Characterization of Soluble Microbial Products and Their Fouling Impacts in Membrane Bioreactors

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Membrane bioreactor (MBR) fouling is not only influenced by the soluble microbial products (SMP) concentration but by their characteristics. Experiments of separate producing biomass associated products (BAP) and utilization associated products (UAP) allowed the separation of BAP and UAP effects from sludge water (SW). Thus, filtration of individual SMP components and further characterization becomes possible. Unstirred cell filtration was used to study fouling mechanisms and liquid chromatography−organic carbon detection (LC−OCD) and fluorescence excitation−emission matrix (EEM) were used to characterize the foulant. Generally, the SMP exhibiting characteristics of higher molecular weight, greater hydrophilicity and a more reduced state showed a higher retention percentage. However, the higher retention does not always yield higher fouling effects. The UAP filtration showed the highest specific cake resistance and pore blocking resistance attributed to their higher percentage of low molecular weight molecules, although their retention percentage was lower than the SW and BAP filtration. The UAP produced in the cell proliferation phase appeared to have the highest fouling potential.

Introduction

Soluble microbial products (SMP) in membrane bioreactors (MBRs) are reported to concentrate in sludge water (SW), that is, the soluble and colloidal phase of sludge mixed liquor (*1, 2*), and have also been identified as a primary MBR foulant (*3*−*5*). SMP can be divided into two categories: biomass associated products (BAP), associated with biomass decay, and utilization associated products (UAP), associated with substrate uptake and biomass growth (*6*). Chemically, SMP are a pool of complex organic matter, for example, proteins, polysaccharides, humic substances, nucleic acids, organic acids, amino acids, extracellular enzymes, etc. (*7*−*9*). The molecular weight (MW) distribution of SMP varies widely from very low (<0.5 kDa) to very high (>100 kDa). The distribution is typically bimodal with a peak in the low molecular weight (LMW) region (<1 kDa) and a peak in the high molecular weight (HMW) region (>10 kDa) (*2, 6, 10*). An earlier study using ^{14}C labeled substrate reports that UAP are mostly composed of small molecules (86% and 76% <1 kDa for phenol and glucose, respectively) and BAP are mostly composed of large molecules (47% and 52% >10 kDa for phenol and glucose substrates, respectively) (*10*). Another study has shown that the high molecular fraction of SMP appears to increase with bioreactor sludge retention time (SRT) (*11*). Some studies have shown that SMP are biodegradable (*12*), whereas others have reported that SMP are refractory (*11*). In MBR systems, SMP typically accumulate during the start-up stage and are partially degraded thereafter (*1, 2, 13*).

MBR fouling is mostly related to the organic components present in the SW, that is, colloidal and soluble compounds. Filtration resistance has been found to correlate with the chemical oxygen demand (COD) in the SW, but not to the bound extracellular polymeric substance (EPS) (*5*). More rapid membrane fouling has been attributed to a high colloidal total organic carbon (TOC) of SW (*14*). Six MBR studies have shown a clear relevance of liquid phase constituents, either colloidal or soluble, to membrane fouling (*4*).

Liquid chromatography−organic carbon detection (LC−OCD) has been used to characterize the colloidal and soluble organics in SW (*3, 4, 15*). However, only SW and MBR effluent (both containing mixtures of BAP and UAP) were characterized. BAP and UAP have not been characterized separately and therefore the impacts of microbial activity on SMP characteristics are still not clear. Recently, BAP and UAP were characterized separately focusing on the short-term (hours) biomass response to shock loadings in batch experiments (*16*). However, BAP and UAP were not isolated and their fouling potential was not studied. To manipulate the biological operational parameters and minimize membrane fouling, the amount and characteristics of SMP, and their fouling potential in relation to microbial metabolism, should be studied. The objectives of this study were (1) to produce BAP and UAP separately in dedicated batch experiments; (2) to characterize SW, BAP and UAP including their composition, molecular weight (MW), hydrophobicity, and biodegradability; and (3) to study the filtration characteristics of SW, BAP, and UAP separately, and identify the SMP fractions contributing to membrane fouling.

Experimental Section

Lab-Scale MBR. A side-stream MBR was operated for biological nutrient removal fed with synthetic wastewater resembling domestic sewage (*17*). The hydraulic retention time (HRT), total SRT and aerobic SRT were controlled at 6.4 h, 17 days and 7.2 days, respectively. The bioreactor was divided into an anaerobic compartment and an aerobic/anoxic compartment using alternating aeration. A tubular, hydrophilic polyvinylidene fluoride (PVDF) membrane module (normalized pore size = 0.03 μm or 200 kDa, tube diameter = 5.2 mm, X-Flow, The Netherlands) was operated under

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TABLE 1. Comparison of Filtration Characteristics of SW, BAP, and UAP in Nonstirred Constant Pressure Filtration (TMP = 14.3 kPa)

parameter	SW	BAP	UAP
feed concentration (DOC mg/L)	40.2	77.4	12.4
retained by membrane (% of DOC)	84.8%	33.1%	16.9%
MFI-UF (s/L^2)	2.91 ± 10^5	4.27 ± 10^5	0.95 ± 10^5
MFI-UF (s/L^2) normalized to feed DOC of 40 mg/L	2.90 ± 10^5	2.21 ± 10^5	3.06 ± 10^5
apparent α (m/kg DOC)	5.60 ± 10^{15}	4.20 ± 10^{15}	5.31 ± 10^{15}
true α (m/kg DOC)	6.61 ± 10^{15}	12.7 ± 10^{15}	31.4 ± 10^{15}
pore blocking resistance (m^{-1})	1.29 ± 10^{11}	3.06 ± 10^{11}	4.17 ± 10^{11}

air-lift and inside-out mode. Both cross-flow velocities for the feed sludge and air were controlled at 0.5 m/s. For every 7.5 min of filtration at a flux of 31.8 L/(m^2·h), the membrane was backwashed for 18 s at a flux of 106 L/(m^2·h) and relaxed for 7 s. The entire bioreactor and the membrane module were maintained at constant temperature (15 °C) and operated for over one year to reach steady state conditions (maintained for 4 months). Samples of the effluent and sludge were collected during a stable operational period.

Sampling of SW. The SW was separated from the sludge mixed liquor by centrifugation (534*g* for 5 min) and two successive membrane filtrations, that is, a glass microfibre filter (GF/C, 1.2 μm, Whatman, UK) and a flat sheet microfiltration membrane (DURAPORE 0.45 μm PVDF, Millipore, U.S.).

Sampling of BAP and UAP. BAP and UAP were produced in two different batch experiments. In both experiments freshly washed sludge collected form the lab-scale MBR was used. The washing process removes soluble colloidal organics by replacing the SW with a Milli-Q water solution containing the same inorganic content as the synthetic influent but without organic components. Both BAP and UAP production batches were conducted under the same temperature (15 °C) and pH (7.5 ± 0.2) conditions as the lab-scale MBR. By the end of each experiment, all sludge was sampled to extract the SW and afterward used in unstirred cell filtration experiments described below.

The BAP production batch experiment was conducted under starvation conditions for 19 days. Alternating aeration was conducted to maintain the same aerobic: anoxic time ratio as in the lab-scale MBR (49.4 min aerobic with DO = 1.5−2.5 mg/L, 70.6 min anoxic). Every few hours to one day, mixed liquor was sampled and the SW was extracted using the method described for the SW sampling. This SW is henceforth referred as BAP (dominated by BAP since no external substrate was added).

The UAP production batch experiment was conducted for approximately 24 h. The washed sludge was spiked with acetate (target concentration of 1000 mg/L). As a control, a reference batch was conducted in parallel without acetate addition to estimate the background SMP production. Both UAP and reference batches were conducted under completely aerobic conditions (DO = 1.5−2.5 mg/L). Mixed liquor was sampled every few hours, and the SW was extracted using the method described for the SW sampling. These SWs are henceforth referred as UAP (dominated by UAP but also contains some BAP) and UAP reference (dominated by the BAP).

Unstirred Cell Membrane-Filtration. The SW, BAP, and UAP samples were filtered with a dead-end filtration unit (Stirred Cell 8200, Millipore, U.S.) under constant pressure (TMP = 14.3 kPa) conditions. A flat sheet 0.03 μm PVDF membrane was used, which represents the same material, structure and morphology as the tubular membrane used in the lab-scale MBR. By the end of each filtration, filter-cake was carefully removed with a flat stick by wiping the membrane surface. The membrane was put back into the unstirred cell, and flux was estimated again using Milli-Q water. The pore blocking resistance and cake resistance were estimated assuming that the blocking foulant had not been removed by surface wiping.

Collecting Backwash Water. The SW sample was filtered using a mini-filtration unit equipped with a membrane tube identical to the lab-scale MBR membrane but shorter in length (10 cm only) under constant flux conditions at 31.8 L/(m^2·h). The membrane was periodically backwashed with permeate (31.8 L/(m^2·h) for 45 s every 450 s filtration). Backwash water, which contains hydraulically reversible foulant retained by the membrane, were sampled and analyzed by LC-OCD.

Sample Analysis. The COD, NH_4^+−N, NO_3^-−N, NO_2^-−N, and total nitrogen (TN) concentrations were measured using colorimetric methods (Hach Lange, Germany). BOD was measured using an Oxitop (WTW, Germany) at 20 °C. Proteins were measured using the Lowry method (*18, 19*) and polysaccharides were measured using the phenol method (*20*) with corrections for nitrate absorbance.

A liquid chromatography (LC), more specifically a size exclusion chromatography (SEC) column, separates organics according to their molecular size; an organic carbon detector (OCD) and potentially other detectors follow the LC to quantify/characterize the eluted organics. The LC-OCD analysis was performed by a commercial lab (DOC-LABOR Dr. Huber, Germany) (*21, 22*). The precision and reproducibility of the LC-OCD method in two parallel measurements of the same UAP sample on two different days, showed a relative error of less than 1%. Both fine and coarse SEC columns (Alltech, Germany) were used. The SEC column was filled with Toyopearl resin (HW-50S or HW-65S with pores size of 12.5 and 100 nm, respectively). The HW-50S column provides good resolution over a LMW region (<20 kDa) and the HW-65S column provides good resolution over a HMW region (50−2000 kDa). Three detectors were installed

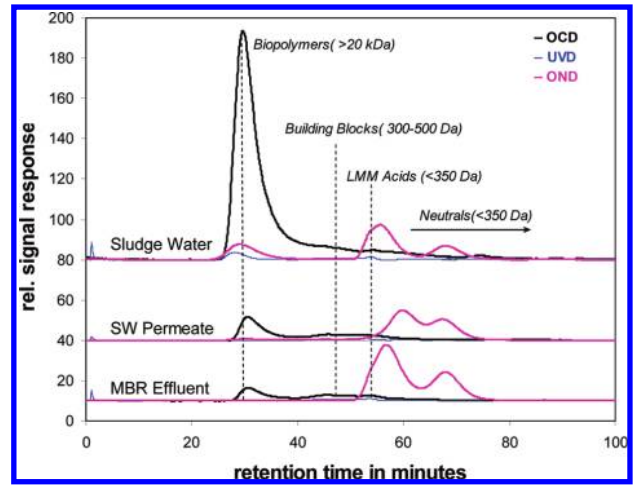

FIGURE 1. LC-OCD chromatograms of SW, SW permeate, and MBR effluent (HW-50S column).

TABLE 2. Characteristics of BAP, UAP, SW and Their Corresponding Permeate (perm), and MBR Effluent (LC-OCD used HW-50S Column)[a]

			feed and permeate of unstirred cell filtration						MBR sample
item	fraction		BAP	BAP perm	UAP	UAP perm	MBR SW	MBR SW perm	MBR effluent
LC-OCD	OC (mg/L)	overall sample	77.4	51.8	12.4	10.3	40.2	6.13	4.66
		biopolymer	48.4	26.1	5.58	1.47	28.0	2.87	1.71
		building blocks (BB)	11.2	10.4	1.78	1.54	3.93	1.71	1.61
		LMW acids (LMWA)	1.17	0.88	0.10	0.17	0.08	0.11	0.13
		neutrals (NT)	6.36	4.62	3.13	3.53	2.64	0.71	0.63
	SUVA UV_{254}/DOC (L/(mg·m))	overall sample	0.46	0.63	0.50	0.56	0.20	0.66	0.70
		biopolymer+Inorg	0.15	0.17	0.07	0.06	0.12	0.11	0.39
		BB+LMWA+NT	na	na	0.74	0.80	0.55	1.44	2.01
	N_{org} of biopolymers (mg/L)	N_{org}	2.85	1.64	0.31	0.09	1.54	0.17	0.09
		N_{org}/OC	5.9%	6.3%	5.6%	6.0%	5.5%	5.8%	5.2%
	other characteristics of overall sample (mg/L)	COD	243	74.4	41.6	29.4	99.3	bdl	10.9
		proteins	22.8	13.9	14.6	12.3	16.4	9.1	5.0
		polysaccharides	93.4	62.4	10.1	3.5	42.4	5.9	6.7
		BOD_5	6.75	na	na	na	1.7	na	2.8
		BOD_{17}	12.1	na	na	na	4.6	na	4.5
		BOD_{28}	18.1	na	na	na	11.5	na	6.2
		MOC	−0.71	1.85	−1.04	−0.29	0.29	na	0.49

[a] bdl = below detection limit; na = not available. HS were below detection limit and trace HS were lumped into BB. The sum of the four DOC fractions was less than the overall DOC due to non-chromatographic DOC.

in series in a sequence of UV detector (UVD), organic carbon detector (OCD) and organic nitrogen detector (OND). First, the UVD (Knauer K200, Germany) measures the spectral adsorption coefficient (SAC) at 254 nm. Second, the OCD oxidizes all organic matter in a thin film UV reactor and the OC present in the sample can therefore be quantified from the produced CO_2 (DOC-LABOR, Germany). Finally, the OND completely oxidizes organic nitrogen (N_{org}) into nitrate and measures the amount of nitrate using a UVD (Knauer K2001, Germany) at 220 nm. The combination of UVD and OCD detectors allows estimation of the specific UV absorbance (SUVA = UV_{254}/TOC). The combination of COD and TOC allows the estimation of mean oxidation number of carbon (MOC = 4−1.5·COD/TOC).

Fluorescence excitation−emission matrix (EEM) data were collected using a FluoroMax-3 spectrofluorometer (Horiba Jobin Yvon Inc., U.S.) at excitation wavelengths of 240−450 nm by 10 nm increments, and at emission wavelengths of 290−500 nm by 2 nm increments, respectively. Fluorescence peaks of protein-like or autochthonous (microbial) organics dominating in sewage normally appear at 270−275 nm/310−340 nm of excitation/emission wavelengths, whereas fluorescence peaks of humic-like or allochthonous (terrestrial) organics from plant materials normally occur at 300−370 nm/400−500 nm of excitation/emission wavelengths (*23*−*25*).

Results and Discussion

Comparison of Filtration Characteristics of SW, BAP, and UAP. The SW, BAP, and UAP samples were filtered in an unstirred cell operating under constant pressure conditions. The UAP filtration curves are presented in Supporting Information (SI) Figure S1 (the SW and BAP filtration curves showed a similar shape). The t/v vs v (time/volume vs volume) curve appeared to be a straight line. The modified fouling index−ultrafiltration (MFI−UF) curve showed only a slight increase in slope except for the initial 5 min, suggesting that cake filtration (more specifically, a gel layer, in this case) was the dominant mechanism (*26*).

The mean MFI-UF values during the last half hour of filtration were estimated to be 2.91×10^5, 4.27×10^5, and 0.95×10^5 s/L^2 for SW, BAP, and UAP, respectively, which were 1−2 orders of magnitude higher than those for non-MBR SW ($6.6-38 \times 10^3$ s/L, converted from specific ultrafiltration resistance (*27*)). The higher MFI-UF values of SW, BAP, and UAP suggest that their filterability was much poorer than that of the non-MBR SW.

The specific cake resistance (α) of SW, BAP, and UAP were estimated to study the filter-cake characteristics (Table 1). The α calculation requires an estimate of the filter-cake mass. The apparent α assumes that all feed DOC formed the cake, whereas the true α assumes only the retained DOC formed the cake (true α = apparent α/retention percentage). The true α of the SW filtration (6.61×10^{15} m/kg DOC) estimated in this study was close to that of a reported MBR SW filtration (3×10^{15} m/kg COD) (*28*). The apparent α and MFI normalized to 40 mg/L of the three samples were not significantly different. However, the true α values were significantly different (6.61×10^{15}, 12.7×10^{15}, and 31.4×10^{15} for SW, BAP, and UAP, respectively). This is because the apparent α and MFI were normalized to the feed concentration (i.e., the *delivered* foulant). Whereas the true α was estimated using the *retained* foulant, which is related to the retention percentage.

In addition to the α estimation, the pore blocking resistances were also estimated as 1.29×10^{11}, 3.06×10^{11}, and 4.17×10^{11} m^{-1} for SW, BAP, and UAP filtration, respectively (Table 1). Thus, the UAP filtration also suffered the most significant blocking resistance. In summary, the UAP showed a lower retention percentage but higher fouling

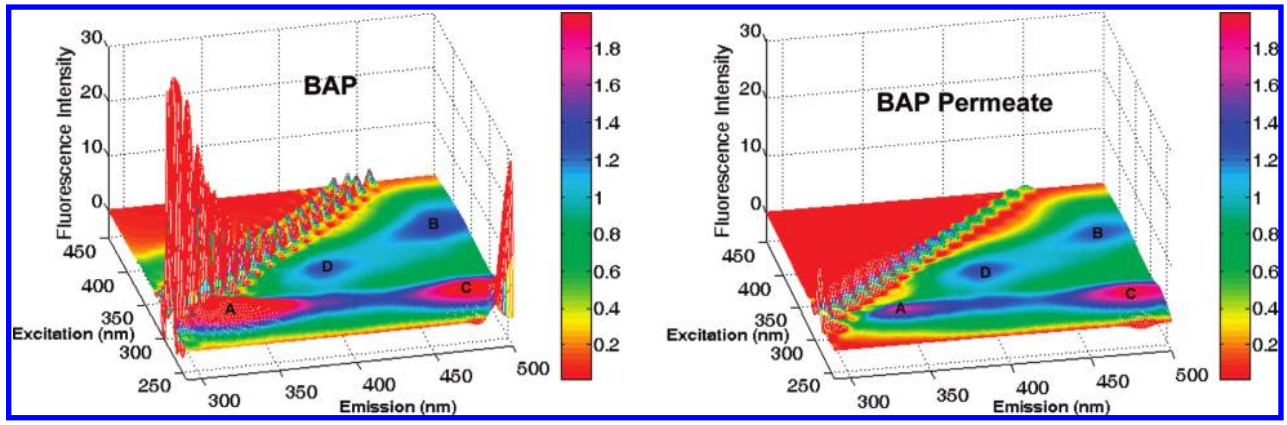

FIGURE 2. Fluorescence EEM of BAP feed (left) and BAP permeate (right).

characteristics, which might be attributed to the higher percentage of LMW compounds (see more characterization results below). In general, the foulant retained by the membrane should be differentiated from the delivered foulant and a lower retention can not guarantee lower fouling.

Characterization of SW. The LC-OCD chromatograms (HW-50S column) of SW, SW permeate collected from unstirred cell filtration (hereafter called *SW permeate*) and MBR effluent from the lab-scale MBR (hereafter called *MBR effluent*) are presented in Figure 1. The major OC fraction of the SW was biopolymers, which counted for 69.8% of the overall DOC. A more detailed characterization of the biopolymer peak using a HW-65S column is shown in SI Figure S2, suggesting that the HMW organics were up to 2000 kDa. Numerical values of each fraction are summarized in Table 2.

A moderate organic nitrogen peak eluted consistently with the biopolymer OC peak (both HW-50S and HW-65S chromatograms). The organic nitrogen contents of the biopolymers were estimated as 5.5%, 5.8%, and 5.2% (as N_{org}/OC) for the SW, SW permeate, and MBR effluent, respectively, suggesting the presence of proteins in the biopolymer peak. In the SW chromatograms, a UV peak eluted slightly earlier than the biopolymer OC peak (both HW-50S and HW-65S chromatograms), which was possibly due to inorganic colloids rather than aromatic/double bond organic compounds (*21*). The apparent SUVA values of the biopolymers were 0.12, 0.11, and 0.39 L/(mg·m) for the SW, SW permeate and MBR effluent, respectively. The true SUVA values (exclude the false UV signal due to inorganic colloids) should be even lower, suggesting that the biopolymers contained few aromatic or double carbon bonds and were generally hydrophilic.

LMW compounds in the SW, such as humic substances (HS), building blocks (BB), low molecular weight acids (LMWA) and neutrals (NT) did not show clear OC and UV peaks, suggesting the percentage of LMW compounds was small. Furthermore, the humic substance peaks were probably overlapped by the biopolymer peak and therefore difficult to identify. The SUVA value of the LMW compounds was also quite low at 0.55 L/(mg·m), suggesting hydrophilic characteristics.

The SW and SW permeate were also analyzed using fluorescence EEM (SI Figure S3). Consistent with the LC-OCD results, a clear protein-like peak (A) was identified and its membrane retention percentage was also high. In addition, two humic-like peaks (B and C) were more visible than those in the LC-OCD chromatogram and their membrane retentions were lower.

The retention of SW organics can be illustrated by comparing the feed (SW) and permeate (SW permeate and MBR effluent). A few interesting points are discussed as follows. First, the UF membrane retained a high percentage of OC, that is, 84.8% (overall sample) and 89.8% (biopolymer fraction) in the unstirred cell filtration tests, which was consistent with earlier studies (*3, 4, 15*). However, the LMW compounds (much smaller than the UF pore size) also showed 61.9% retention on average, which can be attributed to the filter-cake that reduced the apparent molecular weight cut off (MWCO) of the membrane (*29, 30*). It also explains the slight increase in MFI-UF values and the high true α in the above unstirred cell filtration. Second, the SUVA values of the SW permeate and MBR effluent were higher (0.66 and 0.70 L/(mg·m), respectively) than those of the SW (0.20 L/(mg·m)). This suggests that the hydrophilic UF membrane preferentially retained hydrophilic compounds. Finally, the MOC of the MBR effluent (0.49) was higher than that of the SW (0.29), suggesting that the membrane retained more reduced compounds. It should be noted that the preferential retention characteristics are also impacted by the membrane characteristics (such as pore size, hydrophobicity, and charge etc.) in addition to the feed properties. A typical MBR membrane (0.03 μm, hydrophilic and PVDF) was studied here, and one should be careful in generalizing the results.

To further characterize the foulant retained by the membrane, the SW backwash water was analyzed using LC-OCD (SI Figure S4). It was not surprising to find that the DOC of the backwash water was much higher than that of the feed. In addition, the percentage of biopolymers (85.6%) was also higher than that of the SW (68.6%). This suggests that biopolymers were indeed retained by the membrane, and could be significantly removed by periodic backwashes.

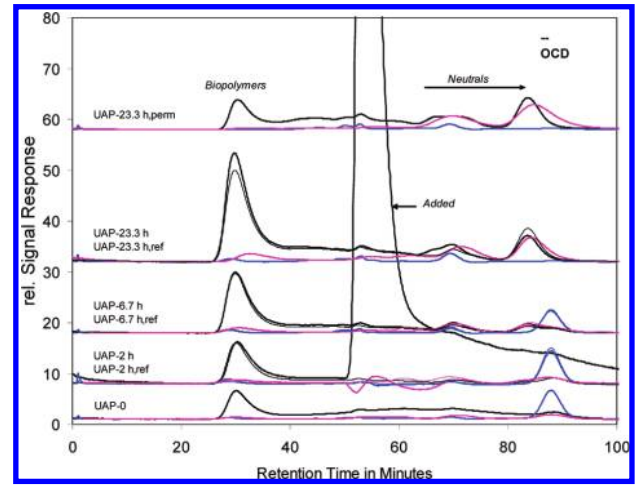

FIGURE 3. LC-OCD chromatograms of UAP samples after acetate addition (the thicker OCD lines represent the UAP production batch; the thinner OCD lines represent the reference batch) (HW-50S column).

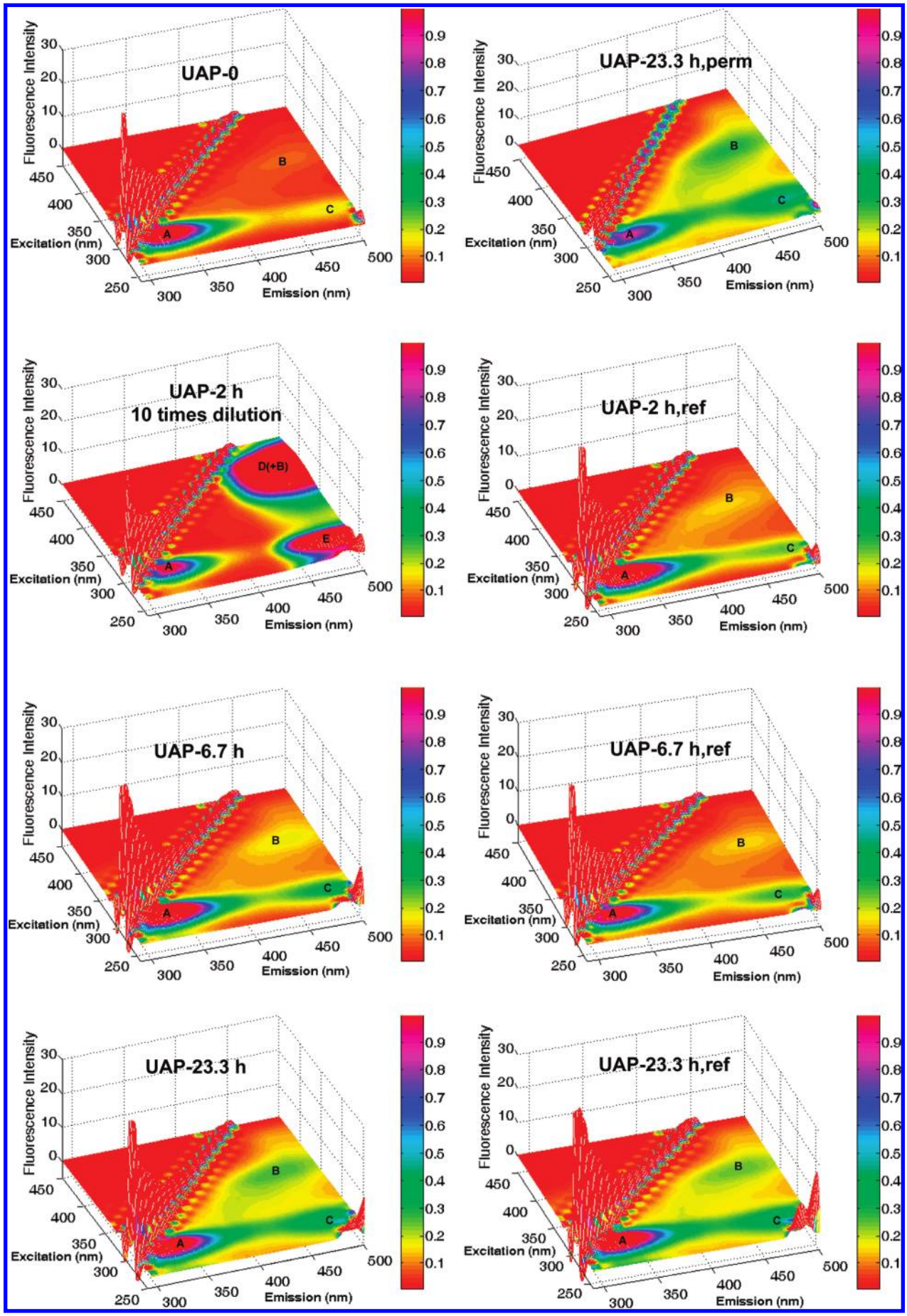

FIGURE 4. Fluorescence EEM of UAP and UAP reference.

The SW BOD_5 (1.7 mg/L) and BOD_5/COD ratio (0.017) were very low. The BOD_{17} and BOD_{28} (4.6 mg/L and 11.5, respectively) were still low, although the incubation times in the BOD test were extended to one sludge age (17 days) or longer. This suggests that the SW organics (mostly SMP) were refractory to biodegradation. In addition, only a small amount of SMP were associated with the permeate, whereas the SMP discharged via sludge wastage should also be limited under long SRT conditions of typical MBRs. Hence, the SW can contain a high steady-state SMP concentration (*31*).

Characterization of BAP. The proteins, polysaccharides, and COD of BAP increased throughout the experiment. The BOD values on day 19 were measured as 6.8, 12.1, and 18.1 mg/L after an incubation of 5, 17, and 28 days, respectively (Table 2). Furthermore, the BOD_5/COD ratio was only 0.028. This suggests that BAP were mostly composed of refractory organics or, more likely, that the biodegradable fraction of BAP had been degraded and only refractory BAP remained.

The BAP and its corresponding permeate from unstirred cell filtration were characterized using LC-OCD (SI Figure S5). The BAP contained less biopolymers but more LMW organics (62.5% and 24.2%) compared with the SW (69.8% and 16.5%). Therefore, the overall and biopolymer retention percentages of BAP (33.1% and 46.1%, respectively) were considerably lower than those of SW (84.8% and 89.8%). Similar to SW filtration, the SUVA and MOC of the BAP permeate were also higher than those of the BAP feed (0.63 vs 0.46 L/(mg·m) and 1.85 vs 0.7, respectively). The BAP retentions, especially the humic substance retention, were more apparent in the fluorescence EEM (Figure 2). The protein-like compounds (peak A) showed a high retention but the humic-like compounds (peak B and C) showed a lower retention. Peak D (probably transphilic) was also identified and showed almost no retention. According to the retention data, the foulant of BAP filtration seemed similar to that of SW filtration, mainly biopolymers and some humic substances. The gel layer was expected to be formed by the retained lower MW organics (but still large enough to be retained). Hence, the true specific cake resistance of the BAP gel layer was found to be higher than that of SW.

A recent study reported that only HMW BAP (4,800 kDa) were produced in the endogenous phase in a 150 min experiment (*16*). However, the batch experiment of this study lasted for 19 days, which represents long-term conditions. Thus, LMW humic-like compounds were also identified in addition to HMW biopolymers.

Characterization of UAP. Samples were collected from the UAP production batch and reference batch at 0, 2, 6.7, 23.3 h after acetate addition and were analyzed by LC-OCD (Figure 3) and fluorescence EEM (Figure 4). Acetate peaks were clearly identified using both LC-OCD and EEM (peak D and E) in the UAP-2 hr sample (sampled 2 h after acetate addition), but were absent in the UAP-6.7 h sample, suggesting it had been completely taken up. The biopolymers/protein-like compounds and LMW/humic-like compounds generally increased after acetate addition in both UAP and reference batches during the 23.3 h.

The true UAP were estimated as the difference between the UAP and reference (see differential chromatograms in ref *31*). Two types of UAP can be identified, associated with two metabolic steps (*32*). In step one, before acetate depletion, the LMW UAP (eluted during 30−50 min) were produced and partially biodegraded (compare the 2 and 6.7 h chromatograms). The UAP produced during this period (before acetate depletion) were designated as UAP_{sto}, as the substrate was taken up and stored as polyhydroxyalkanoates (PHA). The storage process can be confirmed by a high biomass yield (0.83, higher than the normal range 0.6−0.7 (*33*)). In the second step, after acetate depletion, the HMW UAP kept increasing (compare the 6.7 and 23.3 h chromatograms). The UAP produced during this period were designated as UAP_{pro}, as biomass utilized the stored PHA for cell proliferation. The UAP_{sto} corresponded LMW, more biodegradable and lower in concentration (*31*). However, the UAP_{pro} showed HMW and poor biodegradability, and thus they are more likely to accumulate in MBRs. Hence, the UAP-23.3 h sample should be dominated by the UAP_{pro} (also include some BAP) and it was further filtered on a 0.03 μm membrane to study their fouling potential.

The biopolymer fraction of UAP-23.3 h (45.1%) was considerably lower than that of the SW and BAP (69.8% and 62.5%, respectively). Instead, this UAP contained more LMW compounds (40.4% vs 16.5% and 24.2%). The overall retention percentage was, therefore, considerably lower than that of SW and BAP (16.9% vs 84.8% and 33.1%). A recent UAP study reported that the UAP also exhibited a lower MW than the BAP (*16*). Similar to SW and BAP filtration, the SUVA and MOC of the UAP permeate were higher than those of the UAP feed.

In summary, the main foulant of UAP filtration was still biopolymers. The UAP biopolymers most probably attributed to the UAP_{pro} and exhibited lower MW than those of SW and MBR. Thus, the UAP filtration exhibited the highest true α and blocking resistance among the SW, BAP, and UAP filtrations. It should be noted that these results were obtained using acetate as spiking substrate. Future study of UAP under other organic loading conditions and using more complex substrates is recommended to obtain more general results.

Acknowledgments

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Supporting Information Available

Figure S1: Filtration curves of UAP; Figure S2: LC-OCD chromatograms of SW and MBR effluent; Figure S3: Fluorescence EEM of SW and SW permeate; Figure S4: LC-OCD chromatograms of SW, permeate, and wasted backwash water; Figure S5: LC-OCD chromatograms of BAP and permeate. This material is available free of charge via the Internet at http://pubs.acs.org.

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