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Hybrid growth membrane bioreactor (HG-MBR): The indirect impact of sludge retention time on membrane fouling

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ABSTRACT

Membrane fouling in a hybrid-growth membrane bioreactor (HG-MBR) is a complex process affected by many parameters that include operational and environmental conditions, wastewater characteristics, and membrane properties. In this study, we investigated the role of the solid retention time (SRT) on fouling of an ultrafiltration (UF) membrane in an HG-MBR system. Under constant organic loading rate, a decrease in SRT caused a reduction in both mixed liquor suspended solids and sessile biomass. Even though biomass concentration in the reactor was lower, the fouling rate was accelerated. The highest extracellular polymeric substances (EPS) concentration adsorbed to the membrane was observed at the lowest SRT of 2.7 d as compared to SRT of 10 and 26.7 d. The higher organic loading rate per biomass unit tends to increase production of either EPS or soluble microbial products (SMP) that directly induce fouling.

Keywords: Hybrid growth-MBR (HG-MBR); Wastewater; Fouling; Extracellular polymeric substances (EPS)

1. Introduction

Membrane fouling is usually characterized as a combination of microbial biofilms, particles and colloids, inorganic precipitates (scaling), and organics that lead to an increase in hydraulic resistance over time and subsequently in reduced permeate flux. Fouling of microfiltration (MF) and ultrafiltration (UF) membranes is, in most cases, a combination of deposition of the foulants on the membrane surface and some degree of pore blockage. Membrane fouling is associated with membrane properties, operating conditions, and feed–biomass characteristics such as floc and extracellular polymeric substances (EPS) characteristics. There are plenty of studies analyzing the factors influencing fouling in both membrane bioreactors (MBRs) and hybrid growth-MBRs (HG-MBR). These factors include both suspended and sessile components of biomass growth [1] with biomass characteristics that include the concentration of the mixed liquor suspended solids (MLSS) and EPS that impact directly the cake resistance of the fouling layer [1–3]. In addition, soluble microbial products (SMP) (defined as soluble cellular components that are released during cell lysis or diffuse through the cell membrane) reduce membrane performance due to adsorption and blocking of the membrane pores [4,5]. SMP were reported to form gel layers on the membrane surface and can be consumed as nutrients for further biofilm growth [6]. Floc size

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distribution has also been studied and related to cake layer resistance, using the traditional Carmen–Kozeny filtration equation [7].

Membrane physico-chemical characteristics that have major effects on fouling include pore size, porosity, electric charge, surface energy, and degree of hydrophobicity, with a lower fouling propensity of neutral and hydrophilic membranes. Operating conditions include crossflow velocity and aeration, which are able to scour the membrane surface and reduce fouling. Increasing crossflow velocity will increase the permeate flux however, not the membrane permeability since the trans-membrane pressure (TMP) is increased concomitantly. For mitigating convection rates of colloids and other deposits to the membrane surface, a critical maximum permeate flux, in which TMP is relatively stable, needs to be determined [8]. The critical flux depends on characteristics of the MLSS, physico-chemical properties of the membrane, and system hydrodynamics. Hydraulic retention time (HRT) and solids retention time (SRT) are other operational parameters that are indirectly correlated with fouling. Increased HRT values were reported to reduce fouling due to lower MLSS [9], while limited effects on fouling was reported by Nagaoka et al. [10] after an increase of the organic loading rate. In another study by Trussel et al. [11], membrane fouling increased under constant MLSS concentration and elevated organic loading rate, correlated with an increase in the SMP concentration. Changes in SRT directly affect MLSS concentration when longer SRT will increase MLSS concentration. A decrease in EPS concentration and an increase in the mean size of the flocs can be attributed to longer SRT [12,13] that eventually reduce the fouling rate. Even though the increase in SRT leads to a higher MLSS concentration, an observed reduced fouling was probably due to a decrease in sludge production rates at longer sludge ages and a subsequent lower EPS concentration [14].

Changes in SRT in such a hybrid system that includes both suspended flocs and fluidized bed biofilm were hypothesized to affect both MLSS and fixed biomass concentration. Under constant organic loading rate, a decrease in SRT, an associated lower biomass concentration, higher sludge production rates, and a higher organic loading rate per biomass unit are probably the reasons for the increased membrane fouling rate. The objective of this study is to explore the role of sludge retention time in fouling of a UF membrane, under constant organic loading rate, in an HG-MBR system with re-circulated biofilm carriers: (1) to deepen the insight into membrane performance (TMP and permeability), and (2) to examine both the sessile and the suspended biomass concentrations at different locations in the HG-MBR system including the related concentration of extracellular polymeric substances (polysaccharides and proteins) as a function of sludge retention time.

2. Materials and methods

2.1. HG-MBR operational conditions

Fig. 1 shows the schematic diagram of the HG-MBR. A hollow fiber UF membrane module of ZW-10 (Zenon Inc, Canada) with a nominal pore size of 0.04 μm and a total filtering surface area of 0.93 m^2 was submerged in the center of a 190 L reactor. The ZW-10 was surrounded by an 8 mm mesh for avoiding damage from the moving carriers. AqWise carriers (AqWise, Israel) were filled as biofilm support with a filling ratio (carrier volume/reactor volume) of 50% (13.64 kg). The carriers are made from high-density (0.96 g/cm^3) polyethylene with diameter and height of 13 mm and a specific surface area of 600 m^2/m^3. The carriers' circulation was driven by an air diffuser. The system was operated under constant-flux mode with a mode of 5 min filtration and 15 s backwash. The detailed operation conditions are presented in Table 1. The feed wastewater consisted of artificial mix of domestic wastewater and chicken manure under ambient desert conditions (Kiryat Sde-Boker, Ben-Gurion University, Israel). Membrane cleaning was maintained by soaking the membrane module in 750 mg/L sodium hypochlorite supplemented with 250 mg/L sodium dodecyl sulfate (SDS) solution for 16 h, repeatedly for 4 times after each experiment, until the membrane permeability was recovered. Then, the clean module was used for the next experiment. Biofilm culture and adaption was conducted according to Yang et al. [15]. The airflow rate was controlled by a rotameter, the filtration flux was monitored using a volumetric method, and the TMP was monitored by a digital pressure gauge. Under constant-flux conditions, the TMP increase was the indication for membrane fouling over time. The mixed liquor temperature was monitored by a digital thermometer located on the reactor wall. The dissolved oxygen (DO) concentration was the average of the upper, middle and bottom locations in the bioreactor vessel (Model 550, YSI, USA).

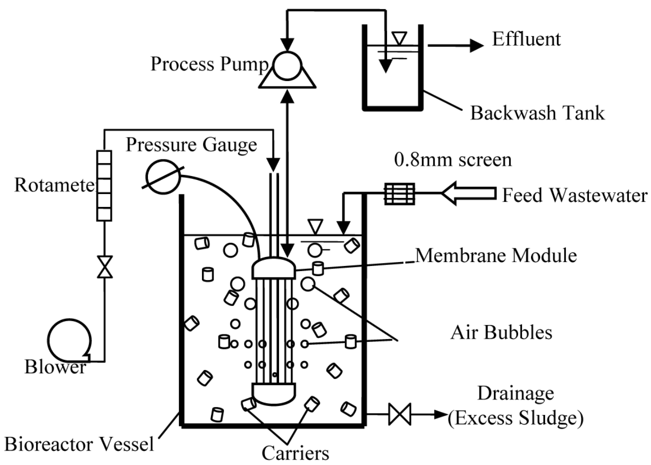

Fig. 1. Schematic diagram of the HG-MBR system.

Table 1
Operational conditions of the HG-MBR

Parameter	SRT = 26.7 d	SRT = 10 d	SRT = 2.7 d
Temperature	15.5–29.4°C (mean 22.3°C)	22.2–28.9°C (mean 26.3°C)	25.5–29.4°C (mean 28.0°C)
Initial membrane permeability at 20°C, L/(m^2.h.bar	631.1	465.5	527.7
Initial membrane resistance, m^{-1}	0.56×10^{12}	0.76×10^{12}	0.67×10^{12}
Filtrate flux, L/(m^2.h)	44.5–38.9	44.8–40.6	45.2–37.7
Aeration rate, m^3/h	2.3	2.3	2.3
Hydraulic retention time, h	5.1–5.8	5.0–5.5	5.0–6.0
pH in the reactor	6.6–7.8	6.2–6.9	6.7–7.1
DO, mg O_2/L	0.31–6.5 (mean 2.6)	0.7–5.6 (mean 2.8)	2.4–6.2 (mean 4.3)
MLSS range, mg/L	2440–4580	1000–3520	1170–575
AqWise carriers, kg per reactor vessel (filling ratio)	13.64 kg (50%)	13.64 kg (50%)	13.64 kg (50%)

2.2. Physico-chemical analysis

Three independent samples from influent, effluent, mixed liquor, and carriers were taken twice a week and the following analysis was conducted according to standards methods [16]: pH, turbidity, TSS, VSS, COD, BOD, ammonium, total nitrogen, phosphate, and alkalinity. Nitrate was determined with a second-derivative spectroscopy according to Ferree and Shannon [17]. The attached biomass was determined by measuring the dry weights (at 105°C) of 20 biofilm carriers before and after washing with 5% sodium hypochlorite and then calculated as biofilm concentration in the reactor and compared with the suspended biomass expressed as MLSS.

EPS extraction and analysis were performed from the MLSS, carriers, and a membrane fiber that was cut-off from the module (its ends were sealed) at the end of every run. EPS extraction was conducted by fixation step with 0.22% formaldehyde following by addition of 1 N sodium hydroxide to facilitate dissociation of the acidic groups in the EPS to the solution [18]. Thereafter, the suspension was centrifuged (20,000 g, 15 min, 4°C), filtered through a 0.2-µm hydrophilic nylon filter (Millipore Co.), and dialyzed through a dialysis membrane of 3500 Da (Spectra/Por). Polysaccharide and protein contents in the EPS were analyzed colorimetrically according to Dubois et al. [19] and Bradford method [20], respectively.

3. Results and discussion

3.1. Removal efficiencies of the HG-MBR

HG-MBR operation showed a relatively high removal of COD, BOD, ammonium, TSS and turbidity with values between 91–99.9%, similar to all SRTs, dictated by a daily withdrawal of MLSS volume (Table 2). Removal of total nitrogen was similar at all SRTs within a range of 24.4 and 33.0%. It seems that the organic loading rate and the uptake of nitrogen (either ammonium or organic matter) and phosphate by the biomass was not affected by reducing the sludge age.

3.2. Decreasing SRT reduces attached and suspended biomass concentration

One of the clearest distinctions between different SRTs is biomass concentration. Fig. 2 shows the suspended and attached biomass concentrations vs. time at different SRTs. An increased washout of the suspended biomass was observed by reducing suspended solid age as expected at a constant organic removal and loading rate. The MLSS concentration was lower at shorter SRT values. The mean MLSS concentrations were 3,564, 2,537 and 1,199 mg/L for the SRTs of 26.7, 10, and 2.7 d, respectively. Interestingly, the attached biofilm concentration was also reduced in a similar rate as for the MLSS concentration (Fig. 2). The suspended biomass concentration is relatively higher than the attached biomass with the MLSS/biofilm ratio of 1.3–2.6. Importantly, these conditions lead to a higher organic loading and removal rates per biomass unit in both biofilm and MLSS, without affecting the reactor wastewater quality.

Traditionally, one can expect that the attached biomass in an HG-MBR should be stable during the changing of SRT conditions. However, the attached biofilm in the HG-MBR was reduced along with the decrease of SRT. The decrease of the biofilm concentration by reducing SRT, without affecting the reactor water quality, is most likely due to the enhanced washout of the biofilm than the growth rate of the attached biomass. The faster washout of the sessile biomass may be due to a lower viscosity of the mixed liquor at lower suspended solids concentrations [21,22]. Under the same aeration rate, the lower viscosity of the mixed liquor led to a higher shear stress which was caused by the air–water upflow, and ultimately influenced

Table 2
HG-MBR influent and effluent characteristics operated at different SRTs

Parameter, m/L	SRT = 26.7 d			SRT = 10 d			SRT = 2.7 d		
	Influent	Effluent	Percent removal	Influent	Effluent	Percent removal	Influent	Effluent	Percent removal
COD	418±123	36±13	91.4	529±205	37±18	93.1	483±140	42±25	91.3
BOD	171±45	1.3±0.4	99.2	231±60	1.1±0.5	99.5	229±63	1.2±0.4	99.5
NH_4-N	30±6.8	1.4±2.8	95.4	38±16	0.1±0.2	99.8	38±5.7	0.3±0.2	99.1
TN	35±8.1	24±7.4	31.2	49±12	37±6.3	24.4	46±6.3	31±3.3	33.0
PO_4-P	10±4.2	7.6±3.3	25.0	14±6.8	12±4.4	15.2	12±3.6	8.4±2.2	29.9
TSS	171±63	0.2±0.5	99.9	176±97	0.8±1.0	99.5	176±70	0.8±1.1	99.5
Turbidity, NTU	231±79	0.2±0.1	99.9	245±186	0.3±0.1	99.9	201±85	0.3±0.3	99.8
EC, mS/cm	1.3±0.2	1.2±0.2	—	1.2±0.1	1.1±0.1	—	1.3±0.2	1.1±0.1	—
pH	7.5±0.3	7.5±0.4	—	7.3±0.2	6.7±0.4	—	7.5±0.2	7.2±0.3	—

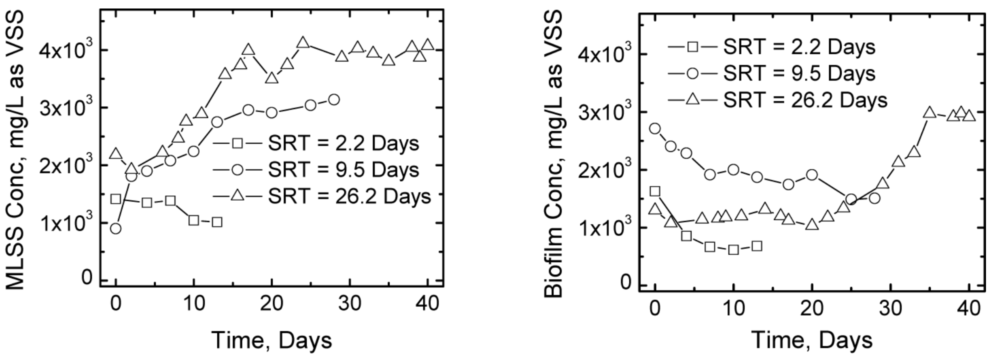

Fig. 2. The effect of SRT (d) on the biomass concentration analyzed as VSS (mg/L) of the fluidized bed biofilm (A) and the MLSS in the HG-MBR (B).

the biofilm adherence on the carrier surface. When the SRT values decreased from 26.7 to 2.7 d, a decrease of total biomass concentration was observed from 5,250 to 2,000 mg VSS/L.

3.3. The relationships between SRT, membrane permeability and adsorbed EPS on the membrane

As has already been mentioned, the lower attached and suspended biomass concentrations lead to an increase in the organic loading rate per unit of biomass and to a higher average biomass activity of the biofilm and the MLSS. Probably, this higher activity may increase SMP production as reported by Trussel et al. [11] and may also increase EPS production as reported by Chang et al. [12]. In this study, at SRT of 2.2 d and the associated highest organic loading rate per unit of biomass, a faster increase in TMP and a lower permeability was observed (Figs. 3A and 3B). A higher permeability was observed for SRT of 26.2 and 9.5 d with a slightly lower permeability for SRT of 9.5 d (Fig. 3B). In good correlation with the TMP and membrane permeability, concentrations of EPS and extracellular polysaccharides (most sticky fraction of the EPS) on the membrane were highest for SRT of 2.2 d and lowest for SRT of 9.5 d (Fig. 3C). A relatively constant fraction of extracellular proteins and polysaccharides from total VSS was observed in the MLSS and in the biofilm (Fig. 4). However, for the biofilm biomass, EPS fraction is around two-fold higher. The MLSS, as expected, also contains humic acids, SMP, and non-degradable organic matter and therefore, EPS fraction from the total VSS in the MLSS is lower than the corresponding fraction in the biofilm. The changes in SRT from 26.2 to 9.5 d did not change significantly the EPS and biomass concentrations in the HG-MBR. However, concentrations of EPS and polysaccharides in particular, were significantly lower on the membrane surface at SRT of 9.5 d (Fig. 3C) that subsequently mitigated the rate of TMP increase and permeability reduction (Figs. 3A and 3B). Further study referring the relationships between EPS adherence properties, EPS components (including polysaccharide/protein ratio), and operational conditions (including SRT

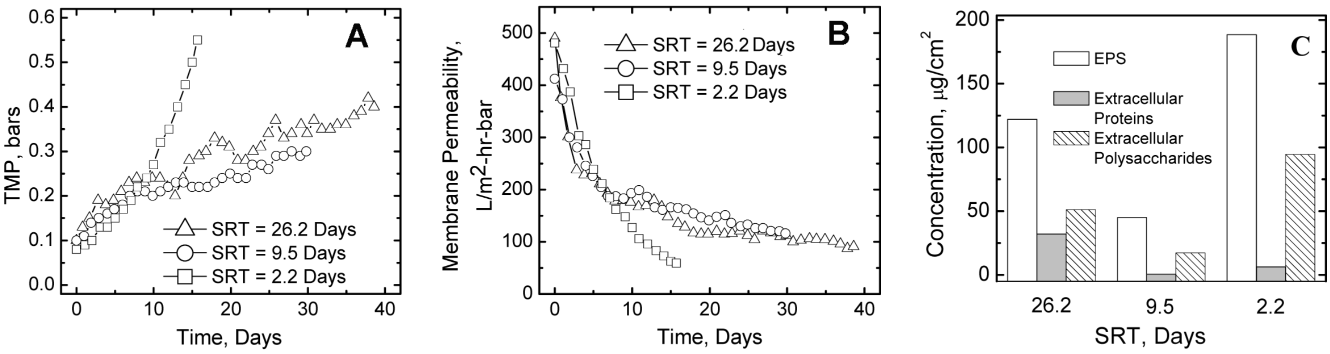

Fig. 3. The effect of SRT (d) on (A) TMP (bar), (B) membrane permeability (L/m²·h·bar), and (C) EPS adsorbed concentration on the membrane.

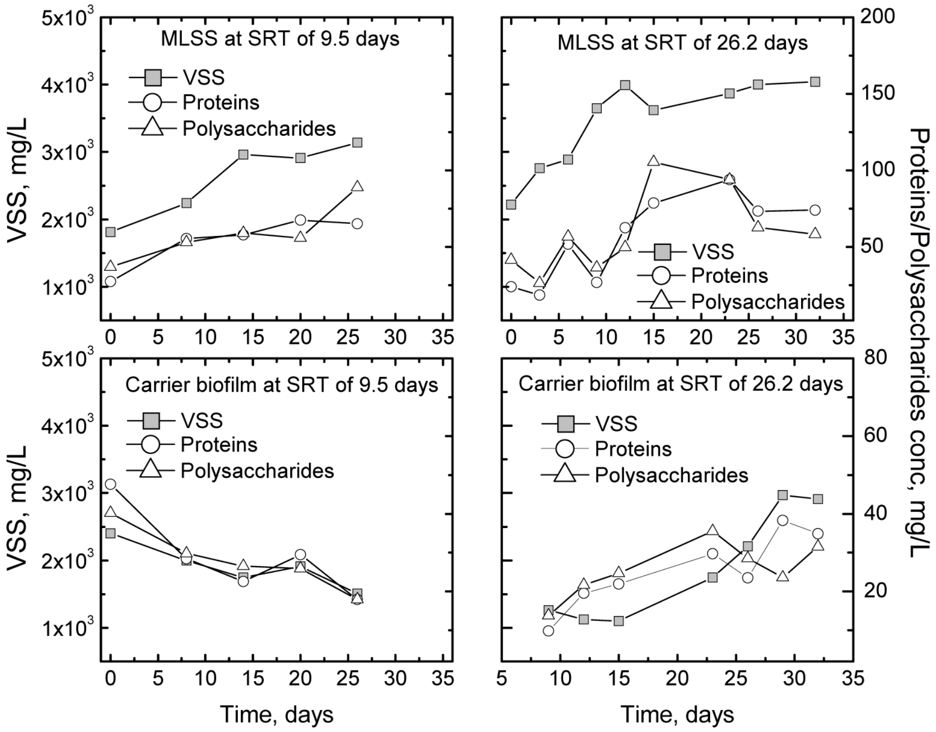

Fig. 4. Biomass and related EPS concentrations (mg/L) analyzed as VSS and extracellular components (proteins and polysaccharides), respectively, in the HG-MBR.

and HRT) needs to be carried out in order to find the reason for this behavior and to minimize fouling of UF membranes in HG-MBR systems.

4. Concluding remark

Fouling of HG-MBR is a complex process that among various parameters is also affected by SRT. Under constant organic loading rate, decreasing SRT reduced both suspended and attached biomass. The biomass reduction and the subsequent increase in the organic loading rate per biomass unit was probably the reason for the evident increase in the membrane fouling rate with EPS. The significant changes in EPS components and concentration on the membrane surface compared to an insignificant changes in biomass and EPS concentration in the reactor at different SRTs, imply that not biomass or EPS concentrations in the HG-MBR influence membrane fouling rate, but EPS adhesion characteristics affect the partitioning of EPS between the reactor and membrane surface.

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