (3–15) kg /$m^3$/day, resulting in variation of % COD removal between (20–91)%. The % COD removal was varied in the range of (50–60)% for the COD loading rates between (12–16) kg/$m^3$/day and bio-carrier concentration between 75 and 100 g/L under the influent COD concentration between 2000 and 2500 mg/L. Similarly, under the same range of organic loading rates and bio-carrier concentration between 25 and 50 g/L and the influent COD between (2000–2500) mg/L, % COD removal decreases sharply in the range of (20–40)%. The % COD removal varied between (65–75)% for the volumetric loading rate between 6 and 8 kg/$m^3$/day and bio-carrier concentration between 75 and 100 g/L. Finally, a volumetric loading rate ranging between (2–4) kg COD/$m^3$/day, % COD removal was observed between (80–90)% under an influent COD concentration (2000–2500) mg/L. Figs. 2a-2d reveal that % COD removal decreases with the increase in OLRs. However, the rate of decrease is greater for the bio-carrier concentration 25 g/L and 50 g/L respectively than 75 g/L and 100 g/L respectively as shown in Figs. 2a and 2b. The profiles of COD removal efficiency are observed to be almost same with each other, with marginal variation in the different influent COD concentrations in case of 75 g/L and 100 g/L as shown in Figs. 2c and 2d respectively. It implies that there

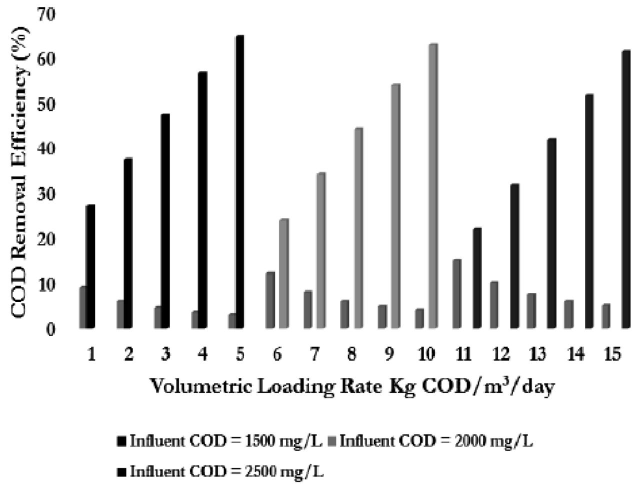


**Fig. 2a.** % COD removal vs volumetric loading rate for attached bio-carrier concentration = 25 g/L.

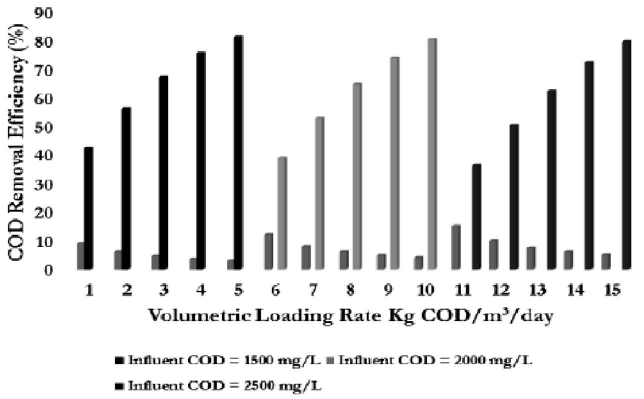


**Fig. 2b.** % COD removal vs COD loading rate for attached bio-carrier concentration = 50 g/L.

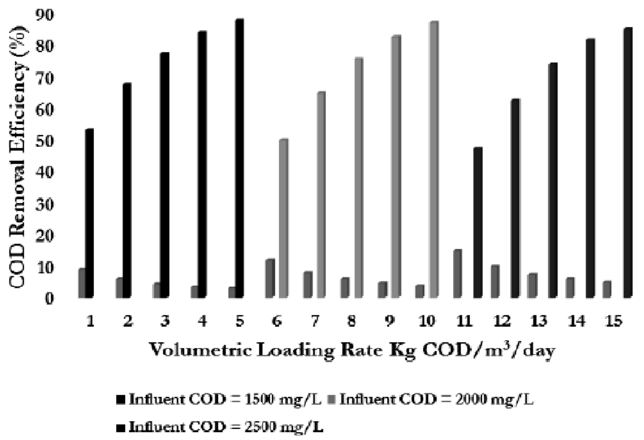


**Fig. 2c.** % COD removal vs COD loading rate for attached bio-carrier concentration = 75 g/L.

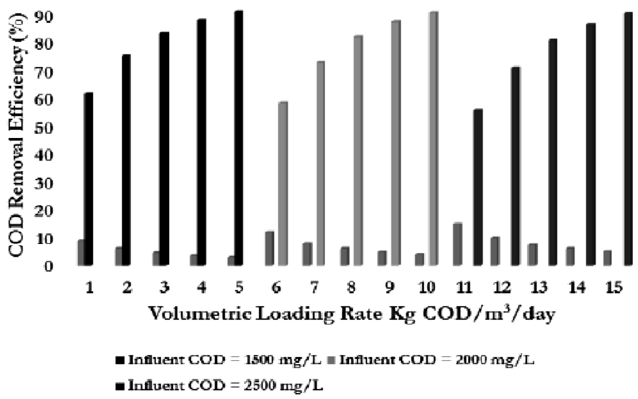


**Fig. 2d.** % COD removal vs COD loading rate for attached bio-carrier concentration = 100 g/L.

will be no further increase in % COD removal efficiency with enhancement in attached bio-carrier concentration for all influent COD concentrations. It is obvious that for a known bio-carrier concentration the biomass can degrade COD up to its maximum capacity beyond that there will be no further increase in % COD removal efficiency. The results clearly present that under an influent COD concentration 2500 mg/L and attached biomass concentration of 75 g/L for 6 kg COD/$m^3$/day organic loading rate, maximum 85% COD removal could be achieved.

Hydraulic retention time varied between 4 and 12 h resulting in variation of COD loading rates between 3 and 15 kg COD/$m^3$/day for an influent COD concentration 1500, 2000 and 2500 mg/L. The FORTRAN program was run for different attached bio-carrier concentration viz. 25 g/L, 50 g/L, 75 g/L and 100 g/L. Accordingly, various % COD removal profile was drawn as shown in Fig. 3a through Fig. 3d. Fig. 3a and Fig. 3b depict that % COD removal efficiency increases almost linearly with the rise in HRT. It implies that the % COD removal is directly proportional to the HRT in case of attached bio-carrier concentration up to 50 g/L. However, in case of attached bio-carrier concentration 75 g/L and 100 g/L, % COD removal profile as shown in Fig. 3c and Fig. 3d respectively exhibited that, COD removal efficiency increased up to 8.0 h. After that no tangible increase in % COD removal efficiency was noticed. Almost same profile has been observed for the attached biomass concentration as shown in Fig. 3d. It depicts that after 8 h onward, a steady-state condition was attained. Maximum % COD removal efficiency varied in the range of 75 to 90% under initial COD concentration of (2000–2500) mg/L for HRT = 8.0 h. In this present optimization study,

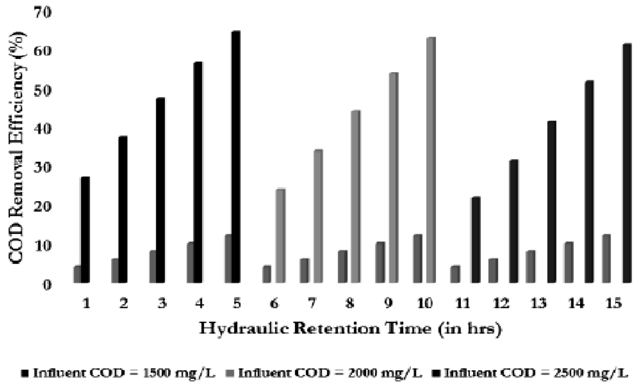


**Fig. 3a.** % COD removal vs HRT for attached bio-carrier concentration = 25 g/L.

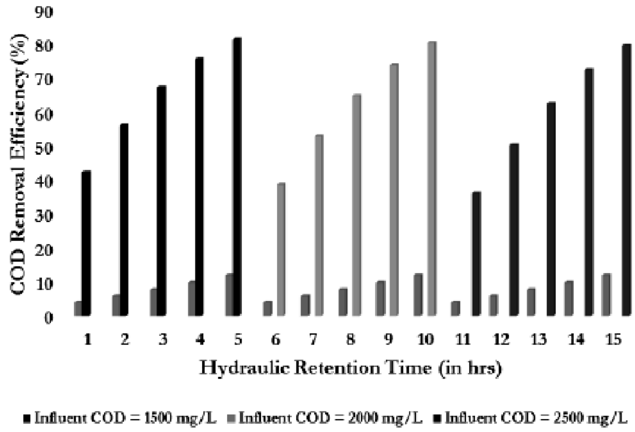


**Fig. 3b.** % COD removal vs HRT for attached bio-carrier concentration = 50 g/L.

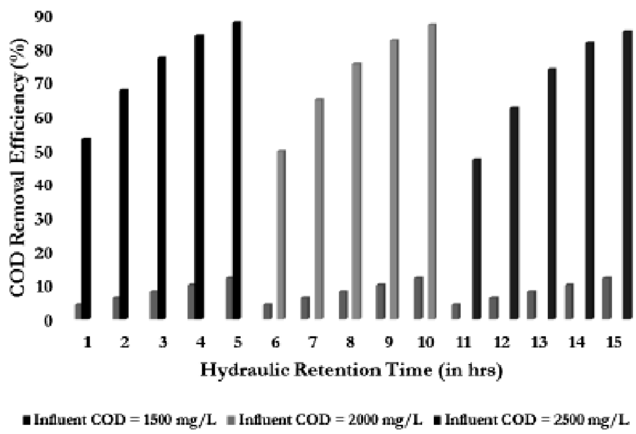


**Fig. 3c.** % COD removal vs HRT for attached bio-carrier concentration = 75 g/L.

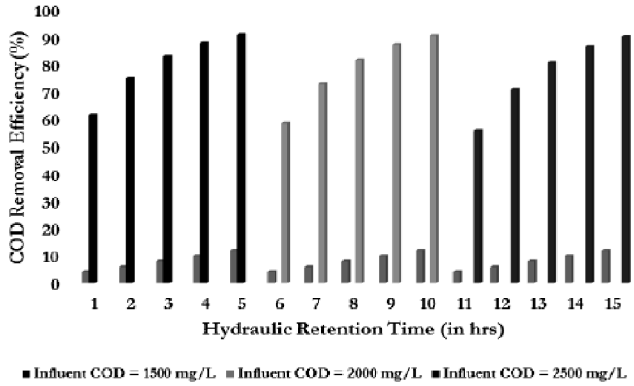


**Fig. 3d. %** COD removal vs HRT for attached bio-carrier concentration = 100 g/L.

to maintain the similarity with conventional activated sludge process (CASP), the HRT was maintained between (8–10) h for the removal of organic carbon in MBHBR system.

The optimization study was also conducted using different attached bio-carrier concentration viz. 25 g/L, 50 g/L, 75 g/L and 100 g/L. The bio-carrier was found to provide 40 mg/g biomass on the surface of bio-carrier at steady state condition. The FORTRAN program was run with initial COD concentration varied between (1500–2500) mg/L. The profiles of variation depict that, % COD removal has been enhanced in all the runs with change in the bio-carrier concentrations. The % COD removal was increased with the increase of bio-carrier concentration. Figs. 4c and 4d showed that (80–85) % COD removal occurred after 8 h. After that very marginal

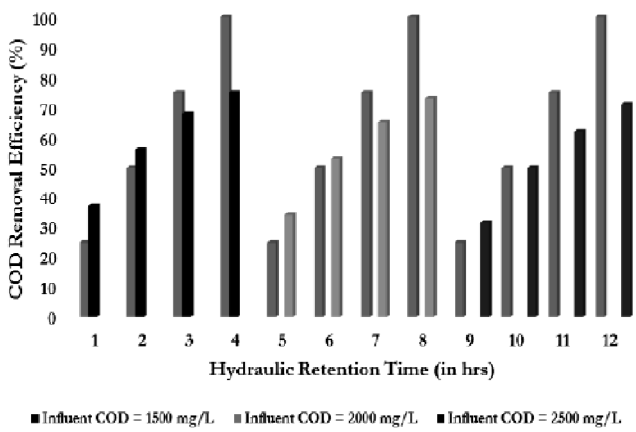


**Fig. 4a.** COD removal efficiency vs attached bio-carrier concentration at hydraulic retention time (HRT) = 6 h.

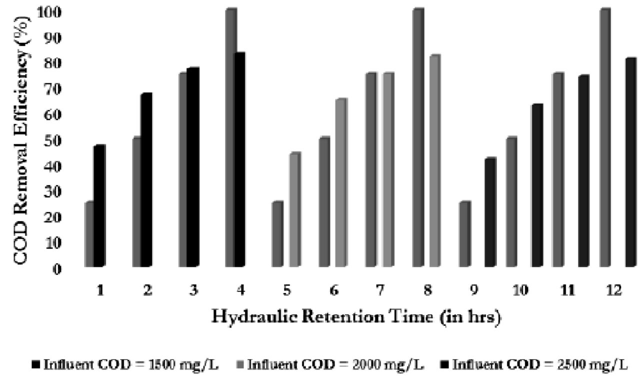


**Fig. 4b.** COD removal efficiency vs attached bio-carrier concentration at hydraulic retention time (HRT) = 8 h.

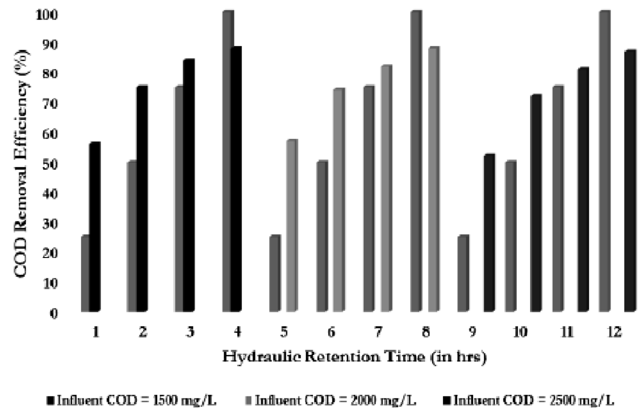


**Fig. 4c.** COD removal efficiency vs attached bio-carrier concentration at hydraulic retention time (HRT) = 10 h.

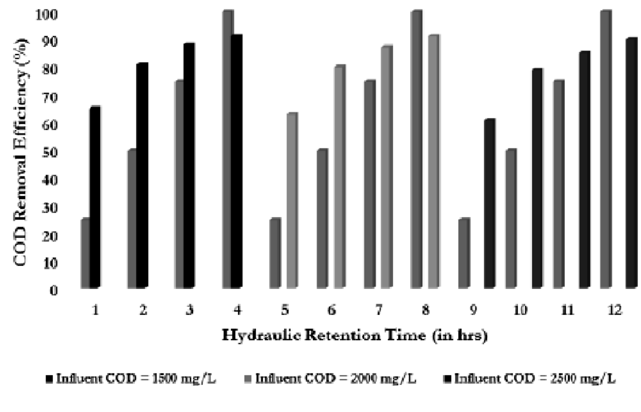


**Fig. 4d.** COD removal efficiency vs attached bio-carrier concentration at hydraulic retention time (HRT) = 12 h.

COD removal has been observed up to 90%. This is because with the rise in $\theta$, total attached biomass also increases and thereafter it reaches a steady state condition with a constant biomass density exhibiting a constant COD removal efficiency. Another possible reason is that with increase in bio-carrier concentration the % COD removal efficiency was not significantly improved because of depletion of DO concentration in reactor resulting in DO constraint in the biofilm. Maximum 85% COD removal was observed after 8 h for bio-carrier concentration 75 g/L.

## Conclusions

The simplified MBHBR model provides an easy method to estimate the effluent COD concentration, substrate flux inside the biofilm along with effective and total biofilm thickness. Apart from that, the same model can be used for an optimization study, which enables to determine the necessary range of input variables like OLR, SRT, HRT and attached bio-carrier concentration, provided all the kinetic parameters and bio-film related properties are given. The present optimization study using FORTRAN program on this present MBHBR model showed that for a given values of kinetic parameters and bio-film related properties, there should be some critical values of input parameters on which the substrate removal efficiency depends. This is also important to understand the influence of important input parameters on process design of a MBHBR system. The flexibility of present approach makes it a useful one to find out the best possible combination to remove the maximum biodegradable substances from wastewater under various operating conditions in MHBHR system. The % COD removal efficiency decreases very marginally upto a limiting value with the increase in OLRs. Practically no influence is noticed up to the limiting value of OLR. Thereafter the % COD efficiency decreases very drastically and the profile is almost linear after the limiting value of OLR, which is presented in graphs. The threshold value of OLR is observed to be 6 kg COD/m$^3$/day. However, the effluent COD concentration is greatly affected by that of the influent.

COD removal efficiency is almost linearly proportional to the HRT upto a limiting value. Thereafter the % COD removal efficiency is more influenced by the HRT with a non-linear profile depicting very marginal enhancement in COD removal efficiency. The limiting HRT value is found to be 8 h. The % COD removal is almost linearly proportional to the bio-carrier concentration exhibiting a positive influence on effluent substance concentration. The COD removal efficiency is affected positively by the bio-carrier concentration upto a limiting value and beyond that there is no influence. The limiting attached biomass concentration is found to be 75 g/L. As a whole, it was found from the optimization study that for 85% or more COD removal in MBHBR system, the optimum conditions of COD loading rate, HRT and the bio-carrier concentrations should be 6 kg/m$^3$/day, 8 h and 75 g/L respectively.

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