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Influence of High Organic Loading Rates on COD Removal and Sludge Production in Moving Bed Biofilm Reactor

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Abstract

A moving bed biofilm reactor (MBBR), where biomass is attached to small carrier elements that move freely along with the water in the reactor, has been tested for organic matter removal at five different organic loading rates. A lab-scale reactor with a volume of 2L was built and fed continuously with synthetic wastewater. The reactor was filled with the Kaldnes biomedia K1 which is used in the patented Kaldnes Moving Bed^{TM} biofilm process at 50% of the volume of empty reactor. Hydraulic retention times (HRT) in the reactor and in the settler were adjusted to between 8 and 4 hours, respectively. A start-up period of about 4 weeks for biofilm growth on the carrier was followed by 10 weeks of testing period. By changing the wastewater composition, the operation of the system was adjusted, one after the other, to five different organic loading rates: 6, 12, 24, 48 and 96 g COD/m^2.d. Organic removal efficiency decreased with increasing organic loading rate, ranging from 95.1%, 94.9%, 89.3%, 68.7% and 45.2% as the organic loading rate was increased form 6 to 96 g COD/m^2.d. In the MBRR reactor, the biofilm reached an average concentration of 3.28 kg TSS/m^3 at the highest organic loading rate. The ratio between the TSS production and the total COD removal was 0.12 kg TSS/kg total COD at an influent total COD of 500 mg/l.

Key words: wastewater treatment, moving bed biofilm reactor, organic loading rate, COD removal, sludge production, biomass yield

Introduction

The patented moving bed biofilm reactor (MBBR) was developed in Scandinavia in the late 1980s by the Norwegian company Kaldnes MiljØteknologi (KMT), in cooperation with the SINTEF research organization. Presently, there are more than 400 large-scale wastewater treatment plants operating in 22 different countries of the world based on this process. In addition there are several hundred small, on-site treatment units based on the MBBR (Rusten et al. 2006).

The Kaldnes MBBR is a completely mixed continuously operating biofilm reactor where the biomass is grown on small carrier elements that move along with the water in the reactor. The interest for MBBR is justified by the following advantages: high sludge age, no sludge recycling, and less bulking problems. In the case of an upgrade in existing plant, the MBBR solution does not increase head loss significantly, allows a continuous feed, does not present clogging problems and does not require backwashing. MBBRs allow applying higher loads compared to those applied to the conventional activated sludge, in case the specific surface is sufficiently high (Andreottola et al., 2002; Andreottola et al., 2003; Rusten et al., 2006).

The biofilm carrier elements are made of polyethylene (density 0.92–0.96 g/cm^3) and shaped like small cylinders with a cross inside the cylinder and longitudinal fins on the outside. In order to keep the biofilm carriers in the reactor, a sieve is placed at the outlet of the reactor. The filling ratio and the specific area of the biofilm carriers are the two main design parameters. The filling ratio ranges from 30–70% of the total reactor volume. Ødegaard (2000) recommends the filling fractions to be under 70% for the carriers the carriers to be free.

MBBRs have already been used in the treatment of dairy wastewater (Rusten et al., 1992; Andreottola et al., 2002), forest industry wastewater (Dalentoft and Thulin, 1997), cheese factory wastewater (Rusten et al., 1996), newsprint mill wastewater (Broch-Due et al., 1997), thermo mechanical pulping whitewater (Jahren et al., 2002), municipal wastewater (Ødegaard et al. 1993; Orantes and González-Martinez, 2002), and for nitrification (Rusten et al., 1995; Walender et al., 1997) and denitrification (Rusten et al., 1995; Aspegren et al., 1998; Maurer et al., 2001; Walender and Mattiasson, 2003).

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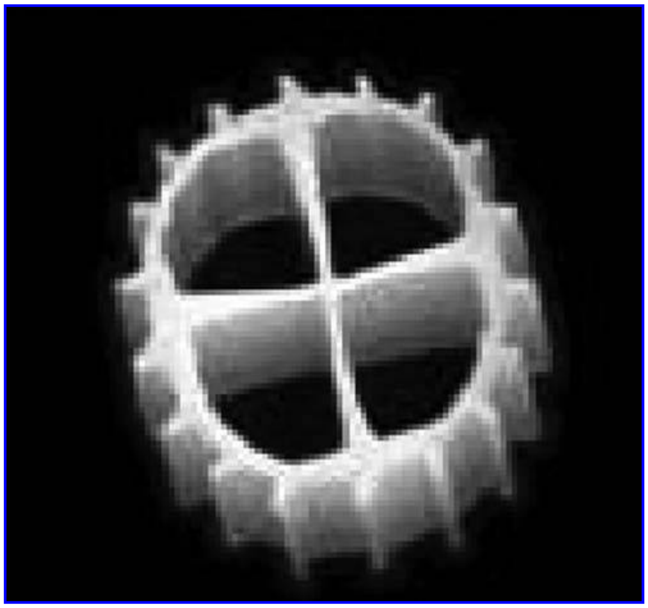

FIG. 1. Kaldnes biofilm carrier

MBBR is a good process for upgrading current wastewater treatment systems. Many studies regarding successful operation for new wastewater treatment plants and upgrades of existing wastewater treatment plants have been reported (Ødegaard et al., 1993; Hem et al., 1994; Orantes et al., 2002; Daude and Stephenson 2003; Andreottola et al., 2003). Andreottola et al. (2000) found that hydraulic retention time (HRT) affected the COD removal in MBBR processes and suggested that the HRT should be higher than 5 h. Another study was performed by Andreottola et al., (2003), in which they evaluated the application of MBRR system for the upgrading of an overloaded MWWTP. A preliminary experimentation at pilot-scale was carried out in order to evaluate the efficiency of the system in the removal of organic matter using a high loaded MBBR. KMT plastic media was applied with a filling ratio of 50%. The applied surface loads ranged between 5.4 and 32 g totalCOD/ m^2.d.

With the rising costs of sludge disposal, the minimization of sludge production has become increasingly important. The expense of excess sludge treatment has been estimated to be 50–60% of the total cost of municipal wastewater treatment. Therefore, modification of the aerobic treatment process in order to reduce biosolids production is promising (Kulikowska et al. 2007).

The main objectives of this research were to investigate COD removal efficiency and biomass yield coefficient in synthetic wastewater by using the kaldnes biomedia K1, which is used in the patented Kaldnes Moving Bed^{TM} biofilm process, at various organic loading rates starting from 6 to 96 g totCOD/ m^2.d).

Material and Methods

Carriers

The Kaldnes K1 biofilm carrier elements are made of polyethylene and shaped like small cylinders (a nominal diameter of 9.1 mm and a nominal length of 7.2 mm) with a cross inside the cylinder and longitudinal fins on the outside. The Kaldnes carriers have a specific gravity of 0.96 with a specific biofilm protected surface area of 500 m^2 per m^3 bulk volume of carriers. The Kaldnes biofilm carrier element is illustrated in Figure 1.

Microscopy of the biofilm media from several pilot and full scale moving bed biofilm plants has shown no sign of biofilm growth on the outside of the smooth plastic elements. The reason is believed to be the erosion caused by the frequent collisions between the pieces. Therefore, the biofilm surface area has been calculated based on the internal (protected) surface of the plastic elements (Rusten et. al, 1992). With a filling ratio of 50%, the available surface area (referred to the reactor volume) was 250 m^2/m^3 (considering only the internal surface of cylinders).

Lab-scale reactor and wastewater

A laboratory scale plexiglas reactor with a total liquid volume of 2 l and a final settler (volume equal to 1.2 l) was used in the study (Figure 2). The reactor was filled with the kaldnes biomedia K1 to 50% of the volume of empty reactor and without recycle. Diffusers were used for oxygen supply and mixing.

Activated sludge was obtained from a local municipal WWTP as a seeding material to the reactor. The MBBR was continuously fed with a dosage pump. The theoretical hydraulic retention time (HRT) in the oxidation tank and in the

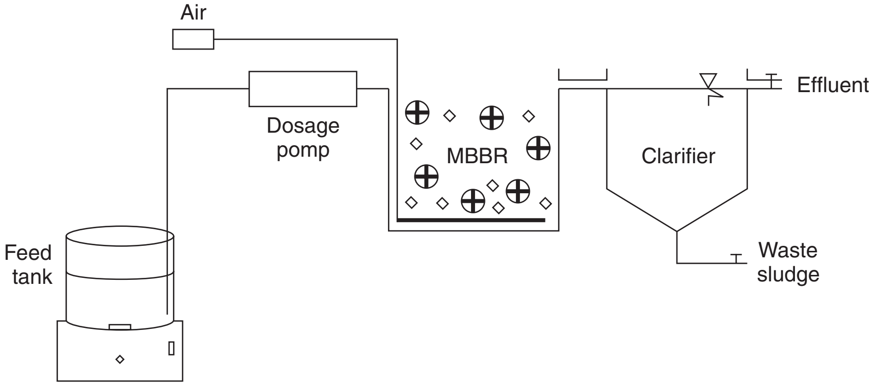

FIG. 2. Simplified flow-sheet of the lab-scale MBBR.

TABLE 1. COMPOSITIONS OF SYNTHETIC SUBSTRATE (COD = 1000 MG/L)

Glucose	258 mg/l
Sodium Acetate	471 mg/l
NH_4Cl	95.5 mg/l
KH_2PO_4	22 mg/l
$NaHCO_3$	295 mg/l
$MgSO_4.7\ H_2O$	100 mg/l
$CaCl_2.2\ H_2O$	50 mg/l
$FeCl_3.\ 6\ H_2O$	50 mg/l

settler was adjusted to 8 hours and 4 hours, respectively. The settled sludge was removed from the bottom of the settler.

Synthetic wastewater was used to provide a source of carbon, nitrogen, phosphorus and trace metals required for biomass growth. It was prepared daily with deionized water at a Chemical Oxygen Demand (totalCOD) of 500, 1000, 2000, 4000 and 8000 mg/l. The synthetic wastewater compositions are shown in Table 1. The calculated COD/N/P ratio of the synthetic wastewater was 100/5/1.

A start-up period of about 4 weeks for biofilm growth on the carrier was followed by 10 weeks of testing period. The steady state condition is defined as the period during which the effluent quality was relatively constant at a constant loading with regard to the parameters of COD, and SS. Steady-state conditions were resumed for a minimum of one week before the next trial commenced. The dissolved oxygen (DO) concentrations in the MBBR ranged from 0.30 to 3.00 mg O_2/l depending on the influent organic loading rates. The temperature and pH in the reactor varied from 18.4 to 23.6 ^{0}C and 6.72 to 7.88, respectively. Table 2 shows operational conditions for the reactor during all the experimental periods.

Analytical methods

To measure the performance of the lab-scale MBBR, samples were taken from the biofilm reactor and the final effluent. Total COD, filtered COD (on membrane of 0.45-μm porosity), TSS, VSS, N-NO_3, N-NH_4, DO and pH were measured on samples every day.

Closed reflux colorimetric method (Method 5220 D) was used for COD analysis as specified in the Standard Methods (APHA, AWWA, WEF, 2005). TSS and VSS concentrations referred to the fixed biomass in the MBBR were also measured. TSS analysis of fixed biomass was obtained detaching the biomass from 10 KMT elements, diluting the biomass in a known amount of demineralized water, referring the values to the surface of an element and taking into account the number of elements per liter (Andreottola et al. 2000; Andreottola et al. 2003). N-NO_3 and N-NH_4 were analyzed with Orion 710A advanced ion selective meter with Method 4500-NO_3-D nitrate and 4500-NH_4-D ammonia-selective electrode method (APHA, AWWA, WEF, 2005). DO and pH measurements were done by using the WTW Multiparameter 340i.

Results and Discussion

Experimental work in the laboratory was carried out in order to evaluate the efficiency of the system for the removal of organic matter and relationship between organic removal and observed yield using a high loaded MBBR. During the experimental works, five different organic loading rates were applied to the reactor.

Effluent totalCOD and COD removal rates versus time are shown in Figure 3. At the lowest organic loading rate corresponding to 6 gCOD/m^2.d, average effluent totalCOD concentration was 24.5 mg/l and average totalCOD removal efficiency was 95.1%. At 12, 24, 48 and 96 gCOD/m^2.d organic loading rates average effluent totalCOD concentrations were 50.8, 213, 1253, 4381 mg/l respectively, while the average totalCOD removal efficiencies were 94.9%, 89.3%, 68.7%, and 45.2% (Figure 3a,b,c,d,e).

The DO was measured in the reactor every day at 2 hours interval. The average DO levels in the MBBR ranged from 0.30 to 3.00 mg O_2/l depending on the influent organic loading rate. Although the amount of air increased to 1.8 and 2.3 l/min, DO levels decreased to an average of 0.83 mg/l and 0.30 mg/l when 48 and 96 g totalCOD/ m^2.d surface organic loading rates were applied, respectively. Low dissolved oxygen concentrations could affect COD removal efficiency at 48 and 96 g totalCOD/ m^2.d surface organic loading rates.

Figure 4 shows the removal efficiency versus volumetric and surface applied loads. By applying a volumetric organic loading rate between 1.5 and 6 kg totalCOD/m^3.d (corresponding to the range 6–96 g totalCOD/m^2.d), it was possible to obtain the highest removal efficiency of the totalCOD in the MBRR. However, removal efficiency of the totalCOD decreased to 45.2% when 96 g totalCOD/ m^2.d surface organic loading rate was applied.

Sludge production ranged from 0.35 gTSS/d at the lowest organic loading rate to 12.25 gTSS/d at the highest organic loading rate. The detachment of the biomass from the biofilm appears to follow a linear relationship with the organic loading rate (Figure 5). Sludge production is in agreement with the findings by Orantes and Martinez (2002).

TABLE 2. OPERATIONAL CONDITIONS OF MBBR REACTOR

Influent totCOD (mg/L)	500	1000	2000	4000	8000
Influent NH_4-N (mg/L)	25	50	100	200	400
Volumetric load (kg totCOD/ m^3.d)	1.5	3	6	12	24
Surface load (g totCOD/m^2.d)	6	12	24	48	96
TSS (kg/m^3)	2.34	2.49	2.75	3.23	3.28
VSS (kg/m^3)	1.73	1.89	2.10	2.46	2.39
Biofilm Age (days)	13.3	2.2	1.4	0.9	0.5
Air (l/min)	0.5	0.5	1.8	1.8	2.3
Dissolved oxygen (mg/l)	3.00	2.83	2.53	0.84	0.30
Length of Operation (days)	15	10	14	13	10

Table 3. Effluent COD and Average COD Removal Efficiencies

Organic loading rate	*Number of samples*	*Influent COD (mg/l)*	*Effluent COD (mg/l)*		
			min.	*max.*	*mean*
6 g totCOD/m^2.d	15	500	19	34	24.5 ± 4.8
12 g totCOD/m^2.d	10	1000	48	54	50.8 ± 2.3
24 g totCOD/m^2.d	14	2000	136	450	213 ± 102
48 g totCOD/m^2.d	13	4000	896	1522	1253 ± 180
96 g totCOD/m^2.d	10	8000	3982	4381	4576 ± 173

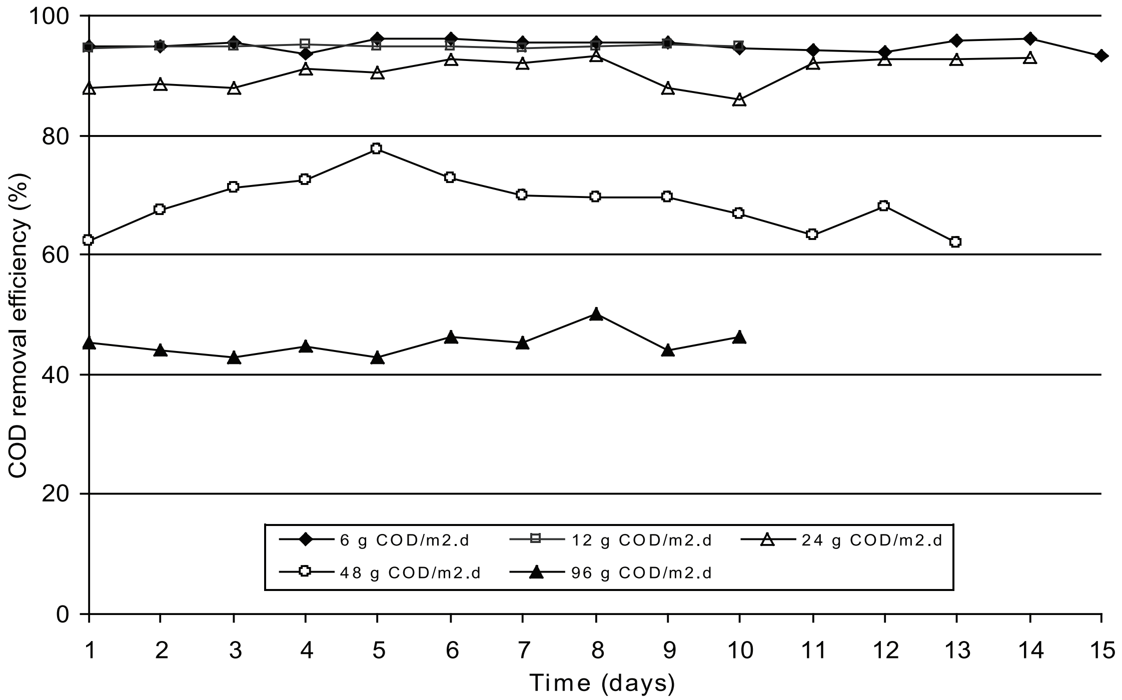

FIG. 3. COD removal efficiencies at different organic loading rate

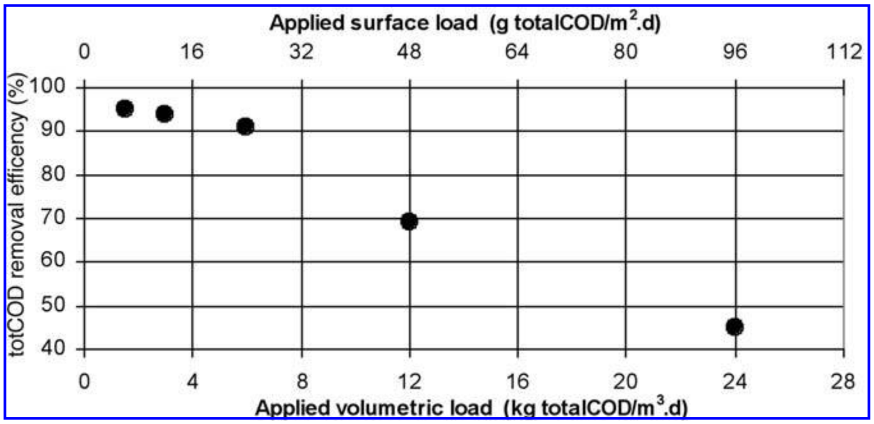

FIG. 4. Total COD removal efficiency versus applied organic loading.

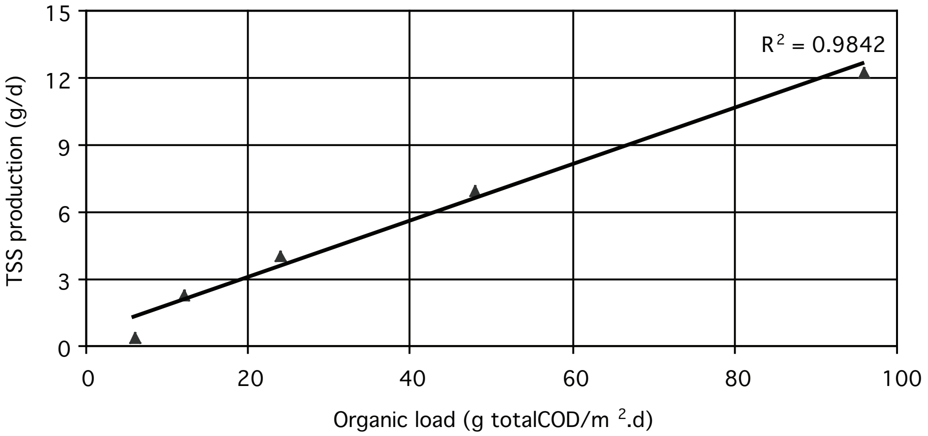

FIG. 5. TSS productions versus organic loading

The amount of biomass attached to the carrier material increased as the organic loading rate increased (Figure 6). In the MBBR reactor biofilm reached an average concentration between 9.36 and 13.12 gTSS/m^2 at different organic loading rates. The ratio of VSS/TSS was measured to be between 69% and 80% in the carriers.

The observed solids yield accounts for the actual sludge production that would be measured for the system. The sludge production (or solid yield) in the MBBR was calculated by measuring the sludge volume extracted from the settler and the TSS concentration in the sludge, in a period with an average totalCOD concentration in the influent and in the effluent of 500 mg/l and 24.5 mg/l respectively. A sludge production of 0.35 g TSS/d occurred with the of about 2.85 g totalCOD/d. Therefore, the ratio between the TSS production and the totalCOD removal was 0.12 kg TSS/kg totalCOD. This value is lower than conventionally activated sludge processes. Average of observed yields were taken for each test period and calculated as 0.12, 0.39, 0.37, 0.42, and 0.56 kg TSS/kg totalCOD, for influent totalCOD 500, 1000, 2000, 4000, and 8000 mg/l, respectively.

Orantes and Martinez, (2002) observed yield coefficients 0.12 and 0.40 kg TSS/kg totalCOD at 2 and 35 g totalCOD/m^2.d organic loading rates, respectively. Rusten et al., (1994) and Andreottola et al. (2003) reported a value of 0.36 kg TSS/kg totalCOD for a full-scale plant designed for nitrification and post-denitrification and upgraded from a small activated sludge plant, respectively. Jahren et al., (2002) reported a yield of 0.23 g VSS/g sCOD at COD loading rates between 2.5–3.5 kg COD/m^3.d.

The mean residence time of the biomass on the carriers, i.e. the biofilm age, is not the same as the residence time of unattached particulates. This phenomenon is known to be an important characteristic of biofilm systems and it plays a decisive role in the hydrolysis of particulate organic matter (Morgenroth et. al., 2002). The biofilm age can be calculated analogous to the sludge age in an activated sludge plant using the biofilm solids, the MBBR compartment volume, the ideal clarifier underflow, the detachment split fraction and the concentration of particulates. (Plattes et. al., 2006).

Conclusions

There are several advantages of the Kaldnes MBBR process such as upgrading of existing treatment plant against higher organic and hydraulic loading conditions with minor mechanical adjustments, improving nitrification within ex-

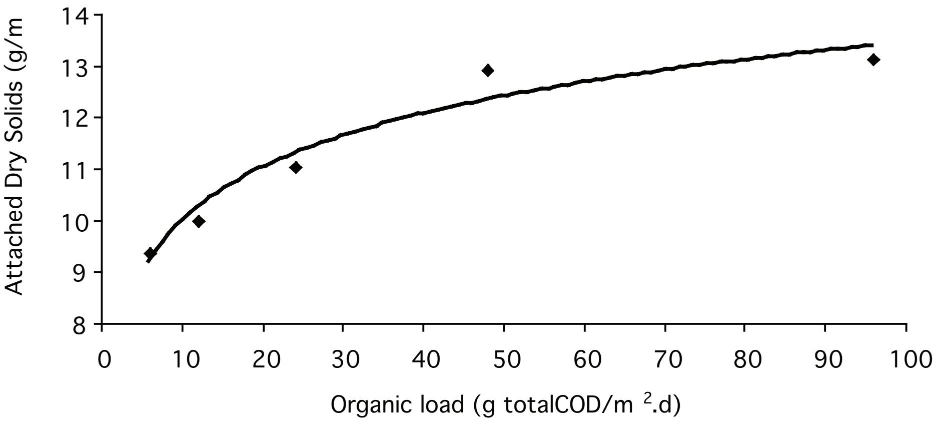

FIG. 6. Solid attached to the biofilm carriers versus organic loading

isting biological volumes and obtaining less land requirements compared to the conventional activated sludge.

This study focused on the performance of MBBR at relatively higher organic loading rates. Various organic loading rates applied to the MBBR process studies showed that it can be operated at organic loading rates up to 6 kg total-COD/m^3.d (corresponding to 2000 mgCOD/L) providing a removal efficiency of 91% at 8 HRT. Further, the MBBR could be employed as a pretreatment process to relieve the load on any biological treatment processes.

As sludge disposal costs are likely to increase significantly in the future, the use of MBBR unit would became a more attractive alternative. Observed yields of 0.12 kg TSS/kg totalCOD were obtained with the lowest and 0.56 kg TSS/kg totalCOD with the highest organic loading rates, respectively. A low sludge production with good sludge settlement characteristics was obtained with the lab-scale MBBR treatment.

The MBBR process offers an efficient alternative to the conventional biological treatment processes for organic matter removal at high organic loading rates or for upgrading existing facilities to achieve satisfactory results.

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