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Evaluation of high rate MBBR to predict optimal design parameters for higher carbon and subsequent ammoniacal nitrogen removal

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The high rate moving bed biofilm reactor (MBBR) processes were designed for wastewater treatment to meet the past effluent discharge norms of biological oxygen demand (BOD) <50 mg/l. However, they are incapable of meeting current effluent discharge norms which consist of BOD <10 mg/l and total nitrogen <10 mg/l. This study analyses the effect and variation of organic loading rate from 1.21 kg to 4.59 kg chemical oxygen demand (COD)/(m³ day) and surface loading rate from 4.9 g to 24 g COD/(m² day) on a high rate MBBR performance. The results of COD reduction (COD_{red}) and subsequent ammoniacal nitrogen reduction (NH_3–N_{red}) were in the range of 65.4% to 87.8% and 11.8% to 47.2% respectively. The projected graphical optimization defines the design parameters for MBBR and also predicts COD_{red} and subsequent NH_3–N_{red}. By understanding this subsequent NH_3–N_{red} in the MBBR system, future designs for engineering technologies will be aided.

Keywords: Graphically, HRT, MBBR, optimized, organic load, wastewater.

THE moving bed biofilm reactor (MBBR) technology is commonly known for its high rate wastewater treatment process. In the last decade of the 20th century, this process was studied with great interest, eventually developing in its own technological space. In the 'moving bed biofilm' process, a suspended, porous polymeric is used as a carrier which then moves continuously in the aeration tank, causing the active biomass to grow as a biofilm on the surface of the carrier[1]. In addition, more than 90% of the biomass is attached to the media rather than suspended in the liquid[2]. A number of these characteristics has made the MBBR process more acceptable in the current era. It is a complete mix, compact, with continuous flow through, has high stability against load variation, lower process head loss, and less reactor maintenance including air grid cleaning. There is no sludge recycling, and there is an easy retrofit for existing activated sludge process (ASP) plants with nitrifiers retention and high solids retention time (SRT).

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MBBR processing technology can sustain and effectively treat wastewater of varying organic load due to the self-modifying microbial characteristics of the biofilm. While effective, there are also some processing disadvantages such as, high operating costs, chemical requirements and dedication of large areas entirely to sludge separation and high sludge production[3]. Different combined schemes have been proposed to MBBR process to remove organics and nutrients from wastewater[4]. It is an attached growth (biofilm) process where the available surface area for microbial attachment is one of the designing parameters. Biophysical parameters such as 'provision of surface area for biofilm growth' also termed as 'specific area removal rate' (kg substrate/m² reactor volume per day) or surface loading rate (SLR) and rate of biodegradability also termed as 'volumetric removal rate' (kg substrate/m³ reactor volume per day) or organic loading rate (OLR), are studied as MBBR design parameters. The performance of the MBBR process depends on the percentage of media provided in the reactor[5]. A number of different carriers have been designed and developed for MBBR applications and are differentiated in terms of the types of material used (polyethylene/polypropylene), density (0.9 to 1 g/cm³), and the specific surface area (100 to 1000 m²/m³). Hydraulic retention time (HRT) decides the volume of the reactor and hence the foot print of the secondary process. Based on design data obtained from practical operations of various plants, it was demonstrated that the MBBR may be used in an extremely compact, high-rate process (<1 h total HRT) for secondary treatment[6].

Some of the industrial effluents, such as coking wastewater, was also successfully treated in this process (achieved chemical oxygen demand (COD) reduction 89%) which was designed for 20 h of HRT with a 50% carrier filling ratio[7]. For effective nitrogen removal, MBBR process was based on the modified Ludzack–Ettinger configuration, resulting in higher HRT of 8–18 h (ref. 8). A recent study investigated the behaviour of nitrification in MBBR system which was subjected to high COD input with OLR up to 3.2 kg COD/(m³ day), whereas the MBBR performance which registered above 3.2 kg COD/(m³ day) has not been assessed[9].

In India, MBBR process is accepted, established, and has been in use over the last two decades. There are about 300 to 400 MBBR-based wastewater treatment plant installations found throughout the country[10]. MBBR plants vary from smaller, decentralized capacities of 10 m³/day, to higher capacity sewage treatment plants of up to 20,000 m³/day (ref. 11). Old Indian MBBR installations are designed for a high rate organic carbon removal process, with 2–3 h of HRT, with no focus on nitrogen removal. Although these processes are not designed for ammoniacal nitrogen removal, a parallel or subsequent reduction of ammoniacal nitrogen occurs on account of: (1) Microbial utilization for biological synthesis, and

(2) Conversion through slow rate nitrification. This subsequent nitrogen removal process in high rate MBBR has not been quantified and evaluated. This requires further detailed study and understanding to suitably apply the advantages of MBBR process in the existing and future wastewater treatment designs.

The aim of the present study is to evaluate various process parameters, viz. SLR, OLR, HRT and percent carrier media for maximum simultaneous COD and ammoniacal nitrogen removal in the old MBBR system, thus providing valuable results to further optimize the design conditions for complete nitrogen removal.

A MBBR is prepared by using two cylindrical tanks with a height and diameter of 310 mm and 250 mm respectively, and a 15.2 l volume. Air grid and influent pipes are at the bottom of the reactor as shown in Figure 1. Air from the bottom of the reactor is supplied with a calculated flow rate of 1.8 m³/h to provide oxygen for biological activity of microbial mass, and also for fluidizing the carriers. Two separate peristaltic pumps (Make: Ravel Hitek) are used to feed the influent to both the reactors by maintaining their respective HRTs. Two sludge settlers of 5 litre volume are constructed downstream of the reactors for the purpose of solids separation from the effluent, as well as for the proposed sampling. Considering the range of flow rates studied here, HRT and OLRs varied in the ranges of 2–3 h and 1.21 kg to 4.59 kg COD/(m³ day) respectively. In the present study, circular biofilm carriers were made of PE (polyethylene) plastic (density 0.94–0.96 g/cm³) and were designed specially to provide protected surface areas for microbial biofilm to develop. This inner surface area protected the grown biofilm from shared forces generated by the carrier's movement. Carrier media used in this study offered a specific surface area of 500 m²/m³ (with an outer diameter of 19 mm and inner diameter of 17 mm). The effects of variable carrier media filling/loading fraction from 30% to 60% volume/volume on MBBR performance was also evaluated in this study.

Synthetic wastewater is used as an influent source, which has biodegradable organic and inorganic pollutants such as glucose ($C_6H_{12}O_6$), ammonium chloride (NH_4Cl), di-ammonium phosphate (DAP) and sodium bicarbonate ($NaHCO_3$). Every day fresh synthetic wastewater is prepared as a feed system to meet the targeted concentrations of COD 300 ± 50 mg/l, ammoniacal nitrogen (NH_3–N) 40 ± 5 mg/l and orthophosphate (PO_4–P) 10 ± 3 mg/l.

Pilot experiments were performed in different operating conditions mentioned in Table 1. Synthetic wastewater was prepared in the laboratory and used throughout the experiment, maintaining a constant contaminant's composition. The study included the effect of carrier filling rate, HRT, SLR and OLR on the performance of MBBR in terms of COD and NH_3–N reduction (using 30%, 40%, 50% and 60% of carriers with HRTs of 2 h and 3 h duration). Plastic carrier media were acclimatized
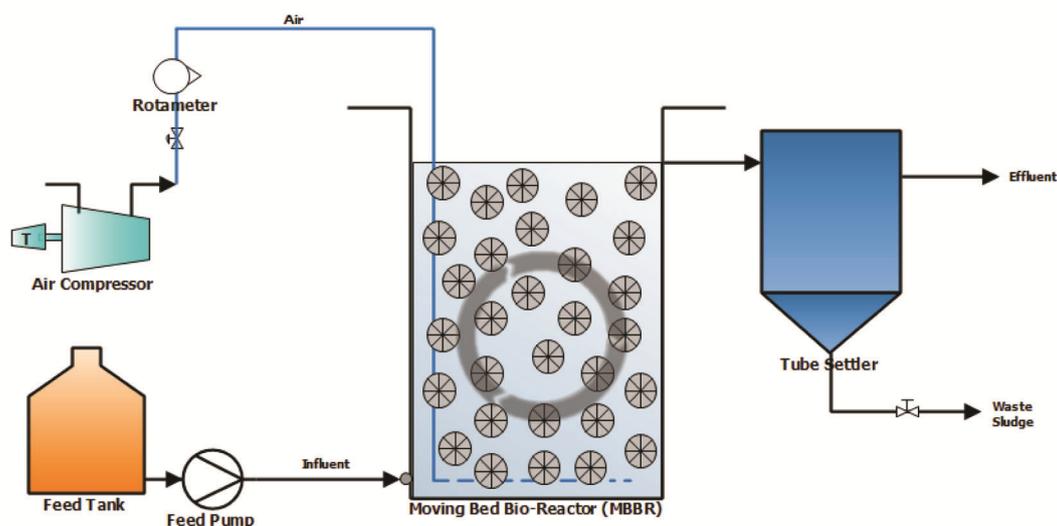
Figure 1. Laboratory setup of high rate moving bed biofilm reactor.

Table 1. Experimental moving bed biofilm reactor operating parameters with given respective organic loading rate (OLR) and surface loading rate (SLR)

| Flow (l/h)	HRT (h)	Media (%)	Average OLR kg $COD/(m^3\ day)$	Average SLR g $COD/(m^2\ day)$
8.5	2	30	3.7	24.65
		40	3.63	18.16
		50	3.32	13.27
		60	3.48	11.56
5.7	3	30	1.56	10.4
		40	2.02	10.09
		50	1.63	6.54
		60	1.48	4.94

COD, Chemical oxygen demand.

in the reactor by providing synthetic wastewater as feed to the system. This acclimatization of carriers lasted for three weeks. Respective sets of carriers were added to the reactors and samples collected every day for analysing total organic carbon (TOC), COD and NH_3–N. During this period, all the above mentioned conditions were monitored, and pH of the reactor was maintained at 7.0 ± 0.5 using $NaHCO_3$. The effect on COD and NH_3–N reduction due to variation in percent carrier media and HRT was a targeted evaluation. Using these readings design parameters such as OLR and SLR were also analysed for their optimization.

During the experimental phase, samples of influents and effluents were collected and filtered with crude filter paper every day. These samples were analysed according to standard and methods[12] protocols. TOC was analysed using TOC analyser (TOC–V CPH, Shimadzu Ltd), while COD was analysed by the APHA method, 5220B (potassium dichromate method), and the analysis of total organic nitrogen and NH_3–N was done by titrimetric method

described in the APHA method (number 4500-NH_{org}B and 4500-NH_3E for all the samples). Finally, graphical method was applied to analyse the experimental readings and to find the optimized design parameters.

Experiments with lower HRT were performed to evaluate the higher rate aerobic oxidation of organics and nitrogen contaminants in the wastewater. HRT governs the reactor volume/sizing as well as influences the treatment efficiencies directly. Effects of 2 h and 3 h HRT experiments were evaluated for COD reduction (COD_{red}) and NH_3–N reduction (NH_3–N_{red}) (Figure 2). The average COD and NH_3–N in the feed water was 294.3 mg/l and 41.1 mg/l respectively, during 2 h HRT experiments. The load increase of the carrier media from 30% to 60% v/v is also shown in Figure 2. The average output (treatment effluent) readings after 2 h aerobic oxidation treatment were COD_{Out} 67.5 mg/l (77.4% COD_{red}) and NH_3–N_{Out} 34.8 mg/l (15.4% NH_3–N_{red}) (Figure 2 a). The analysis of COD and NH_3–N reduction done for a 3 h of HRT shows the average COD_{In} and NH_3–N_{In} to be 209.2 mg/l and
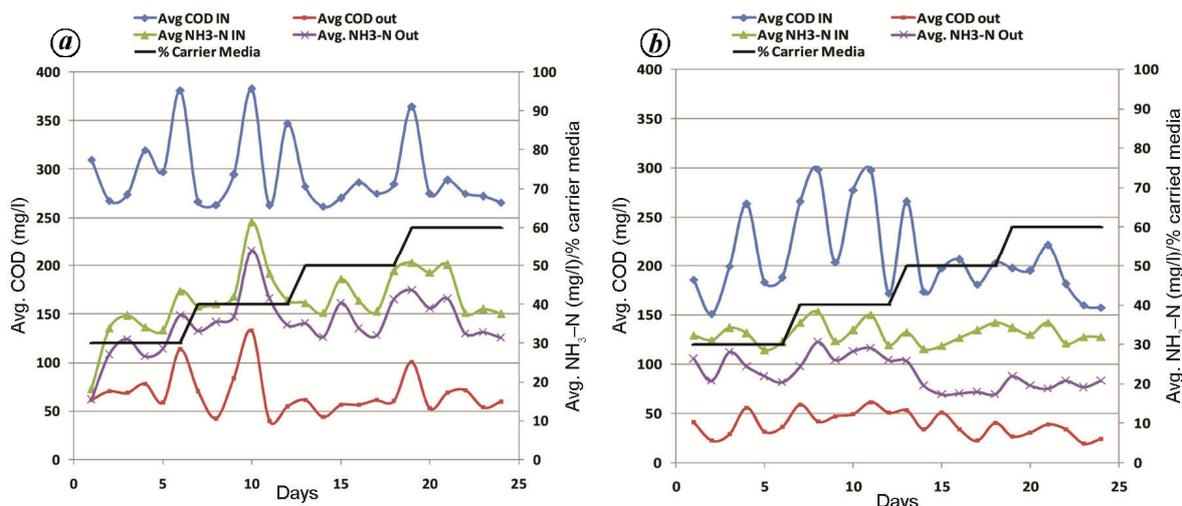
Figure 2. MBBR data analysis of chemical oxygen demand reduction $(COD)_{red}$ and ammonical nitrogen reduction $(NH_3–N_{red})$. *a*, 2 h of hydraulic retention time (HRT) with different percent carrier media. *b*, 3 h of HRT with different percent carrier media.
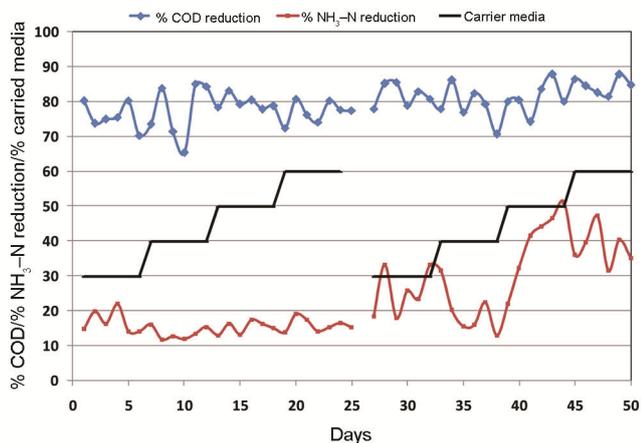

Figure 3. Effect of percent carrier media filling on percent COD_{red} and percent $NH_3–N_{red}$.

32.6 mg/l respectively. The treated effluent of 3 h HRT trials was COD_{out} 38.7 mg/l (i.e. 81.6% COD_{red}) and $NH_3–N_{out}$ 22.6 mg/l (i.e. 30.8% $NH_3–N_{red}$) (Figure 2 *b*). The 3 h HRT process showed a higher COD and $NH_3–N$ removal than the 2 h process. Contrary to the above results, an earlier study reported that variation in higher HRT did not affect the COD and $NH_3–N$ removal efficiencies, but considerably influenced the organic-nitrogen removal and distribution of oxidized nitrogen in the final effluent[13]. Another study of septic tank effluent treatment using a moving bed biological reactor showed an increase in the rate of average ammonia removal from 0.279 kg to 0.540 kg N/m^3 when the reactor's HRT changed from 5.7 to 13.3 h (ref. 14). Figure 2 also shows the variation in v/v percent carrier media loading during experimentation with respect to input/output treatment values. However, mere observation of the graph does not show its significance.

Due to variations in inlet and outlet concentrations of COD and $NH_3–N$, significance of the percentage of carrier media variation on treatment efficiency is not clearly observed in Figure 2. Figure 3 shows the effect of percent carrier media on COD_{red} and $NH_3–N_{red}$ percentages, distinctly. Results of 2 h HRT did not show much difference in the treatment efficiencies influenced by variation in percent carrier media (i.e. surface area). At 30% (lower) and 60% (higher) v/v carrier media loading, the reactor showed 75.8% and 76.9% of average COD_{red} and 16.9% and 16.1% average $NH_3–N_{red}$ respectively. However, 3 h HRT trials with 30% and 60% v/v carrier media loading showed 81.8% and 84.6% average COD_{red}, and 25.3% and 38.3% average $NH_3–N_{red}$ respectively (Figure 3). There is a marginal enhancement due to higher percentage media loadings. At lower HRT (or higher loading rate), variation in percentage of the carrier media loading did not show any major effect on degradation efficiencies.

According to a study carried out on MBBR with polyethylene (PE) carriers, the filling rates were 10%, 20%, 30% and 40%, while the average COD removal efficiency was at 75.7%, 91.1%, 85.5% and 79.6% respectively[15]. These results also showed that the MBBR system achieved higher COD removal efficiency at 20% PE carrier filling rate under the same conditions of influent organic loading rates. Another study of COD polishing by using MBBR showed that the average removal rate of 41.75%, 32.85%, 24.80% and 35.77% of initial COD were achieved under HRT of 24 h, 12 h, 6 h and 2 h respectively[16].

Thus higher HRT shows higher degradation, but it is not linear as the system reduces HRT to just 2 h. This validates similar results shown in the present study. Not much difference was observed in COD_{red} for 2 h and 3 h HRTs, and variation in carrier media filling, whereas,
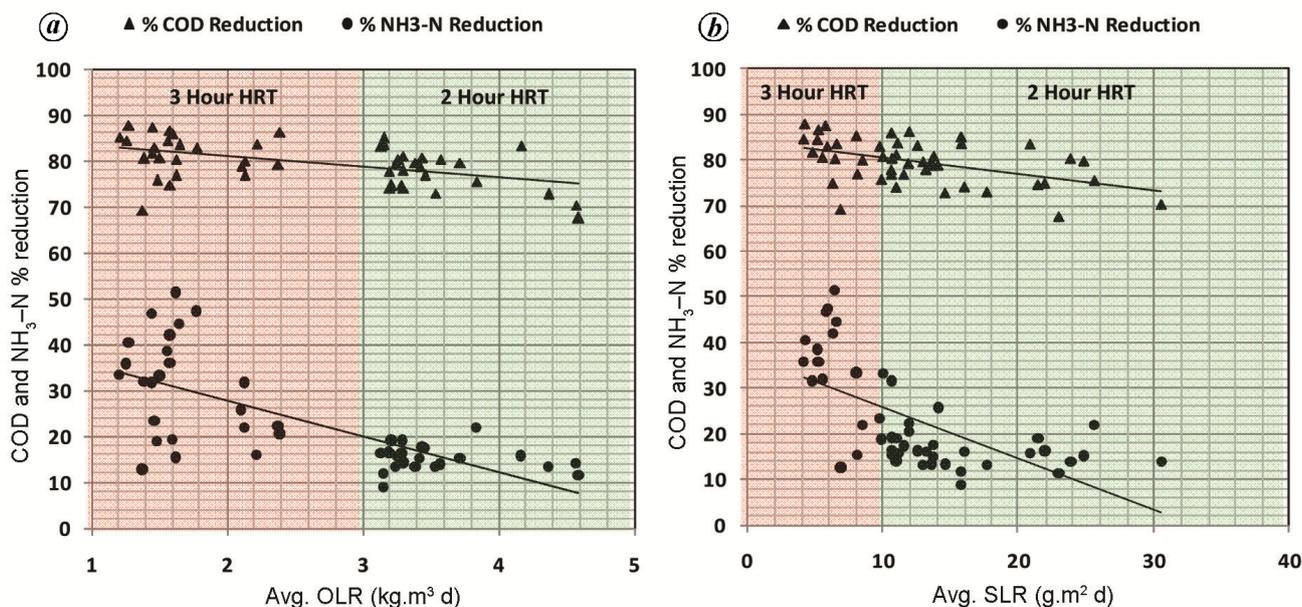
Figure 4. (*a*) Organic loading rate, (*b*) surface loading rate dependent outcome of 2 h and 3 h HRT for COD_{red} and $NH_3–N_{red}$ percentage.
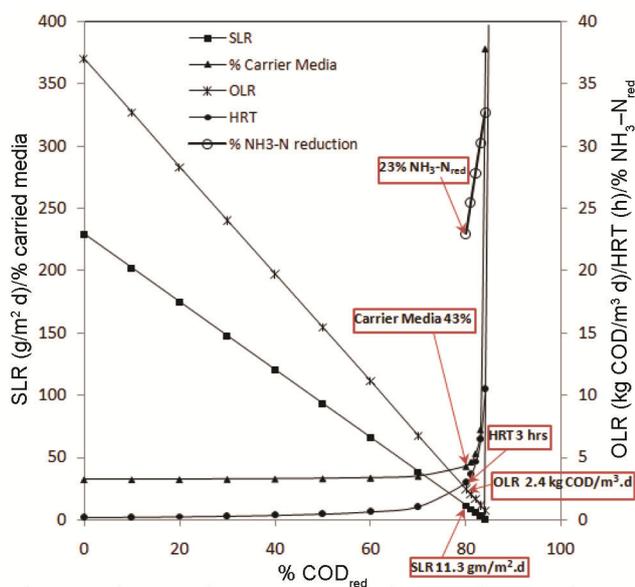
Figure 5. Interaction and selection of optimized MBBR design parameters for higher COD_{red} and $NH_3–N_{red}$.

there was notable effect on $NH_3–N_{red}$. As the HRT and percent carrier filling increases, there was an increase in $NH_3–N_{red}$ due to higher reaction time and more available surface area for nitrification. This study was performed at a wastewater temperature of $20° ± 2°C$, whereas at lower temperatures the rate of COD_{red} and $NH_3–N_{red}$ would drastically reduce[17]. Hence, the MBBR system always needs to be designed based on lower wastewater temperatures to achieve the desired effluent quality, as well as to

cater to the negative performance effects of seasonal variation.

Experimental data obtained in this study was plotted to analyse the effects of varying OLR and SLR on percent COD_{red} and percent $NH_3–N_{red}$. Figure 4 *a* shows that the high OLR received by the system of 2 h HRT trials, which was in the range of 3.14 kg to 4.59 kg COD/ (m^3 day) with an average value of 3.53 kg COD/(m^3 day), showed an average 77.66% of COD_{red} and 15.24% of $NH_3–N_{red}$. The trials of 3 h HRT operated at an OLR range of 1.21 kg to 2.39 kg COD/(m^3 day) with an average value of 1.67 kg/(m^3 day), showed an average 81.47% of COD_{red} and 30.78% of $NH_3–N_{red}$. Similarly, SLR values were also analysed for per cent COD_{red} and percent $NH_3–N_{red}$. The SLR of 2 h HRT trials varied from 24.7 g/m^2 d to 11.6 g/(m^2 day) with an observed average COD_{red} ranging from 75.9% to 79.9%, and average $NH_3–N_{red}$ from 12.9% to 16.8% (Figure 4 *b*). Similar SLR analysis for 3 h HRT trials showed the average COD_{red} in the range of 78.6% to 84.6%, and average $NH_3–N_{red}$ in the range of 19.7% to 39.7% with varied SLR from 10.4 g to 4.9 COD/(m^2 day). A MBBR study carried out by Melin *et al.*[18], kept the HRTs range between 45 min and 4 h, and the COD loading rates (SLR) between 4.1 g and 26.6 g COD/(m^2 day). It showed that the average COD removal efficiencies in the total process were 87% at 3– 4 h HRTs, and 83% at 0.75–1 h HRT with relatively small observed differences in the removal efficiencies at different loading rates in MBBR. These results validate the present study's outcome which indicates that the wastewater treatment efficiency is non-linearly proportional to lower range HRTs. A similar MBBR study was

done with SLR in the range of 3.6–17.37 g COD/(m^2 day) and OLR in the range of 0.8–4.2 kg COD/(m^3 day) which showed high COD removal efficiency in case of organic loading in the range of 87.3–98.8% (ref. 8). Further, the overall experimental data was analysed graphically to predict COD$_{red}$ and NH$_3$–N$_{red}$ performance which depended on the selected design parameters.

Performance equations from the above graphs (Figure 4) were used to optimize the reactor sizing using a graphical method. Figure 5 shows that the studied high rate MBBR has a technological limitation of maximum COD$_{red}$ up to 84% and maximum NH$_3$–N$_{red}$ up to 33%. This data could be used to select desired design parameters and predict the respective percentage reductions of COD and NH$_3$–N or vice-versa. In this case, the total optimized graphical results was used to design a process which was predicted to give 80% of COD$_{red}$ and 23% of NH$_3$–N$_{red}$ with respective design parameters consisting of OLR of 2.4 kg COD/(m^3 day), SLR of 11.3 g COD/(m^2 day) and HRT of 3 h, with 43% of carrier media loading.

Lowering the SLR in high rate MBBR has shown an enhancing effect on nitrification, but no major effect was observed on the COD oxidation process. Non-linear relationships between design's HRT (OLR) and design's percent carrier media loadings (SLR) have shown measured amount of contaminants removal in high rate MBBR processes. Graphical optimization of design parameters (SLR, OLR, HRT and percent carriers) could be applied effectively to select optimum parameters to design efficient and predictable MBBR processes. Studying and understanding this high rate degradation could be further applied to design complete nitrogen removal processes with the aid of extended nitrification and anoxic de-nitrification.

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