Energy saving in the operation of submerged MBRs by the insertion of baffles and the introduction of granular materials

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ABSTRACT

A membrane bioreactor (MBR) is not a mainstream wastewater treatment technology, mainly because the energy consumption in an MBR operation is high. This study investigated the mitigation of membrane fouling and the reduction in aeration through the introduction of granules into a pilot-scale baffled membrane bioreactor (BMBR) used to treat municipal wastewater. With granular materials, the BMBR could be stably operated, even when the filterability of the mixed liquor suspensions was considerably low due to low temperatures. The aeration rate could be reduced by more than 50% with the help of granules. However, it was found that the introduction of granules damaged parts of the membrane surface. The damage might be avoided by adjusting the contact intensity of the granules and the membrane surface.

Keywords

membrane fouling; granular materials; baffled membrane bioreactor; aeration rate; filterability of mixed liquor suspensions

1. INTRODUCTION

Membrane bioreactors (MBRs) have many advantages over conventional wastewater treatment systems; these advantages include high quality effluents, a small footprint and ease of operation [1]. High quality effluent is suitable for a variety of water reuse applications [2,3]. Additionally, MBRs are a suitable technology for decentralized wastewater management and satellite wastewater treatment systems [2]. Therefore, MBR is a promising technology for future wastewater management systems.

However, submerged MBRs are not currently a mainstream treatment technology because the energy consumption associated with operating an MBR is two times higher than that associated with a conventional activated sludge process [4]. Aeration to mitigate membrane

fouling represents the largest contribution to operating energy, and it requires up to 60–70% of the total operating energy in MBRs [5]. Membrane fouling must be efficiently mitigated to expand the use of MBRs. Granular materials were introduced into submerged MBRs to overcome problems with membrane fouling [6,7]. The introduction of granules into MBRs can mitigate membrane fouling because the granules mechanically clean the membrane surface. The aeration rates during the operations of submerged MBRs might be reduced when the granules are used, thus leading to significant energy savings required for operation.

Additionally, the energy required for sludge recirculation and mixing in an anoxic tank accounts for 10-20% of the total energy consumption in a common MBR [8,9]. The authors have proposed a baffled membrane bioreactor (BMBR), in which baffles are inserted in a submerged MBR, and the level of water in the reactor is controlled to facilitate simultaneous nitrification/denitrification without sludge recirculation [10]. The inner zone of the baffles maintains an aerobic condition because of aeration, whereas the outer zone alternately creates aerobic and anoxic conditions. A BMBR has the potential to reduce the total energy consumption during operation. The baffles inserted in the BMBR create circulation flows in the membrane tank, which force the granules to move vigorously and enhance the efficiency of mechanical cleaning. Therefore, the introduction of granules into a BMBR would effectively control membrane fouling, leading to a significant decrease in operating energy.

In this study, a pilot-scale BMBR was operated with granules. To evaluate the effect of granules on the mitigation of membrane fouling, TMP increases were compared before and after introducing granules into the BMBR. The filterability of the mixed liquor suspensions, the dissolved organic matter in the mixed liquor suspensions and the foulants extracted from the fouled membranes were analysed to investigate changes in the characteristics of membrane fouling caused by granules. Additionally, damages to the membrane surface caused by the granules were examined at the termination of each operation.

2. MATERIALS AND METHODS

2.1. The operation of a pilot-scale BMBR

A pilot-scale BMBR was operated continuously at a municipal wastewater treatment facility (Soseigawa Wastewater Treatment Center, Sapporo, Japan). A schematic of the pilot-scale BMBR is shown in Fig. S1 of the supporting information. The BMBR used in this study was equipped with 6.8 m² flat-sheet membrane modules (Toray, Japan). Half of the membrane area was used for adjusting hydraulic retention time (HRT) of the BMBR. Coarse bubble diffusers were placed under the membrane modules, and aeration was performed continuously (aeration rate: 9 m³/h). The membrane was made from a polyvinylidene fluoride (PVDF) polymer and had a nominal pore size of 0.1 µm. The membrane flux was set at a high value, 33.3 LMH (0.8 m³/m²/d), in this study to accelerate membrane fouling and to facilitate the

1 observation of the effect of the granules. Intermittent operation of a suction pump (operated
2 for 15 min with a 1 min pause) was also performed. The BMBR had an effective reactor
3 volume of 450 L. The resulting HRT in the BMBR was 3.4 h. The solid retention time (SRT)
4 was set at 20 days throughout the operation. When membrane fouling became significant, the
5 membrane module was removed from the reactor, and the membrane surface was wiped with
6 a sponge and rinsed with tap water. The feed wastewater was transported from the inlet of the
7 primary sedimentation basin of the facility and then sieved using a bar screen (openings = 1
8 mm). For acclimatization of biomass, the BMBR was operated under the condition mentioned
9 above for 2 months.

10
11 The granular materials used in this study (BCN, Nisshinbo Chemical Inc., Japan) had a
12 cylindrical shape. The photo of the granules is shown in Fig. S2 of the supporting information.
13 The size (both diameter and height) and specific gravity of the granules were approximately 4
14 mm and 1.01, respectively. The main component of the granules was polyethylene glycol.
15 The volume of the granules introduced into the pilot-scale BMBR was 5% of the reactor
16 volume in this study. When similar suspended materials are used in conventional activated
17 sludge process to gain benefits of a fixed-film system, the volume of the materials added is
18 normally 20–30% of the reactor volume [11]. Therefore, it is considered that adding 5% of
19 the reactor volume is economically feasible.

20
21 Continuous operation of the BMBR was divided into three periods (Runs 1–3). Throughout
22 Run 1, the BMBR was operated without granules. In the middle of Run 2, in which the
23 aeration rate was the same as that of Run 1, the granules were introduced into the BMBR. In
24 Run 3, the granules were present from the beginning, and the aeration rate was reduced from
25 9 to 4 m³/h. Table 1 summarizes the operating conditions in each run. The temperatures in
26 Runs 2 and 3 were lower than that in Run 1 because these runs were carried out in the winter.
27 The DO concentrations in the inner zone of the BMBR were maintained at 4–6 mg/L in Runs
28 1 and 2, whereas they were lowered to below 1 mg/L in Run 3 because of the reduced
29 aeration rate. Prior to the initiation of each run, the membranes were cleaned with NaClO and
30 oxalic acid to restore membrane permeability. Twenty-four-hour composite samples were
31 collected from the feed wastewater, and the permeate of the BMBR was collected for analysis
32 of general water quality.

33 34 35 **2.2. Batch filtration experiments**

36 The effect of the introduction of the granules on the filterability of the mixed liquor
37 suspensions was assessed by a series of batch filtration experiments using a dead-end stirred
38 cell system. The membrane used in these experiments was identical to that in the BMBR. The
39 effective membrane area in the batch filtration experiment was 37.4 cm². The stirred cell was
40 filled with 300 ml of mixed liquor suspensions collected from the BMBR, and compressed air

was used to filter the suspension under a constant pressure. During the batch-test, the permeate of the BMBR was supplied to the stirred cell to maintain a constant volume of suspension in the cell. The filtration pressure was fixed at 5 kPa, and the stirring speed in the cell was set at 170 rpm. In each filtration, virgin membranes were used. The membrane permeate flux was measured using an electronic balance. The membrane filtration resistance was calculated using the following equation:

$$R = \frac{\Delta P}{J \cdot \mu}$$

where R is the membrane filtration resistance (m^{-1}), J is the membrane permeate flux ($\text{m}^3/\text{m}^2/\text{s}$), ΔP is the trans-membrane pressure (TMP) (Pa), and μ is the viscosity of the permeate (Pa s). In the series of batch filtration experiments, the membrane permeate flux reached a plateau when the membrane permeate volume exceeded 20 ml. The membrane filtration resistance (i.e., the filterability of the suspension) was calculated based on the plateaued membrane flux.

At the termination of each run, the filtration resistances of the fouled membrane in the pilot-scale BMBR were measured using the same system that was used in the filterability test described above. A membrane element in the reactor was removed, and the fouled membrane was cut such that the specimen could be used in the dead-end cell. Distilled water was filtered under a constant pressure (30 kPa).

2.3. Scanning electron microscopy (SEM)

At the end of each run, the fouled membrane surfaces were examined using a SEM (S-4000, Hitachi, Japan). The fouled membranes were cut into 1 cm^2 squares, and the structure of the fouled membrane was fixed with 2% glutaraldehyde in 0.1 M phosphate buffer (pH = 7.2) at 5°C overnight. The treated samples were then fixed with 1% osmium tetroxide with 0.1 M phosphate buffer at room temperature for 2 h. The fixed samples were dehydrated in ethanol. After dehydration, the samples were immersed twice in an isoamyl acetate solution for 15 min. The samples were then dried in a critical point drying apparatus (HCP-1, Hitachi, Japan) to avoid the deformation of the foulant structures. Finally, the samples were coated with ultrathin platinum to avoid the accumulation of a static electric charge during the measurements.

2.4. Extraction of the foulants

At the end of each run, the foulants were extracted from the fouled membranes and analysed. In this study, irreversible fouling, which can be defined as fouling that cannot be restored by physical cleaning, was the focus. Prior to the extraction of the foulants, the membranes were manually wiped with a sponge to remove the accumulated cake that accounted for physically reversible fouling. Sodium hydroxide (pH = 12) was used to extract the foulants from the

fouled membranes [12,13]. The membranes were soaked in the alkaline solution at 30°C for 24 h.

2.5. Analytical methods

The concentrations of total organic carbon (TOC) and dissolved organic carbon (DOC) were determined using a TOC analyser (TOC-VCSH, Shimadzu, Japan), which could also be used to determine the concentration of total nitrogen (T-N). The samples containing suspended solids were subjected to a TOC/T-N analysis after sonication for 3 min. Analysis of DOC, dissolved carbohydrates, and dissolved proteins in the activated sludge collected from the membrane separation zone was performed after the suspensions had been filtered using a mixed cellulose ester membrane (Advantec Tokyo, Japan) with a pore size of 0.45 μm . The phenol-sulfuric acid method [14] and the Lowry method [15] were used to determine the concentration of carbohydrates and proteins, respectively. Glucose and bovine serum albumin (BSA) were used as standards for the measurements of carbohydrates and proteins, respectively. The particle size distributions of the mixed liquor suspensions in the BMBR were analysed using a laser diffraction analyser (SALD-7100, Shimadzu, Japan). The concentrations of NH_4^+ -N, NO_2^- -N, NO_3^- -N were determined by using an ion chromatograph (DX-100, DIONEX, USA).

3. RESULTS AND DISCUSSION

3.1. Continuous operation of the pilot-scale BMBR

Table 2 summarizes the characteristics of the feed wastewater (TOC, T-N) and the treated water (TOC, T-N, NH_4^+ -N, NO_2^- -N, NO_3^- -N) during operation. The average concentrations of TOC in the treated water in all of the runs were within the range of 6 to 8 mg/L, regardless of the influent concentration of TOC. The concentrations of TOC in the treated water in Runs 2 and 3 (with granules) were similar to that seen in Run 1 (without granules). It was found that introducing granules into the BMBR did not affect the TOC concentration in the treated water. However, in Run 3, in which a reduced aeration rate was examined, the concentration of NH_4^+ -N in the treated water significantly increased. In Run 3, the supply of oxygen to the biomass was apparently not sufficient, resulting in limited nitrification.

In our previous study of the pilot-scale BMBR, which was operated with an HRT of 4.7 h, the removal rate of T-N exceeded 70% [10]. In this study, the HRT was reduced to 3.4 h, and the removal rate of T-N was limited to approximately 40%. The cycle time between aerobic and anoxic conditions in the outer baffle zone is critical for nitrogen removal in the operation of the BMBR [10]. In this study, care was not taken to investigate the cycle time for the optimization of nitrogen removal. Therefore, the removal rate of T-N in this study was lower than that seen in the previous operation.

Fig. 1 shows the time course change of the TMP. The data shown in Fig. 1 were adjusted to 20°C equivalent values considering the influence of water viscosity. In Run 1, in which the BMBR was operated without granules, the TMP increased to 40 kPa within 10 days of the operation, and the operation could not be continued. After the physical cleaning of the membrane surfaces, the TMP significantly decreased but quickly increased again. In Run 1, long-term continuous operation of the BMBR was difficult. In Run 2, the TMP increased rapidly before the granules were introduced. After the granules were introduced into the reactor, the TMP dropped, and then an increase in TMP was effectively mitigated. The operation could be continued for 50 days without any physical cleaning. In Run 3, in which aeration rate was reduced from 9 to 4 m³/h and the granules were used, operation could be continued for 20 days without physical cleaning. The rate of TMP increase observed in Run 3 was comparable to that observed in Run 1. This result implies that the introduction of granules can reduce the aeration rate in MBRs by more than 50%.

3.2. Time course change of the filterability of the mixed liquor suspensions

Fig. 2 shows the time course change of the filterability of the mixed liquor suspensions, the concentration of dissolved carbohydrates and proteins in the mixed liquor suspensions and the temperature in the reactor. Prior to the introduction of the granules (day 76), the membrane filtration resistances recorded in the batch-filtration tests were lower than $4 \times 10^{11} \text{ m}^{-1}$. However, the filterability of the mixed liquor suspensions rapidly deteriorated when the water temperature in the reactor was less than 14°C (day 94). The concentration of dissolved carbohydrates increased with the deterioration of the filterability of the mixed liquor suspension. Conversely, the concentration of dissolved proteins in the mixed liquor suspensions was stable. The deterioration of the filterability of the mixed liquor suspensions was reported to be attributed to high concentrations of dissolved organic components [16]. Van den Brink et al. [17] and Lyko et al. [18] reported that low temperature caused increasing concentrations of dissolved carbohydrates in the mixed liquor suspensions of an MBR. Additionally, after the introduction of the granules in Run 2, the mean particle size of the mixed liquor suspensions decreased from 3.86 µm (day 76) to 0.12 µm (day 84). Although the accuracy of the analytical instrument that we used for measurements of particles size distribution might not be very high for sub-micron particles, it seemed that particle size shifted towards small sizes with introduction of the granules. Huang et al. [19] reported that the introduction of the granules broke sludge flocs and increased the amount of small particles and total organic carbon in the supernatant. Thus, the increase in the concentration of dissolved carbohydrates observed in this study may be related to low temperature and the breakage of sludge flocs.

The characteristics of carbohydrates may also have an effect on the filterability. Although the concentration of dissolved carbohydrates on day 3 (temperature: 25°C) was comparable to that on day 94 (temperature: 14°C), the sample collected on day 94 at a low temperature

exhibited a much lower filterability than the high-temperature sample. The characteristics of carbohydrates produced by microorganisms at low temperatures were thought to be different from those produced at high temperatures, which may cause differences in filterability.

Table 3 summarizes the concentration of dissolved organic components in the mixed liquor suspensions in each run. As mentioned before, after the introduction of the granules in Run 2, the concentration of dissolved carbohydrates increased. The concentrations of dissolved proteins were rather constant over Runs 1 and 2. However, in Run 3, in which the DO concentration in the reactor was low (<1 mg/L), the concentrations of dissolved organic components obviously increased. The degree of SMP elimination decreased at very low DO and nitrate concentrations [20]. As shown in Table 2, the concentration of nitrate in Run 3 was also lower than that of Runs 1 and 2. The high concentration of dissolved organic components in Run 3 might be explained by the poor elimination of SMP induced by low DO and nitrate concentrations. Additionally, as discussed above, low temperature and the breakage of microbial flocs caused by the introduction of the granules in the reactor might also increase the concentration of dissolved carbohydrates.

3.3. Analysis of the fouled membranes

Fig. 3 shows photos of the membrane modules, which were collected from the BMBR at physical cleaning (Run 1) and the termination of operation (Runs 2 and 3). In Run 1, the membrane surface was entirely covered by cake (Fig. 3 (a)). However, in Run 2, in which the granules were introduced into the reactor in the middle of the operation, the cake layer was not observed on the membrane surface, whereas part of the membrane was distinguished by a brown colour (indicated by an arrow in Fig. 3 (b), described later). In Run 3, in which the granules were used with a reduced aeration rate, accumulated cake was removed from the membrane surface of some modules (Fig. 3 (c)); however, some membrane modules were covered by cake, as shown in Fig. 3 (a). It seems that the spatial distribution of the granules was not uniform in the membrane tank due to reduction of the aeration rate in Run 3; therefore, the cake could not be removed from the membrane surface for some modules. As discussed before, the rate of TMP increase in Run 3 was comparable to that observed in Run 1 (Fig. 1). If the spatial distribution of the granules had improved, a lower TMP increase would have been observed in Run 3. Modification of the configuration of the reactor and/or increasing the volume of the granules in the reactor might address the formation of the cake at low aeration rates, which should be investigated in future research.

As mentioned above, a portion of the membrane surface was coloured brown in Run 2, and this colour could not be removed by physical cleaning; thus, the colour was not caused by the accumulated cake. Table 4 summarizes the filtration resistance of the membranes collected at the termination of each run. The filtration resistance of the fouled membrane was calculated from the permeate flux (33.3 LMH) and the recorded TMP at the termination of the operation.

The other filtration resistances shown in the table were measured using the dead-end cell. Additionally, the filtration resistances of the fouled membrane collected in Run 2 were separately analysed based on the colour. The filtration resistance of the membrane fouled in Run 1 was significantly reduced by physical cleaning (sponge wiping), indicating that membrane fouling in Run 1 was mainly physically reversible fouling. The filtration resistances remaining after physical cleaning were attributed to irreversible fouling, which cannot be restored by the physical cleaning. The coloured area of the membrane fouled in Run 2 (indicated by the arrow in Fig. 3 (b)) exhibited a significantly high filtration resistance, even after the physical cleaning was conducted. Additionally, the effectiveness of the chemical cleaning for the coloured area was limited. Conversely, the filtration resistance after the physical cleaning of the non-coloured area in Run 2 was comparable with that of the sample obtained in Run 1. The membrane permeability of the non-coloured area could be sufficiently restored by the chemical cleaning. **These results indicate that the fouling characteristic of the coloured area were totally different from those of the non-coloured area.** Additionally, In Run 2, the cake did not accumulate on the membrane surface due to the granules; however, the filtration resistance recorded for the overall membranes at the termination of Run 2 ($22.3 \times 10^{11} \text{ m}^{-1}$) was much higher than that specifically measured for the non-coloured area ($7.5 \times 10^{11} \text{ m}^{-1}$). This indicates that the coloured area with the significantly high filtration resistance contributed to the elevation of the filtration resistance of the overall membranes in Run 2. In Run 3, irreversible fouling was promoted compared with Runs 1 and 2 (non-coloured area).

Table 5 summarizes the amount of organic components extracted from the fouled membranes at the termination of each run. The amount of foulants and the ratio of carbohydrates to protein (C/P) in Runs 1 and 2 (non-coloured area) were nearly identical. However, the amount of foulants extracted from the coloured area of Run 2 was significantly higher, and the C/P ratio was also high. In Run 2, the characteristics of foulants were different between the coloured and the non-coloured area, even though these samples were collected from the same membrane element. In Run 3, the amount of proteins extracted from the fouled membrane was comparable to those extracted in Runs 1 and 2 (non-coloured area), although the filtration resistance recorded after the physical cleaning was twice as high as those recorded in Runs 1 and 2 (non-coloured area). Additionally, the extracted amount of carbohydrates and the C/P ratio observed in Run 3 were higher than those in Runs 1 and 2 (non-coloured area). Carbohydrates were reported to be major components of the foulants [21,22]. Elevated concentrations of carbohydrates in mixed liquor suspensions might promote irreversible fouling in Run 3.

Fig. 4 shows the SEM images of the membrane surfaces observed after chemical cleaning. The surface morphology of the fouled membrane with the brown colour, which was obtained in Run 2 (Fig. 4 (c)), was significantly different from those of the other samples. For the fouled membrane with the brown colour in Run 2, damage to the membrane surface caused by

the granules was clearly recognized. Conversely, in Run 3, which was performed with a reduced aeration rate, the surface morphology of the fouled membrane remained similar to those observed in Runs 1 and 2 (non-coloured area). It should be noted that the SEM images of the membrane surface in Run 3 were obtained from the area that was not covered by cake. When the aeration rate was high, the granules contacted with the membrane surface vigorously, resulting in damage to the membrane surface. This result indicates that the damage to the membrane surface was dependent on the contact intensity of the granules and the membrane surface. The contact intensity of the granules could be affected by cross flow velocity near the membrane surface, bubble size and clearance between membrane plates. Additionally, the sharp edge of the cylindrical granules used in this study might cause membrane damage. Further study of the adjustment of the contact intensity is necessary to avoid damage to the membrane surface caused by the granules.

4. CONCLUSIONS

The introduction of granules into the BMBR mitigated membrane fouling because it efficiently removed cake from the membrane surface, regardless of the deterioration of the filterability of mixed liquor suspensions. It was estimated that the aeration rate to control membrane fouling of the BMBR could be reduced by more than 50% by introducing granules. However, the introduction of the granules can potentially damage the membrane surfaces and promote physically irreversible fouling. Further study is necessary to avoid the membrane damage observed in this study. Determination of the appropriate contact intensity between membranes and granules is important. Also, the configuration of the reactor (e.g., clearance between membrane plates) should be modified to mitigate damage to the membrane surface when introducing granules.

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Fig. 1. Time course change of TMP during operation (corrected temperature at 20°C).

Fig. 2. Time course change of filterability of mixed liquor suspensions, concentration of dissolved organic components and temperature in the reactor.

Fig. 3. Photos of the membrane modules collected at the termination of each run:

(a) Run 1 (without granules),

(b) Run 2 (with granules; an arrow indicates the coloured region),

(c) Run 3 (with granules).

Fig. 4. SEM images of the membrane surface at the end of each run (after chemical cleaning):
(a) Run 1, (b) Run 2 non-coloured area, (c) Run 2 coloured area and (d) Run 3.

1 Table 1. Operating conditions of the BMBR in each run.

	MLSS (mg/L)	pH	Temperature (°C)	DO (mg/L)
Run 1	9100 ± 1300	6.6 ± 0.1	22.7 ± 1.5	2.5 – 5.6
Run 2 (without granules)	9100 ± 400	6.4 ± 0.2	17.0 ± 1.4	4.0 – 6.9
Run 2 (with granules)	11300 ± 800	6.6 ± 0.1	14.1 ± 1.6	3.8 – 8.4
Run 3	13700 ± 1900	7.0 ± 0.2	13.1 ± 0.3	0.3 – 1.8

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1 Table 2. Characteristics of the feed wastewater and treated water.

	Influent		Permeate					Removal rate	
	TOC mg/L	T-N mg/L	TOC mg/L	T-N mg/L	NH ₄ ⁺ -N mg/L	NO ₂ ⁻ -N mg/L	NO ₃ ⁻ -N mg/L	TOC %	T-N %
Run 1 (Aug–Oct 2012)	45.1 ± 20.8	17.7 ± 3.6	7.9 ± 2.1	9.3 ± 2.4	ND*	0.1 ± 0.1	9.5 ± 1.8	81 ± 4	47 ± 15
Run 2 Without granules (Oct–Nov 2012)	38.1 ± 6.2	16.7 ± 4.0	7.2 ± 1.4	10.6 ± 1.4	ND*	0.1 ± 0.03	10.1 ± 0.1	81 ± 2	35 ± 8
Run 2 With granules (Nov–Dec 2012)	33.0 ± 6.7	16.8 ± 2.5	5.9 ± 1.8	10.7 ± 1.0	ND*	0.1 ± 0.04	10.3 ± 1.4	82 ± 4	35 ± 7
Run 3 (Jan 2013)	44.0 ± 3.5	23.4 ± 0.5	6.0 ± 0.9	13.8 ± 2.7	12.5 ± 3.6	0.1 ± 0.1	1.7 ± 2.5	86 ± 2	41 ± 11

ND* = Not detected

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Table 3. Concentrations of dissolved organic components in mixed liquor suspensions in each run.

	Run 1	Run 2		Run 3
		Without granules	With granules	
Carbohydrates(mg/L)	8.0 ± 1.3	5.5 ± 0.9	9.9 ± 2.8	20.1 ± 6.9
Proteins(mg/L)	6.2 ± 2.2	5.4 ± 0.6	6.0 ± 0.8	16.1 ± 2.6

1 Table 4. Filtration resistances of the fouled membrane at the termination of each run.

	Run 1	Run 2 (10^{11} m^{-1})		Run 3
	(10^{11} m^{-1})	Non-coloured area	Coloured area	(10^{11} m^{-1})
Fouled membrane	37.7	22.3		30.0
After physical cleaning	7.4 ± 2.7	7.5 ± 1.5	200 ± 48	13.0 ± 1.5
After chemical (NaClO) cleaning	0.5 ± 0.03	0.5 ± 0.06	2.1 ± 1.0	0.6 ± 0.05

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1 Table 5. Amounts of organic components of the extracted foulants.

	Run 1	Run 2 With granules		Run 3
	Without granules	Non-coloured area	Coloured area	With granules
TOC (mg/m ²)	100	131	760	140
Carbohydrates (mg/m ²)	96	91	760	114
Proteins (mg/m ²)	239	232	1098	224
C/P	0.40	0.39	0.69	0.51

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