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The development of a biofilm membrane bioreactor

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Abstract

Membrane bioreactors (MBRs) are commonly understood as the combination of membrane filtration and biological treatment using activated sludge. Development of a biofilm-MBR has been investigated combining a moving-bed-biofilm reactor with a submerged membrane biomass separation reactor. Treatment efficiencies were found to be high with the production of a consistent high-quality effluent, irrespective of loading rates on the bioreactor or membrane reactor operating modes. Membrane performance (fouling) is a function of the biofilm reactor effluent quality and varies with loading rates (HRT). Sustainable operation was found to correlate to the fate of the submicron particle size fraction throughout the treatment process.

Keywords: Membrane bioreactors; Biofilm; Membrane fouling

1. Introduction

Membrane bioreactors (MBR) are commonly understood as the combination of membrane filtration and biological treatment using activated sludge (AS) where the membrane primarily serves to replace the clarifier in the wastewater treatment system [1,2]. The first generation of MBRs (late 1970s, 1980s) applied the use of cross-flow operated membranes installed in units outside the AS tank with high flow velocity circulation pumps. A disadvantage of the cross-flow membranes is the high energy required to generate sufficient sludge velocities across the membrane surface, and this process option was therefore considered nonviable for treating municipal wastewater. The development of submerged low pressure configurations in the late 1980s–1990s, by immersing the membranes into the AS tank, was an important step in making viable commercial solutions for the MBR process [3–5]. Today a variety of process configurations exist where the membrane is installed either in an external unit or immersed in the aeration tank and where the systems are designed to be operated under low-pressure vacuum. Compared to conventional AS systems,

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several advantages of the AS-MBRs have been identified [6] which have promoted the development of commercial AS-MBR options. These include compact units with small footprints, complete solids removal, effluent disinfection, operation at higher suspended biomass concentrations resulting in long sludge retention times, low sludge production, and no problems with sludge bulking. One of the major drawbacks of AS-MBRs is fouling, which is common for all membrane systems, where the efficacy of the process is constrained by the accumulation of materials on the surface of or within the membrane resulting in a reduction in the membrane permeability. Membrane fouling is caused by different substances and the mechanisms are rather complex and interrelated. Deposition of solids as a cake layer, pore plugging/clogging by colloidal particles, adsorption of soluble compounds and biofouling are some of the main forms of fouling that have been identified [7]. Fouling is particularly a problem in AS-MBRs since the process deals with liquors having high concentrations of total solids as well as dissolved compounds such as extracellular polymeric substances (EPS). Fouling is defined as reversible, i.e. can be removed by backwashing strategies, or as irreversible, i.e. fouling which is only recoverable by chemical cleaning, where the dominating fouling mechanism subsequently determines the performance of the process. Optimizing fouling control and cleaning strategies is therefore an important aspect of developing and designing MBR processes.

An alternative to the AS-MBR is combining a biofilm reactor with membrane separation of the suspended solids (BF-MBR) which may reduce the effect of membrane fouling by high biomass concentrations [8,9]. Although efficient in removing soluble organic matter, biofilm reactors designed as trickling filters or submerged filters using granular media are prone to clogging when the wastewater contains high loads of particulate matter. Consequently, there is a limit to the loading rate that can be applied to such processes, often necessitating a pretreatment step for particle removal prior to the biofilm unit. The moving-bed-biofilm reactor (MBBR) is an alternative process design which utilizes the advantages of a biofilm reactor and which at the same time can handle high loads of particles. The objective of this study has been to develop and investigate the potentials of a BF-MBR combining the MBBR with membrane separation.

2. Materials and methods

A schematic of the BF-MBR process concept is shown in Fig. 1, where the treatment train consists of two reactors, the MBBR followed by a membrane reactor with submerged modules and the process can therefore be defined as a

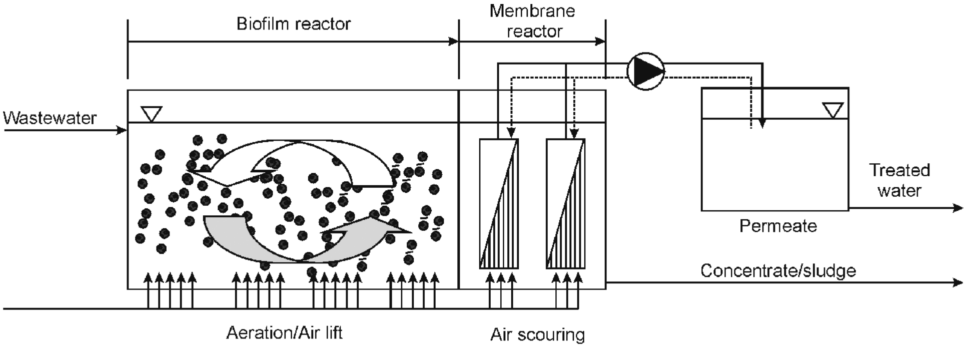


Fig. 1. Schematic of biofilm-MBR process concept.

biomass separation membrane bioreactor. By dividing the two reactors into separate entities, each process step can be designed and operated at optimal conditions. For the pilot plants investigated in these studies, municipal wastewater from a combined sewer system was pretreated using a small gravity settler and then pumped from an overflow into the MBBR reactor. The outlet of the bioreactor is subsequently led into the membrane reactor tank from where permeate is extracted through the membrane under vacuum. A small volume of the concentrate, i.e. retentate, is removed as excess sludge.

2.1. The biofilm reactor

In the MBBR, the biomass grows on carriers that move freely in the water volume by aeration or a mechanical mixer and are kept within the reactor volume by a sieve arrangement at the reactor outlet [10]. The biofilm carriers are made of high-density polyethylene (density 0.95 g/cm^3) and shaped as small cylinders with a cross on the inside of the cylinder and “fins” on the outside. The size of the carrier varies from lengths of 7–15 mm and diameters of 10–15 mm. The carrier filling fraction (percentage of reactor volume occupied with carriers in empty tank) is normally 60–70%. For secondary treatment only, the process is normally designed for a volumetric loading of 4–5 kg BOD_7/m^3 d at 67% carrier filling (12–15 g BOD_7/m^2 d). The concept of the reactor and illustration of carriers is shown in Fig. 2. K1 media (supplied by AnoxKaldnes AS, Norway) was used in the pilot plant reactors at 70% filling-fraction giving an effective specific surface area of 350 m^2/m^3 tank volume. An important advantage with the process is that the filling fraction may be subject to preferences and design criteria as a function of wastewater properties and treatment requirements [11]. The process can therefore be designed to accept both a high particulate load as well as a high soluble organic load [12]. Studies have been conducted with varying organic loading rates; COD: 7 g O_2/m^{2}d (2.3 kg O_2/m^3 d) to 24 g O_2/m^2 d (7.8 kg O_2/m^3 d) and FCOD: 3.4 g O_2/m^{2}d (1.1 kgO_2/m^3 d) to 12.1 g O_2/m^2 d (3.9 kg O_2/m^3 d).

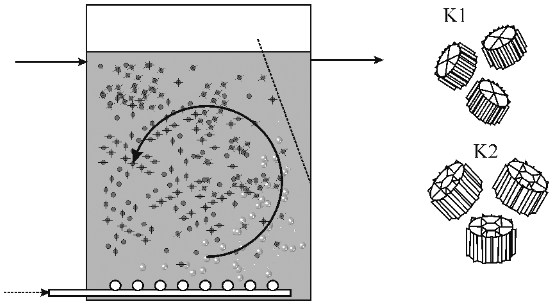


Fig. 2. The moving-bed-biofilm reactor (MBBR) concept and illustration of carrier types.

2.2. The membrane reactor

The membrane reactor was designed as an external submerged unit where the dimensions of the reactor are adjusted for particle separation only. Different modes of operation were applied; (a) continuous filtration with and without aeration for air scouring and (b) periodic backwashing with and without aeration for air scouring. The cyclic mode of operation consisted primarily of a production period of 9.5 min with a 0.5 min backwash. A constant flux mode was applied where fluxes ranged from 20 to 60 L/m^2 h (LMH) and the transmembrane pressures (TMP) varying between 0.1 and 0.5 bar. Air scouring of the membrane was applied continuously but with varying flow rates.

The development of TMP for different fluxes was measured continuously using an online pressure transducer connected to a data acquisition system from National Instruments, FieldPoint (FP1000 with FP-AI-110 analogue input), in combination with the LabVIEW data acquisition and analysis program. The water temperature was also logged continuously with a temperature transducer. Water flow rates were measured manually with rotameters on the respective lines of flow. Fouling rates for the membrane performance were calculated as rate of permeability decline, expressed as normalized flux divided by the TMP pressure (L/m^2 h bar).

2.3. Analysis

All analyses were performed according to national or international standards. Suspended solids, according to the Norwegian Standard NS 4733, were filtered through Whatman GF/C 1.2 μm filters. Chemical Oxygen Demand (COD) was measured with the Dr Lange LCK314 cuvette test. For the filtered chemical oxygen demand (FCOD) samples were first filtered through a Whatman GF/C glass microfiber filter. Total phosphorus was analyzed according to NS-EN ISO 4725. Ammonia was analyzed by ammonia selective electrode (ORION, model 95-12) and by Dr Lange Dosi Cap Zip Ammonium LCK 303. Particle size distribution analyses were measured using laser diffraction spectroscopy (Beckman Coulter LS230) and Zeta potentials were analyzed using laser Doppler velocimetry (Coulter 440SX).

3. Results and discussion

Initial studies were conducted combining the MBBR process with membrane separation designed as a MBR to investigate the feasibility and potentials of the BF-MBR process. The first pilot plant consisted of a MBBR reactor followed by an AS-MBR unit. A variety of operating modes were investigated to evaluate overall treatment efficiencies and to determine fouling behavior of the biofilm effluent on the membrane. Variations of operating modes tested for the membrane reactor consisted of continuous dead-end operation with/without air scour to cyclic operation applying periodic backwashing with/without air scour, where the effect of continuous air scouring with periodic backwashing of the membrane module proved to be the most efficient means of fouling control. Results showed that the membrane unit was capable of operating with a sustainable flux around 60 L/m^2 h with a relatively low fouling rate, i.e. permeability decline. The overall treatment efficiencies where found to be more or less the same irrespective of how the membrane reactor was operated giving average values of 99.5% removal of suspended solids (SS <5 mg/L) and turbidity (<1 NTU), and ~85% COD removal [13]. In effect, the biodegradable constituents were removed in the MBBR while the particulate matter was removed in the membrane reactor with no measurable biodegradation occurring in the membrane reactor. High HRTs were measured in the membrane separation unit with the design of the first pilot plant and the pilot plant was therefore modified to optimize the membrane separation phase. Consequently, the membrane reactor in a BF-MBR process can be designed and operated for optimal biomass and particulate separation.

New pilot plants were built to investigate the interaction between the biological stage and the membrane stage in the process where two operating conditions were chosen, defined as high-rate (COD removal only) and low-rate (nitrifying). The specifications of the operating conditions are given in Table 1. A schematic of the pilot plant configuration is shown in Fig. 3, where the membrane reactor has been designed for biomass separation only with relatively short HRTs and more efficient excess sludge removal.

The process treatment efficiency was investigated as a function of organic loading rates for given operating modes. Analysis of treatment efficiencies show that the permeate quality is consistently high with average removals around 85–90% for COD, 70–75% for FCOD and 100% for suspended solids, irrespective of loading rates. Performance and operation of the membrane reactor, however, varied as a function of loading rate. The average values measured for COD, FCOD and SS for the two operating conditions tested are given in Table 2

Table 1
Operating conditions

High-rate operation (45 min HRT)	Low-rate operation (180 min HRT)
Average load on MBBR	Average load on MBBR
COD 24 g O_2/m^2 d (7.8 kg O_2/m^3 d)	COD 7 g O_2/m^2 d (2.3 kg O_2/m^3 d)
FCOD[a] 12.1 g O_2/m^2 d (3.9 kg O_2/m^3 d)	FCOD[a] 3.4 g O_2/m^2 d (1.1 kg O_2/m^3 d)
Average SS in membrane reactor ~800 mg SS/L	Average SS in membrane reactor ~500 mg SS/L

[a] FCOD:COD in filtered sample (Whatman GF/C-filter).

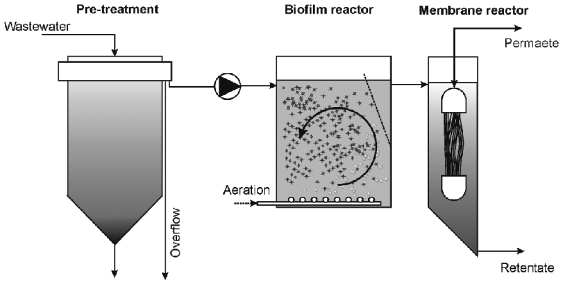


Fig. 3. Schematic of the revised pilot plant design.

and the average treatment efficiencies for COD and FCOD are shown in Fig. 4.

Reports from AS-MBR studies have shown that the efficacy of MBRs is largely constrained by fouling resulting in a reduction in the membrane permeability. This was also found to be the case for the treatment concept investigated in these studies. Variations in wastewater quality are significant for membrane fouling and studies have identified dominating fouling mechanisms in MBRs to be related to soluble sugars and proteins (extracellular substances, EPS) and suspended solids concentrations, in particular the submicron particle size fraction [14–17]. The effect of the suspended solids particle size characteristics on the performance of the BF-MBR process has therefore been investigated. Changes and development of particle characteristics throughout the process was monitored by analyzing particle size distributions (PSD) on the influent and effluent of the MBBR unit and in the membrane reactor i.e. concentrate of the membrane unit. An emphasis has been to identify the fate of the submicron particles in particular. Particle development and interaction in a biofilm reactor is not clear since the characteristics of both the soluble and the particulate organic

Table 2
Average treatment efficiency of the overall process (min and max values given in parenthesis)

	Inlet biofilm reactor	Outlet biofilm reactor	Permeate membrane reactor
Low rate			
COD	242 (157–312)	178 (111–310)	–
FCOD	118 (58–173)	53 (23–72)	31.9 (22.8–42.3)
SS (mg/L)	74 (30–136)	88 (24–211)	0
High rate			
COD	251 (190–296)	222 (119–358)	–
FCOD	127 (102–152)	65 (55–78)	37.8 (29–46.5)
SS (mg/L)	92 (35–151)	126 (16–377)	0

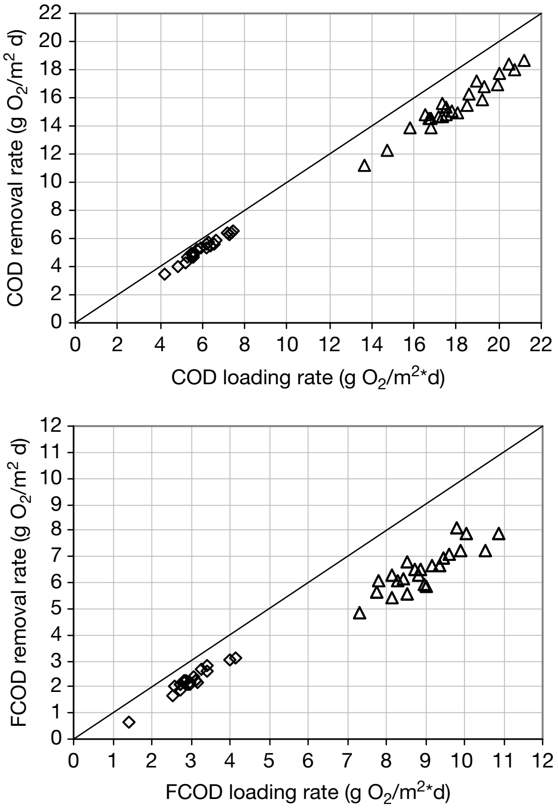


Fig. 4. Treatment efficients of chemical oxygen demand (COD) and filtered chemical oxygen demand (FCOD).

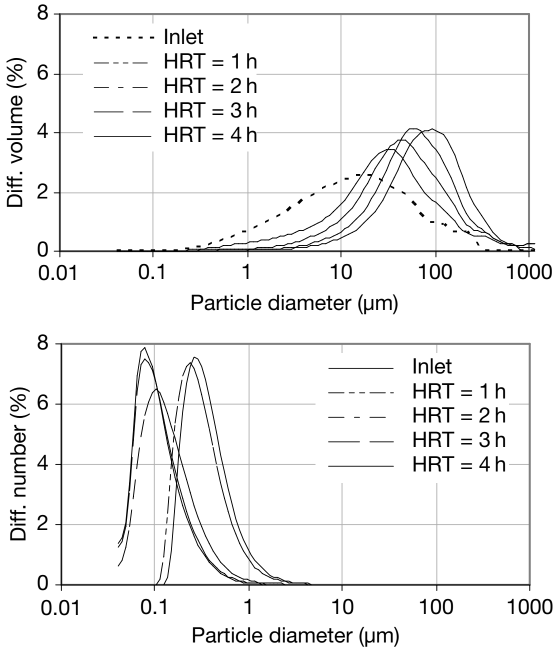
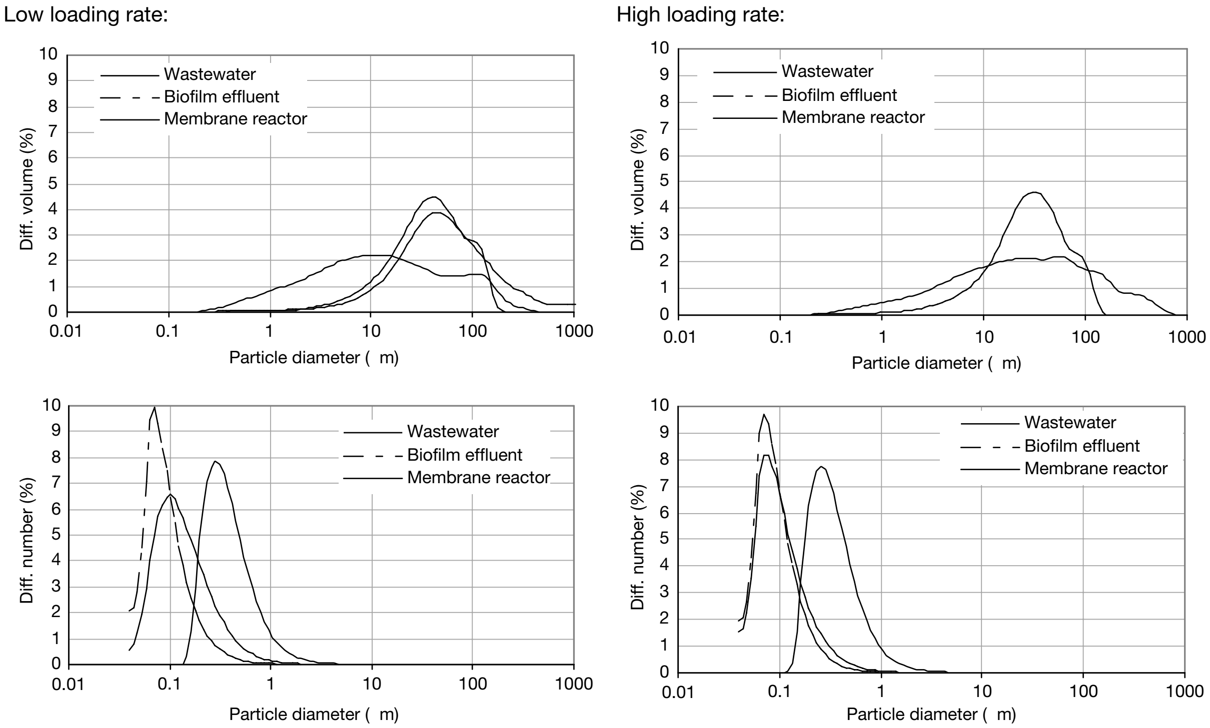


Fig. 5. Particle size distributions in the moving-bed-biofilm reactor (MBBR) effluent as a function of HRT.

matter change through the reactor by hydrolysis, assimilation etc., as a function of organic loading rates, HRTs and through the generation of bio-particles, i.e. bacteria, flocs etc. The particle size distributions in the effluent as a function of the HRT in the MBBR reactor, illustrated in Fig. 5, clearly indicate that the biomass characteristics experienced by the membrane reactor will differ as a function of loading rates. There is a clear shift to larger particles with increasing HRT (differential volume %), which may be attributed to the hydrolysis of colloidal organic particles or an enhanced effect of flocculation mechanisms. The differential number % measurements, however, show a relative increase in the submicron particles with increasing HRT. The observed changes may be due to a redistribution of the numbers of particles in the various size fractions as a function of particle aggregation in the larger particle size range, giving a relative increase in the number of submicron particles. Average Zeta potential measurements for several experimental runs were found to be around –15 to –20 mV, indicating relative stable colloids [18–20]. Subsequently one would expect the performance of the membrane separation step to vary as a function of loading rates (HRT) in the biofilm reactor.

Analysis of typical particle size distributions found throughout the BF-MBR process is illustrated in Fig. 6. Results for a “low” and “high” loading rate are shown to illustrate how the PSD changes as a response to how the biological reactor is operated.

When the process is operated with low loading rates there is a minor shift in the particle sizes based on the differential volume % analysis,



Low loading rate:

High loading rate:

Fig. 6. Example of particle size distributions in the BF-MBR process as a function of loading rate on the moving-bed-biofilm reactor (MBBR).

where predominantly larger aggregates (>100 µm diameter) are formed in the membrane reactor. This indicates formation of relatively strong aggregates where the particles are not broken by the aeration in the membrane tank. More significantly a major reduction in the differential number % of the submicron particles is found in the membrane reactor indicating that submicron particles <1 µm are incorporated into the larger aggregates. For high loading conditions, results show no significant change in the differential number % of the submicron particles in the membrane reactor. Differential volume % analysis shows an increase in particles in the 10–50 µm diameter range suggesting that the particle aggregates are destroyed by the aeration in the membrane reactor. If membrane fouling by submicron particles is a dominating mechanism one would then expect higher fouling rates when operating the process with high loading rates.

The response of the membrane unit to the variations in the particulate characteristics can be determined by measuring overall fouling rates as a function of process loading rates. Fouling rates are determined by measuring the change in TMP over time for constant flux operation. Fig. 7 shows examples of membrane performance for biofilm reactor HRTs ranging from 0 to 4 h where it is clear that an increase in HRT reduces membrane fouling. The observed response correlates well with results from the PSD analysis (Fig. 6) on the premises that fouling by submicron colloidal particles is a dominating mechanism. The relative number of submicron particles in the membrane reactor is reduced for low loading rate operation of the biofilm reactor and subsequently the overall fouling rate is less, Fig. 4.

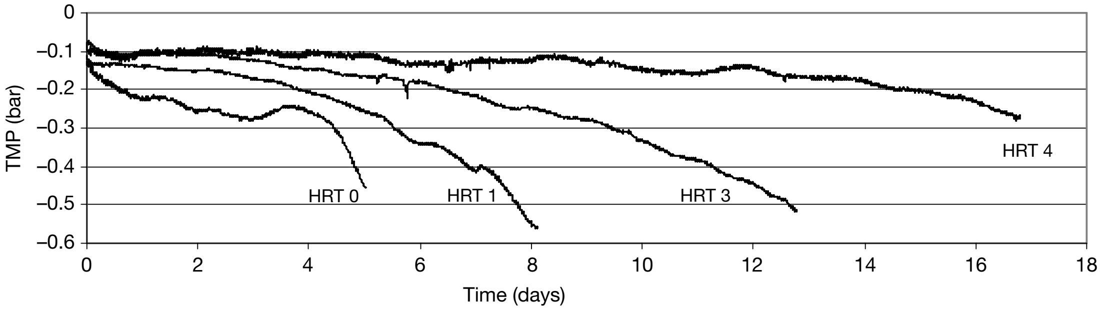


Fig. 7. Example of transmembrane pressures (TMP) development (fouling rate) measured as a function of HRT (hours).

4. Conclusion

BF-MBR process has the potential of operating with volumetric loading rates of 2–8 kg COD/m^3 d and HRTs up to 4 h. Sustainable process operation with membrane fluxes around 50 LMH have been achieved under the conditions tested. In comparison, typical operating conditions for AS-MBR configurations are reported to have volumetric loading rates of 1–3 kg COD/m^3 d, HRT 4–10 h and fluxes of 15–25 L/m^2 h. The BF-MBR is an alternative strategy to reduce the effect of membrane fouling by high biomass concentrations, particularly under low loading rates. The process has good treatment efficiencies and produces a consistent high-quality effluent, irrespective of loading rates. Membrane performance, however, is dependent on wastewater quality and correlates to the submicron particle size fractions in the suspended solids. Strategies to reduce the effect of the submicron particle size fraction in the membrane reactor have the potential of improving the overall performance of the BF-MBR process.

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