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Comparison of membrane filtration performance between biofilm-MBR and activated sludge-MBR

Cheng Sun*, TorOve Leiknes, Ranveig Haukeland Fredriksen, Eline Riviere

Department of Hydraulic and Environmental Engineering, NTNU – Norwegian University of Science and Technology, S.P. Andersensvei 5, N-7491 Trondheim, Norway
Tel. +47 9381-5130; email: chengsunmail@gmail.com

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ABSTRACT

Both a moving bed biofilm (BF)-MBR and an activated sludge (AS)-MBR pilots were operated in parallel to investigate and directly compare the membrane filtration performances. Experimental results show that a slightly better permeate quality and less membrane fouling were observed in the AS-MBR. Membrane feed quality parameters (i.e., SS, FCOD, CST, PSD, Zeta potential) were compared for the two MBR systems. Several measurements indicate a large amount of submicron and colloidal particles are found in the biofilm reactor. To obtain a sustainable operation of a BF-MBR with low fouling rates it is therefore very important to choose operating conditions and system configurations in which the submicron colloidal component is managed and controlled.

Keywords: AS-MBR; BF-MBR; Membrane; Fouling; Suspended solid; Submicron particles

1. Introduction

Membrane bioreactor (MBR) is a promising technology for advanced wastewater treatment. However, membrane fouling is a major challenge for this process since excessive fouling may reduce the productivity and increase the requirement for membrane cleaning, hence increasing operational costs while simultaneously decreasing membrane lifetime. Membrane fouling in MBR is commonly associated with the nature and characteristics of the biomass in the reactor, both the physical properties (i.e., floc size, densities, structure, etc.) and the chemical properties (i.e., nature of biomass, EPS, etc.) that contribute to the dominant fouling mechanisms. By exchanging the activated sludge (AS) with a biofilm (BF) process for the biodegradation step, there is a potential for improved fouling control and mitigation due to a decreased suspended solids (SS) environment in the process [1,2]. Other possible advantages of utilizing a biofilm process in MBR are prospects of an even more compact reactor, with lower energy demands, and options for different process configurations.

Literature reports on biofilm systems coupled with membrane filtration have given varying results on the BF-MBR performance. Some studies by using moving bed biofilm reactor (MBBR) system show that BF-MBR generally appears to have potential benefits over the conventional AS-MBR [2–5]. In other studies, reports mostly demonstrate a better performance in the AS-MBR configuration [6–8], where less membrane fouling was observed. Due to the different systems and configurations used in these studies it is difficult to make direct comparisons or concise conclusions on the findings reported. Differences in biomass characteristics

*Corresponding author.

and the much lower SS concentrations typically measured in the BF-MBR processes result in a different composition and properties of the membrane feed solution. This further results in different dominant membrane fouling mechanisms being reported and hence different optimized operations and configurations. There is therefore a knowledge gap about the potential benefits of the BF-MBR process and how this may be used more efficiently in practice. The overall objective of this study was to directly compare these two systems by operating an AS-MBR and BF-MBR pilot plants in parallel.

2. Materials and methods

Two small pilot plants were operated in parallel to compare the performance and membrane fouling behaviour of an AS-MBR and a BF-MBR under as equal operating conditions as possible. Fig. 1 shows a schematic of the pilot plants used for this study.

2.1. The pilot plant systems

The reactors were made of Plexiglas. Each reactor consisted of two chambers, one for the bioreactor and one for the submerged membrane module used. The two chambers were separated by a vertical baffled wall with a coarse screen on the upper and lower parts, thus allowing the suspended material to pass into the membrane chamber. For the biofilm reactor configuration this also served as a means of retaining the biofilm carriers in the bioreactor chamber and not entering the membrane chamber. The total reactor volume was 13 L. Pilot plant modules of flat sheet microfiltration membranes were submerged in the membrane chambers, supplied by Kubota. The system and membrane specifications are listed in Table 1.

Table 1
General system specifications

System specifications	
Volume of each reactor, L	13
Membrane flux, $Lm^{-2}h^{-1}$	10.3
Sludge removal, L/d	0.3
Membrane type	Flat sheet
Membrane area, cm^2	1160
Membrane pore size, μm,	0.4
Aeration for bio-growth, L/min	4
Aeration for membrane scouring, L/min	4
Membrane relaxation,min/h	2
AS reactor	
Average SS, g/L	5
SRT, d	43
BF reactor	
Average SS, g/L	0.7
Biofilm carrier	K1*
Area specific growth, m^2/m^3	335

*K1 – Kaldnes moving bed biofilm carriers.

The biofilm reactor was based on a MBBR (moving bed biofilm reactor) system using biofilm carriers (Kaldnes K1-carrier), with a typical design criterion of a 67% filling degree. This equals a total theoretical

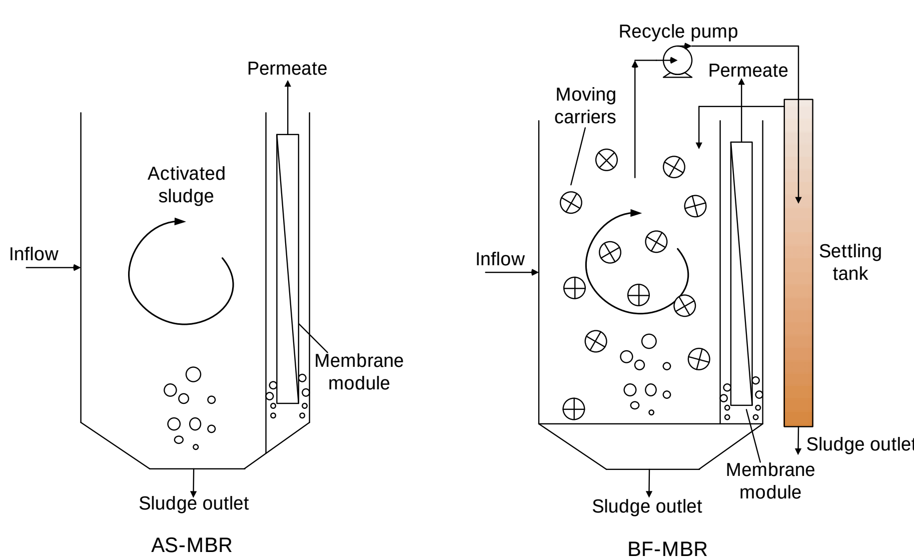

Fig. 1. System configuration of the AS-MBR and BF-MBR pilot plants.

biofilm surface area of 14.7 m^2 in the biofilm reactor. The biological reactor chamber was initially designed to easily remove excess sludge. The settling and removal of larger particles formed in the reactor was initially designed to take place in a zone at the bottom of the reactor, covered with a coarse screen. However, due to the scale of the pilot unit this design did not work entirely as intended and increasing SS concentrations in the biofilm reactor was observed. An alternative design was therefore introduced by adding an external 1 L settling tank to the biofilm reactor (Fig. 1). Mixed liquor was pumped into the middle of the settling tank allowing the sludge to settle with the overflow returning to the bioreactor chamber (recycle flow: 20 mL/min, recycle ratio: 1). In this way the SS concentration in the biofilm reactor could be controlled and held bellow 1.1 g/L. Three hundred millilitre/day of sludge was subsequently removed from the bottom of the settling tank. The AS-MBR was assumed to be completely mixed, with 300 mL sludge removed daily.

Operation of the membrane modules during the filtration trials included both air scouring and relaxation techniques commonly applied in MBR systems to control fouling. Chemical cleaning of the membranes between the different experimental tests was performed by using 0.5% NaOCl and 0.5% oxalic acid solutions. The membranes were soaked in the different solutions for about 24 h in total and rinsed with clean water between each soaking period. A full recovery of the membrane permeability was achieved by the cleaning protocol employed.

2.2. Analytical methods

All analyses were performed according to Norwegian National or International Standards summarized in Table 2. Membrane performance was evaluated by assessing changes in permeability over time during operation, where the decrease measured is caused by membrane fouling. A constant flux mode of operation was chosen where the change in permeability can be expressed as a change in the trans-membrane pressure (TMP). Results are presented showing overall TMP development with time, and subsequent fouling rates. The development of TMP was measured continuously using an online pressure transducer connected to a data acquisition system from National Instruments, in combination with the LabView data acquisition and analysis software.

2.3. Raw water quality

The experiments were conducted on semi-synthetic wastewater consisting of pretreated municipal wastewater from a combined sewer system with the addition of artificial wastewater (i.e., a mixture of molasses, fish peptone, ammonium chlorite, sodium phosphate, magnesium sulphate and iron sulphate). The objective was to increase the loading rates on the biological reactors. The average wastewater quality supplied to the pilot plants together with the respective standard deviations in the period of the experiments is given in Table 3.

Table 2
Measurement methods

Parameter	Method and instrument
Suspended solids (SS), mg/L	Norwegian Standard NS 4733, filtered through Whatman GF/C 1.2 μm filters
Chemical oxygen demand (COD), mg/L	Dr Lange LCK414/314/114 cuvette test
Filter COD (FCOD), mg/L	0.45 μm filter and Dr Lange LCK414/314/114 cuvette test
Ammonia, mg/L	Dr Lange LCK303
Phosphate (PO_4)	Dr Lange LCK348
Total nitrogen (TN)	Dr Lange LCK238/338
Total organic carbon (TOC), mg/L	Apollo 9000 TOC Analyzer
Turbidity, NTU	HACH 2100N Turbidimeter
Colour, Pt	HITACHI U-3000 spectrophotometer
UV_{254} absorbance	HITACHI U-3000 spectrophotometer
Particle size distribution (PSD)	Beckman Coulter LS230
Filter particle size distribution (PSD)	1.2 μm filter and Delsa™ Nano Beckman Coulter
Zeta potential, mV	Delsa™ Nano from Beckman Coulter
Capillary suction time (CST), s	Triton WPPL type 92/1 and Triton CST papers
Normalized CST, s/g	CST value devised by SS concentration

Table 3
Inlet semi-synthetic wastewater quality for experiments

Parameter	TCOD	FCOD	SS	NH_4	PO_4	TN	pH
Average	458.2	364.3	74.0	32.1	9.9	42.3	6.7
Stdev.	134.3	107.8	38.1	11.6	4.0	12.6	0.13

Note: All values except pH are given in mg/L.

3. Results and discussion

3.1. Permeate quality

The first part of the experiments focused on comparing the treatment efficiency and membrane performance between the BF-MBR and the AS-MBR systems. Five trials were conducted with each experimental identified as BF1–BF5 and AS1–AS5, respectively. The average effluent qualities of the BF-MBR and AS-MBR pilot plants are given in Table 4. Results show that the AS-MBR produced slightly higher effluent quality regardless of the parameters measured.

3.2. Assessment of membrane filtrations

The membrane fouling rate of the AS-MBR module was observed to remain very low with negligible increase over time for the duration of these trials (5–6 days) for the operating conditions applied. However, fouling rates for the BF-MBR module were found to vary for each trial, and were always higher than in the case of the AS-MBR, shown in Fig. 2. The AS membrane generally performed better than the BF membrane for the conditions tested, which is in agreement with results reported in similar studies [6–8].

3.3. Assessment of membrane feed solutions

The different properties and characteristics of the feed solutions to the membrane filtration chambers resulted in the different filtration performances observed between the AS-MBR and BF-MBR systems. Fig. 3 shows that a larger amount of FCOD (measured both by 1.2 μm and 0.45 μm filters) were generally observed in the BF-MBR compared to the AS-MBR. The higher FCOD in the biofilm process indicates the presence of more submicron organic material, and hence a greater fouling potential for irreversible fouling. FCOD is also an indicator of soluble microbial products (SMPs), which are considered as a major foulant in MBR systems [9–12].

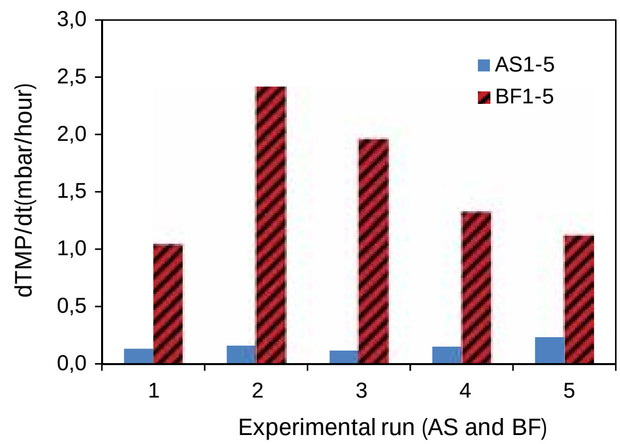

Fig. 2. Membrane fouling rate of the BF-MBR and AS-MBR.

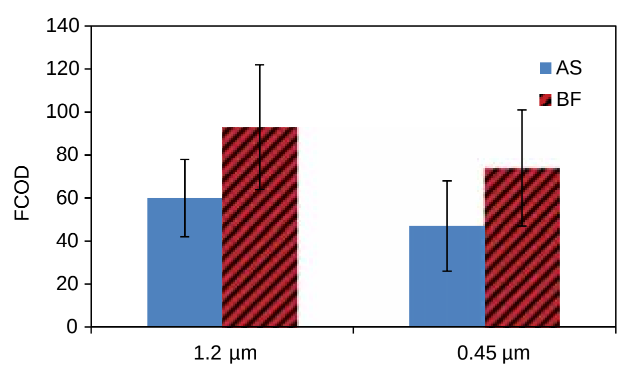

Fig. 3. Comparison of FCOD values between the AS-MBR and BF-MBR.

Table 4
Average effluent water quality

Parameters	AS-MBR		BF-MBR	
	Value	Stdev.	Value	Stdev.
COD removal, %	88.9	2.6	87.3	3.1
COD in effluent, mg/L	44.7	7.2	51.4	8.0
NH_4-N removal, %	99.7	0.2	98.7	0.9
Colour*, Pt	118	14.0	130	17.4
UV_{254}, abs	0.500	0.061	0.525	0.064
Turbidity, NTU	<0.4	–	<0.4	–

*The colour values are rather high due to molasses in the feed semi-synthetic wastewater.

It should be noted that the average fouling rates show large variations for BF-MBR system (tests: BF1–BF5). A correlation between the fouling rates observed and FCOD in the BF-MBR was established, shown in Fig. 4. The results clearly indicate that a higher amount of FCOD in the BF-MBR leads to higher fouling rates. However, more detailed analyses are required to gain a better understanding of the dominant fouling mechanisms observed for the two systems.

Differences in the mixed liquor properties and characteristics generated by the BF and AS processes were therefore investigated. High CST value of a suspension is an indication of poorer dewatering properties, which can further be associated with more filamentous bacteria and more colloidal matter. The CST values measured for the BF suspension were higher than for the AS suspension, as shown in Fig. 5. A much poorer settling behaviour for the BF effluent solution was observed, which is another indication of a higher amount of colloidal matter in the feed water to the membrane filtration stage. Zeta potentials measured throughout the experiments fluctuated between –6 mV and –15 mV, however, the absolute values of the BF zeta potentials were always higher than the AS samples. A difference of around 3 mV between the two suspensions was observed, with an average of –9.7 mV for the AS and –12.3 mV for the BF samples, as shown in Fig. 5. The average values are in the same range and show that both effluents contain a relatively destabilized suspension, though the small difference suggests that the BF effluent is a slightly more stable dispersion than in the AS case. Based on zeta potential values, the repulsion between the particles in the AS reactor is a little weaker thereby in theory promoting more flocculation than in the BF reactor. However, flocculation is also a function of the particle concentrations which varied greatly between the two reactors, on average 5 g/L for the AS reactor and 0.7 g/L for the BF reactor, respectively, which may also explain the much smaller flocs found in the BF system in general. The differences in floc structure, size and concentration between the two systems are illustrated in the microscope picture examples shown in Fig. 6. Several pictures taken at various times confirmed the significantly larger flocs typically observed in the AS reactor compared to the BF reactor. There also appears to be more filamentous bacteria in the AS reactor, however, this was not further analyzed or quantified. Based on these analyses it is therefore apparent that the nature of the effluents from the AS and BF reactors are quite different which subsequently resulted in the different membrane filtration performances due to varying dominant membrane fouling mechanisms.

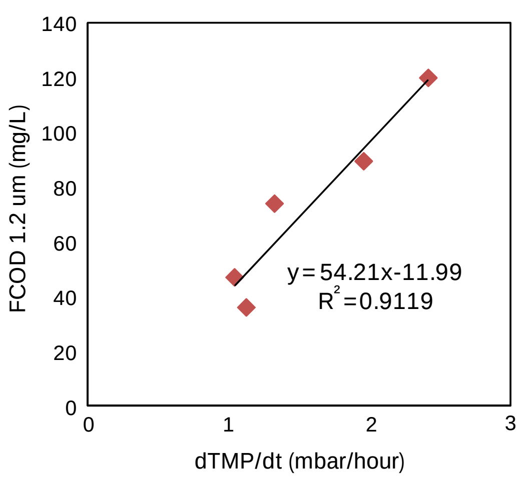

Fig. 4. Correlation between membrane fouling rate and FCOD in BF-MBR.

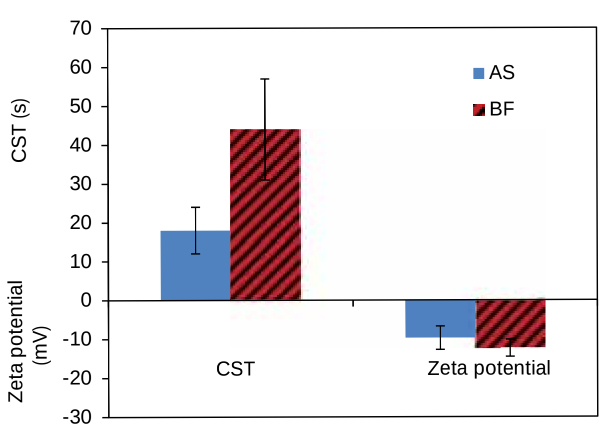

Fig. 5. Comparison of CST and zeta potential between the AS-MBR and BF-MBR.

The significance and nature of the colloidal fraction/submicron particles in MBR systems has previously been identified as a key component in the performance and fouling behaviour of the membranes [1,13–15]. Submicron particles could promote membrane fouling through possible pore blocking, build up of very compact/high resistant cake layers, etc., where a higher percentage of submicron particles is generally considered having a higher fouling potential. However, opposite results have been observed when comparing AS-MBR and BF-MBR systems. PSD results show that more submicron particles (Fig. 7, number %) were observed in the AS-MBR pilot but with overall less membrane fouling. One of the explanations might be that the larger flocs (Fig. 7, volume %) in the activated sludge feed water probably form a more porous cake layer, where many of the submicron particles are ultimately captured thereby reducing serious pore blocking inside the membrane. The AS pilot therefore appears to possess a greater potential for handling these submicron particles.

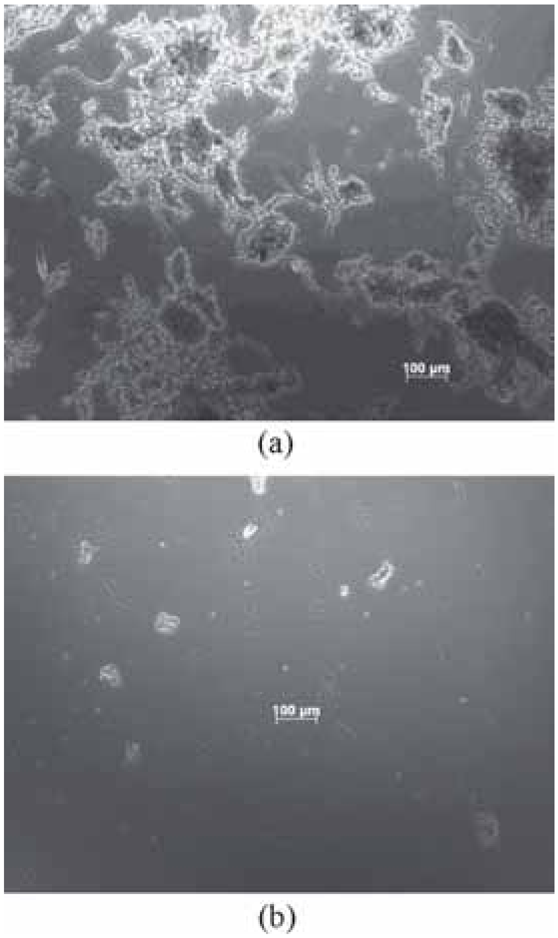

Fig. 6. Microscope pictures of (a) activated sludge flocs, and (b) biofilm flocs.

The total amount of suspended biomass in the system is also considered to play an important role in dominant membrane fouling mechanisms. The much higher SS concentrations found in the AS-MBR system will potentially form a cake layer deposition much faster than for the BF-MBR system, and consequently a thicker but more porous protective layer on the membrane surface may form. This dynamic layer on the membrane further has the ability to prevent or reduce the amount of submicron particles from attaching directly to the membrane surface (i.e., pore blocking and plugging mechanisms). By comparing FCOD, CST, zeta potential, particles and floc sizes in both membrane feed solutions, it appears that a higher degree of irreversibly fouling due to pore blocking/plugging dominates in the BF-MBR system, while the AS-MBR system has a greater potential for a thicker and more porous cake layer deposition taking place, which is more readily removed by air scouring.

One of the major differences of the membrane feed solutions between the BF-MBR and AS-MBR is the SS concentration. For relatively low SS concentrations, typically encountered in BF-MBR systems, it is apparent that the fouling behaviour and response is very sensitive to the characteristics and the amount of the colloidal fraction in the membrane feed water. One approach to improving the filtration properties and reducing the impact of the colloidal material may be to increase the SS concentration in the BF-MBR system to higher values. An experiment was therefore designed where the SS in the BF-MBR system was gradually increased, approaching conditions that compare to AS-MBR systems operating with very low SS concentrations (*i.e.* 3.5 g/L).

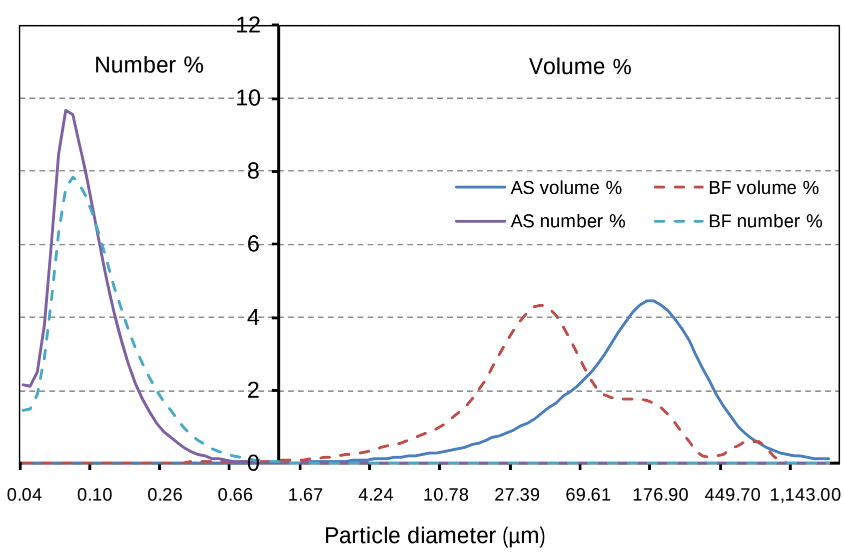

Fig. 7. Comparing of particle size distribution (PSD) between AS-MBR and BF-MBR membrane feed solutions.

3.4. Impact of increasing the SS concentration in the BF-MBR

The impact of increasing the SS concentration in the biofilm reactor was investigated in a separate experiment (test: BF6). In this test, the settling tank installed on the BF-MBR pilot plant was disconnected, thereby allowing the SS to accumulate in the biofilm reactor.

Fig. 8 shows the TMP profile of this test, where three stages can be identified: (1) stage 1 from the beginning of the experiment to the seventh day of operation, where the TMP increased steadily from around 0.02 to 0.13 bar; (2) stage 2 lasting two and half days, where the TMP decreased from around 0.13 bar to 0.10 bar; (3) stage 3 where the TMP continued to increase again, though with a much lower rate than in the stage 1. The decrease in TMP in the stage 2 can be considered as removal of reversible fouling by air scouring due to the changing operating conditions, in particular the increase in SS concentration over time. From the plot of TMP development it is apparent that the membrane fouling rate changed from a SS concentration around 1.76 g/L, indicating a change in the dominating fouling mechanisms. It should also be noted that the decreased fouling rate observed for stage 3 was the same order of magnitude of that measured for the AS-MBR pilot plant with an average SS around 5 g/L (test: AS1–AS5), giving a similar membrane filtration performance as for the AS-MBR system.

Variations of membrane feed characteristics during the increase of SS concentration over time of operation are shown in Fig. 9. The measured parameters display a response in relation to the three TMP stages described above. As the SS concentration increased, both the normalized CST value (i.e., CST/SS) and a negative zeta potential increased, corresponding to a worse dewatering ability. On the third day, these values reached the highest point and then started to decrease. Around the seventh day, which coincided with the point of change in the TMP profile (Fig. 8), the measured values of normalized CST and negative zeta potential are seen to stabilize.

As previously shown in Fig. 4, FCOD was found to give a good correlation with membrane fouling rate, where higher membrane fouling rates are observed with higher FCOD concentrations. In Fig. 9 results show that a relatively higher FCOD was observed during stage 1 with corresponding higher fouling rate. FCOD decreased a little in stage 2 and stabilized in stage 3, again with a corresponding response in the TMP development observed (Fig. 8).

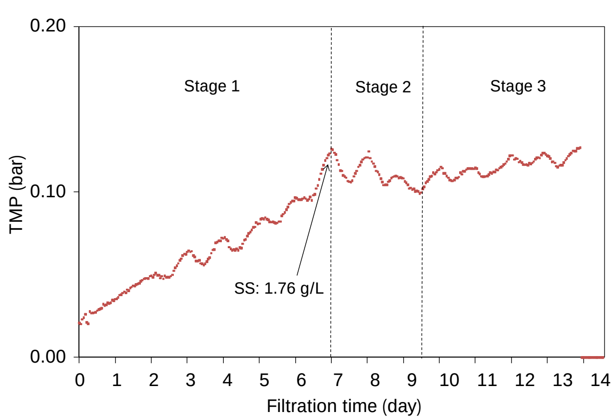

Fig. 8. TMP profile of increasing SS in the BF-MBR, test BF6.

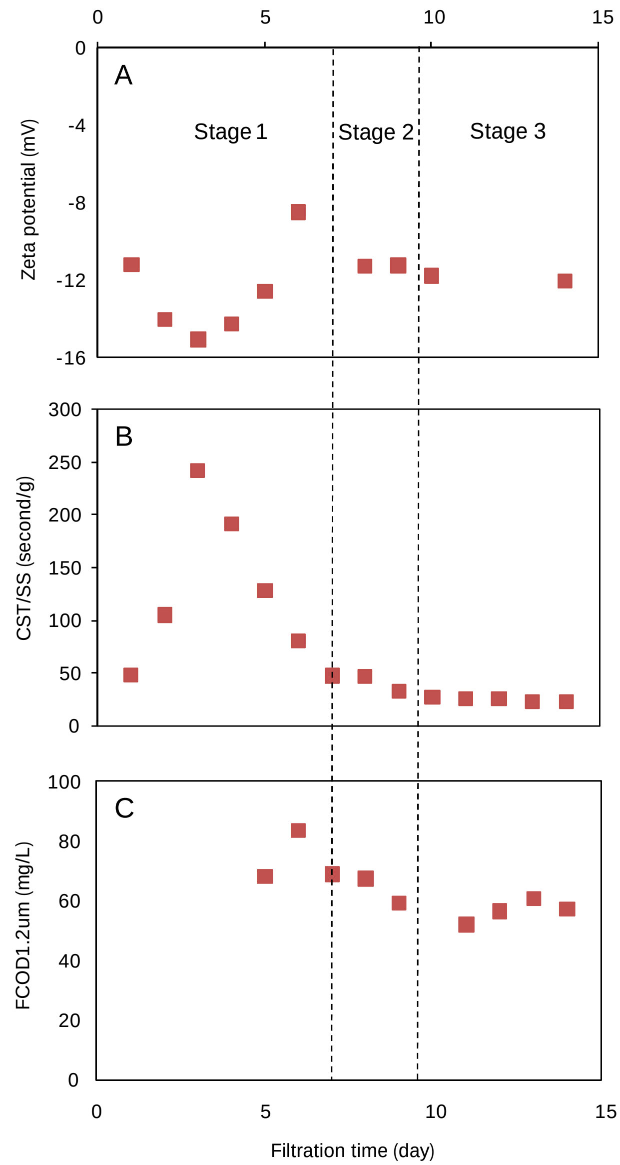

Fig. 9. Variation of membrane feed characteristics during the SS increasing in BF-MBR.

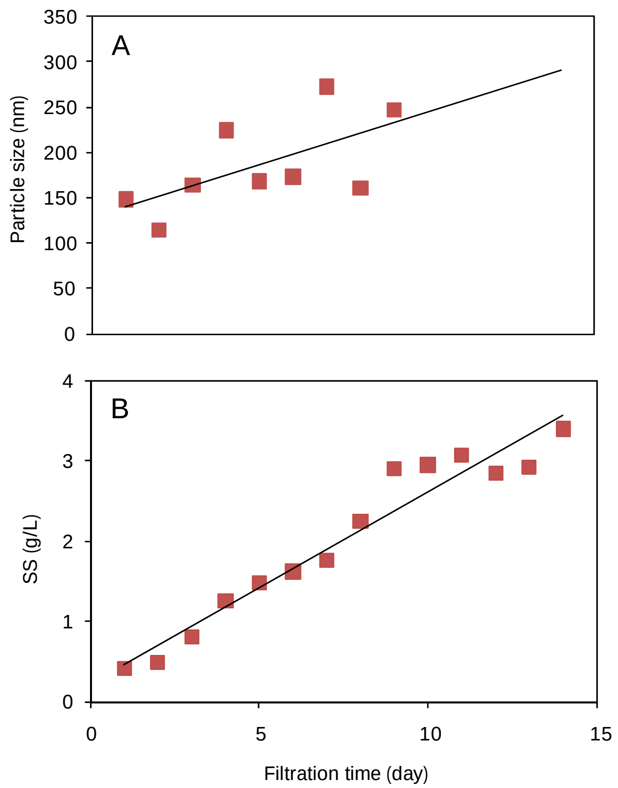

Fig. 10. Variation of submicron particle size when SS increasing in BF-MBR

In Fig. 10, the average submicron particle diameter shows an increasing trend as the SS increased. This indicates a reduction in the amount of the smallest submicron particles with higher SS concentrations, which is further seen to have a positive effect on the membrane filtration performance. Results from this trial indicate that as a certain SS concentration range is reached less fouling is observed in the BF-MBR system. This can probably be attributed to enhanced flocculation conditions with increasing SS and the formation of a cake layer deposit on the membrane surface that reduces the impact of the colloidal fraction on membrane fouling. The elevated SS concentrations clearly had a positive effect on the membrane filtration in the BF-MBR investigated in this study when SS was increased to around 1.76 g/L, giving more stabilized particle characteristics and reducing the membrane fouling rate.

For the process configurations tested in this study, the BF-MBR with low SS concentration (i.e. <1.1 g/L) showed higher fouling tendencies compared to the AS-MBR system operated in parallel. However, the membrane filtration performance could be improved by increasing the SS concentration in the biofilm reactor. Under these conditions the process approaches the hybrid system commonly referred to as the IFAS (Integrated Fixed-Film Activated Sludge) process [16,17], where the biodegradation process utilizes the benefits from both AS and BF systems. The hybrid IFAS process is typically used to improve ammonia and nitrogen removal with shot HRT and SRT by adding the biofilm carriers in the activated sludge reactor. The potential benefit of a hybrid IFAS-MBR could be avoiding problems related to high activated sludge concentration, e.g. sludging/clogging of the membrane module, higher fluid viscosities and increased energy demands, while taking advantage of the benefits of biofilm processes.

The results from this comparative study have confirmed findings previously reported in the literature with regard to BF-MBR processes. BF-MBR configurations have the potential of operating under very low SS concentration environments which are beneficial with respect to significantly reducing sludging/clogging of the membrane module, reducing the particulate load on the membrane filtration, and potentially overall energy demands. However, the results also confirm the impact and sensitivity to the colloidal fraction in the feed water to the membrane filtration unit on membrane fouling. When the submicron particulate fraction increases in amount, as well as decreases in average size, more pronounced membrane fouling in the BF-MBR systems is observed. This is particularly the case when these foulants (measured as FCOD) do not settle well as concentrated sludge resulting in accumulation in the membrane filtration unit and thus causing higher fouling rates. Studies have been conducted where separation of the biofilm reactor and the membrane reactor enables specifically designing the membrane reactor for improved flocculation of submicron particles and better control of this colloidal fraction which further reduced membrane fouling [1–3,15]. These studies used UF membranes compared to the MF membranes applied in this study. Studies on alternative process designs have also found that the AS-MBR performance can be improved by adding biofilm carriers into the activated sludge reactor operated at different SS concentrations compared to the conventional approach [18–23].

4. Conclusions

The results from this study show that the AS-MBR performed better with respect to membrane fouling when compared to the BF-MBR designed with an integrated configuration. The main differences in the membrane feed solutions were a significantly less SS and larger amount of FCOD in the BF-MBR pilot. Analyses of water quality parameters also indicate that a larger amount of submicron and colloidal particles are present in the BF reactor under these conditions. However, results also show that the BF-MBR could be operated with a similar performance as the AS-MBR with an increase of SS concentration in the membrane filtration unit. These results confirm that the membrane filtration performance, expressed as membrane fouling rate, in the BF-MBR can be comparable and competitive with the AS-MBR when operating with an appropriate system configuration and utilizing an elevated SS concentration range in the membrane filtration unit (e.g. ~1.76 g/L in this study).

Although the results presented from this study may suggest that membrane fouling is less severe for an AS-MBR compared to a BF-MBR, the results confirm previously reported findings that the BF-MBR process is more sensitive and exposed to fouling by submicron colloidal material. To obtain a sustainable operation of a BF-MBR with low fouling rates it is therefore very important to choose operating conditions and system configurations in which the submicron colloidal component is managed and controlled. This can be done using various strategies and techniques such as enhanced flocculation prior to or in the membrane filtration unit, alternative designs of the membrane filtration reactor, implementation of hybrid solutions, and more advanced control and monitoring of the operating conditions.

Acknowledgement

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