**Mitigated membrane fouling of anammox membrane bioreactor by
microbiological immobilization**

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24 **Abstract**

25 In this study, membrane fouling behavior of anammox MBR with or without
26 carriers made by magnetic porous carbon microspheres was investigated. The results
27 show that Trans Membrane Pressure was an order of magnitude lower after 50 days
28 due to use of carriers, which did not directly contact with membrane surface.
29 Scanning Electron Microscope analysis indicates that abundance of anammox bacteria
30 formed biofilm on membrane surface. Fourier transform infrared spectroscopy
31 combined with amino acids contents analysis for membrane surface deposition show
32 that metabolite released by anammox bacteria contains more hydrophobic groups than
33 hydrophilic, which was considered as important reason for its abundant existence on
34 hydrophobic membrane surface. Microbiological immobilization not only reduces
35 biological membrane fouling, but also mitigates organic fouling including organic
36 matter containing C=OO, hydrophobic groups (CH₃, CH₂ and CH etc), as well as
37 inorganic deposition. Our finding provides an effective method for mitigating MBR
38 membrane fouling in anammox process.

39 **Key words:** Anammox; MBR; Membrane fouling; Microbiological immobilization

40 **Introduction**

41 Anaerobic ammonium oxidizing (anammox) process has drawn extensive attention
42 for the treatment of ammonium rich wastewater, owing to the large savings in aeration
43 energy, organic carbon and residual sludge disposal (Kuenen, 2008; Abma et al.,
44 2010). A common concept is that anammox bacteria grow very slowly, which causes
45 that the start-up of anammox reactor is very difficult (Strous et al., 1999; van der Star
46 et al., 2008). Therefore, the long sludge retention time (SRT) is needed for the start-up
47 of anammox reactor. Membrane bioreactor (MBR), as an appropriate reactor type for
48 increasing SRT, has previously been selected for the enrichment of anammox bacteria
49 (Wang et al., 2009).

50 MBR could be employed in many municipal and industrial wastewater treatments
51 for its good bacteria retention (Reemtsma et al., 2002; Meng et al., 2009). However,
52 membrane fouling is a major problem for wider application of MBRs, because it
53 would decrease the membrane permeability and further affect the operation of reactor
54 (Bouhabila et al., 2001). The occurrence of membrane fouling is due to many factors,
55 such as the metabolic products produced by bacteria, inorganic matter in feed water
56 and bacteria attached to membrane (Hong and Elimelech, 1997; Le-Clech et al., 2006;
57 Meng et al., 2009). Thus, there has been increasing interest in retarding membrane
58 fouling for MBR operation. Several methods have been developed to decrease
59 membrane fouling, such as changing the reactor grafts or modifying membrane
60 material to reduce attachment of organic matter (Wei and Zhang, 2014; Li et al., 2014),
61 selecting proper membrane material and membrane pore (Choo and Lee, 1996), and

62 applying the electric infiltration device to retard inorganic membrane fouling (Choo et
63 al., 2000).

64 MBR used for anammox has been studied recently for its advantage of perfect
65 biomass retention (Wang et al., 2009; Tao et al., 2012; Zhang et al., 2013). These
66 studies mainly focused on MBR enhanced anammox enrichment and improved
67 effluent quality. Besides, microbiological immobilization by carriers in MBR is
68 previously studied for anammox related Completely Autotrophic Nitrogen removal
69 Over Nitrite (CANON) process, by using the advantage of the microenvironment
70 created by carriers (Wu et al., 2004). The result demonstrated that the formed
71 microenvironment can realize nitrification and anammox simultaneously. In this way,
72 the nitrifiers oxidize ammonium to nitrite by utilizing outer aerobic condition of
73 carriers, and anammox bacteria utilize ammonium and nitrite to anaerobically remove
74 nitrogen in the inner of carriers.

75 Although it was reported that anammox bacteria attached to membrane surface
76 caused membrane fouling (Jiang et al., 2013), the details of membrane fouling in
77 anammox MBR, including the relative importance of organic, inorganic, and
78 biological membrane fouling, are still unclear. Meanwhile, the strategies for
79 controlling membrane fouling of anaerobic MBR employed in anammox remain
80 lacking. The experiments described below investigated the membrane fouling of MBR
81 employed in anammox and verified the application of microbiological immobilization
82 could mitigate membrane fouling.

83 **2. Materials and methods**

2.1 Reactor operation

Experiment was conducted in a 7 L MBR and a 7 L Immobilization–MBR (I–MBR) inoculated with anammox culture. The percentage of *Planctomycetes* bacteria was 80% in the inocula, harvested from an existing reactor (Tang et al., 2015). The filling ratio of carriers (cube shape, 4 cm×4 cm×4 cm) in the I–MBR was 50%. The carriers applied in this study have been verified to have a high absorption capacity for bacteria and organic metabolites in previous research (Bai et al., 2010). A plastic baffle with 1 cm² pores was laid between the membrane and the main body of liquid to avoid the direct contact of carriers and membrane surface. Effective working volumes of both reactors were 5 L. The effluent was obtained through the membrane (Yue Qing Membrane Technology Co., Ltd, China). The membrane material was polyvinylidene fluoride (PVDF) with pore size of 0.03 μm and surface area of 0.11 m². The carriers were made of magnetic porous carbon microspheres with average pore size of 0.12 mm, pore distribution of 96 %, density of 0.024 g/m³ and surface area of 120–150 m²/g.

(NH₄)₂SO₄, NaNO₂ and some trace solutions, the composition of which has been described in previous study (van de Graaf et al., 1996), were added to the reactor. The synthetic wastewater was prepared with tap water including KH₂PO₄ (0.025 g/L), CaCl₂ (0.01 g/L), MgSO₄·7H₂O (0.2 g/L), FeSO₄·7H₂O (0.01 g/L), EDTA·2Na (0.006 g/L). Both of the NH₄⁺ and NO₂⁻ concentrations in influent were increased from 50 to 160 mgN/L during the operation period, which lasted for 50 days. pH and temperature in the reactors were controlled at 7.4–8.3 and 37±0.5 °C, respectively. Anaerobic

condition was kept during all the operation period. The stirring speed of two reactors was set at 80–150 rpm to improve mass transfer. The influent and effluent were taken every 2–3 days for the measurements of NH_4^+ , NO_2^- and NO_3^- concentrations.

2.2 Nitrogen compounds concentration analysis and TMP measurement

NH_4^+ , NO_2^- and NO_3^- concentrations were measured according to standard colorimetric methods, as described by the American Public Health Association (APHA, 1995). Total Nitrogen (TN) was measured by oxidizing all nitrogen species to NO_3^- and then measured NO_3^- concentrations. On the 50th day of the operation, five carriers and five areas (5 cm²) of membrane were randomly selected to evaluate the bacteria distribution profile on the carrier and membrane surface. These samples, fresh carriers and fresh membrane fragments were dried together. After that, the dry weight of bacteria attached on the carriers or the membrane surface could be analyzed. Trans membrane pressure (TMP) was measured by a Vacuum Table (MD–S600, MEOKON, China) with the range of 0–100 kPa.

2.3 Analysis of the supernatant and filtrate in MBR

Supernatant was obtained by centrifuging the liquid of reactor at 3000 rpm for 10 min once every week. Dissolved organic matter (DOM) was obtained by filtering supernatant using 0.45 μm membrane filter. Total organic carbon (TOC), polysaccharide, protein concentrations in supernatant and DOM were measured by TOC analysis equipment (TOC–V CPN, Shimadzu, Kyoto, Japan), phenol-sulfuric acid method and Lowry method, respectively (Lowry et al., 1951; Dubois et al., 1956).

128 Excitation–emission matrix (EEM) was carried out for supernatant at terminal point
129 of two reactors' operation. The EEM spectra were measured by a luminescence
130 spectrometry (F7000, Hitachi Limited, Tokyo, Japan), which were collected with
131 subsequent scanning emission spectra of 300–700 nm by varying the excitation
132 wavelength of 200–600 nm at 10 nm increments. The scanning speed was 1200
133 nm/min for all the measurements.

134 **2.4 Analysis of the fouled membranes**

135 Two samples were got from the membrane surface of MBR and I-MBR at terminal
136 point of two reactors' operation and then lyophilized for 24 h before SEM, XPS and
137 ATR–FTIR [analysis](#) were operated about the fouled membrane. The extraction of
138 polysaccharide and protein from the fouled membrane was performed by cation ion
139 exchange resin method (Frolund et al., 1996).

140 SEM analysis was performed by SEM–EDS (Scanning Electron Microscopy with
141 Energy Dispersive X-ray) Analyzer (Nova_Nano SEM430, USA). The samples were
142 first obtained from membrane surface and fixed with 2.5% glutaraldehyde solution for
143 12 h overnight, then dehydrated by a series of tertiary butanol–water mixture (50, 70,
144 80, 90, 95 and 100 vol.% of tertiary butanol) and each mixture for 15 min. Finally, the
145 samples were dried and coated with a thin gold layer for observation. The inorganic
146 elements accumulated on the membrane surface were analyzed by the conjoint EDS
147 equipment.

148 Attenuated Total Reflectance–Fourier transform infrared spectroscopy (ATR–FTIR)
149 analysis was done by ATR–FTIR equipment (Tensor 27, Bruke) from 190 cm⁻¹ to

150 4000 cm^{-1} . Samples were lyophilized for 24 h before being measured. XPS analysis
151 was realized by Imaging Photoelectron Spectrometer (Axis UltraKratos Analytical
152 Ltd., Japan). In this experiment, dual anode (aluminum/ magnesium target) X-ray
153 source and a power of about 225 W (operating voltage of 15 kV, emission current 15
154 mA for High-resolution C 1s XPS spectra) were applied.

155 The amino acid composition of protein was explored using an automatic amino
156 acid analyzer (Hitachi Co., Japan). 10 mg EPS were hydrolyzed in 30 ml 6 mol/L HCl.
157 Then the hydrolysate was filtrated by 0.22 μm acetate cellulose membranes and
158 analyzed in an injection volume of 50 μm . Sodium citrate system was used for
159 standard analysis.

160 **3. Results**

161 **3.1 Operation performance of MBR and I-MBR**

162 On the 50th day, 75% bacteria were immobilized on the carriers in I-MBR. In order
163 to investigate whether the introduction of carriers would change the basic
164 performance of MBR, a corresponding comparison of the nitrogen concentrations in
165 influent and effluent for MBR and I-MBR was performed. Both anammox reactors
166 could be successfully started up in 50 days, when the ammonium and nitrite
167 concentrations in effluent were below 20 mg/L with their influent concentration of
168 160 mg/L. On day 50, for these two reactors, the TN removal efficiency could achieve
169 80% at HRT of 20 h. The TN removal rate of I-MBR could achieve 314 mg/(L day),
170 which was a little higher compared to that of MBR (304 mg/(L day)) (Fig.1). The pH
171 value in the effluent increased after the anammox treatment, which is quite

characteristic for the anammox reaction (Mulder et al., 1995). It is then concluded that microbiological immobilization did not result in the performance deterioration, instead, a slight enhancement was observed.

Generally, TMP values directly reflect the level of membrane fouling. In the experiment carried out in this study, temperature correction of TMP measured was not required since the temperature of the reactor was fixed at 37 °C. Fig.2 displays TMP values during the operation period of both MBR and I-MBR. TMP values enhanced from 0 to 22 kPa after 50 days' operation for the MBR, in contrast to a much smaller TMP change only from 0 to 3 kPa for the I-MBR. Remarkably, the membrane fouling in MBR was more serious than that in I-MBR. The microbiological immobilization by carriers has good performance to reduce the membrane fouling.

3.2 The qualities of supernatant and filtrate in two reactors

The influence of microbiological immobilization on organic matters in the supernatant of these two reactors was also investigated. EEM spectra of two reactors supernatant are shown in Fig.3. For this experiment, the apparent excitation wavelength at 280–310 nm, 290–310 nm and 225–237 nm correspond to emission wavelength at 350 nm (peak A), 370–410 nm (peak B) and 340–380 nm (peak C) represent the main organic matter with fluorescence in the supernatant. According to the shape of the peak, peak A is likely to be attributed to water Raman. Peak B in EEM spectrum obtained for supernatant is very close to that of marine humic substances, which was previously reported (Chen et al., 2003). Peak C in the EEM spectrum for MBR could be attributed to fluvic acid-like substances (Chen et al.,

2003). The spectra from MBR and I-MBR are qualitatively similar, indicating that two reactors own some of the same organic compounds in the supernatant.

The supernatant and DOM contained more polysaccharide than protein with the ratio of around 2–4 in both MBR and I-MBR. The most striking result here is that the protein and polysaccharide concentrations in the supernatant and DOM in MBR were much higher than that in I-MBR. For MBR, the protein and polysaccharide concentrations in the supernatant were 4.1 mg/L and 13.1 mg/L, respectively, while the values in the DOM were 3.9 mg/L and 12.6 mg/L. Differently, for I-MBR, the protein and polysaccharide concentrations were much lower, irrespectively of the supernatant and DOM, with the values of 2.2 mg/L and 7.4 mg /L, 2.1 mg/L and 7.2 mg/L (Fig.4). This characterization reflects that the carriers could efficiently adsorb organic compounds, such as protein and polysaccharide.

3.3 Membrane surface fouling matter

3.3.1 Biological membrane fouling

In order to identify the bacteria distribution in MBR and I-MBR, biomass on the membrane surface and carrier, as well as the suspended sludge were harvested and weighted after 50 days' operation. The results show that amounts of bacteria on the membrane surface in MBR (37% of the total biomass) were obviously higher than that in I-MBR (only 11% of the total biomass). In case of I-MBR, a majority of bacteria, as high as 75%, were adsorbed on the carrier. Biological membrane fouling is critical for the membrane fouling in anammox MBR, easily deduced from the data that 37% of the total biomass deposited here. Application of carrier for microbiological

immobilization therefore could be greatly benefit to mitigate bacteria disposition on the membrane surface. The visual image of membrane surface deposit sediment was screened by SEM, which confirmed that the bacteria deposition in membrane surface was much less in I-MBR than that in MBR. The membrane surface of MBR formed dense cake layer, while I-MBR was sparse. The anammox bacteria on the I-MBR membrane surface could be clearly seen, when the magnification was 15000x, while there was still compact cake layer on the MBR membrane surface. This once again strongly illustrates dense cake layer was formed on the membrane surface of MBR. The biological membrane fouling was one of the crucial reasons for the formation of membrane fouling.

3.3.2 Organic membrane fouling

Organic matter analysis on membrane surface is also critical to identify the formation of membrane fouling in the reactor. For this analysis, the samples are probed after 50 days operation for protein and polysaccharide analysis. There are two interesting features for this probe (Fig. 6): (i) Protein is easier to be deposited on the membrane surface, compared to polysaccharide for both MBR and I-MBR; (ii) Both protein (1.34 g/m^2) and polysaccharide (0.59 g/m^2) concentrations on the membrane surface in MBR are much higher than their counterparts in I-MBR, 0.44 g/m^2 and 0.19 g/m^2 , respectively.

In succession, FTIR was applied to further compare the differences of the functional group of organic matter on the foul membrane surface. Concomitant results are shown in Table 1. A closer inspection of Fig. 6 shows three main differences

238 between the samples of MBR and I-MBR: (i) peaks at 1403 cm^{-1} (C=OO stretching) ,
 239 1448 cm^{-1} (CH₃ of fat and CH₂ bending) and 2366 cm^{-1} (N≡N stretching) only exist on
 240 the membrane surface in MBR and disappear on that of I-MBR; (ii) the intensities of
 241 peaks at 3445 cm^{-1} (O–H stretching), 1636 cm^{-1} (C=O stretching of protein) and 2924
 242 cm^{-1} (C–H stretching) are much stronger in MBR than that in I-MBR, 1549 cm^{-1} (C–H
 243 stretching and N–H bending) is little stronger in MBR than that in I-MBR. (iii) The
 244 peak 1234 cm^{-1} (C–OH) and peak 1385 cm^{-1} (CH₃ of hydrocarbons) are much
 245 stronger in I-MBR than that in MBR. This indicates that the application of
 246 microbiological immobilization could reduce the deposition of organic compounds
 247 with hydrophobic groups such as CH₃ of fat, CH₂ and CH, organic matter containing
 248 O–H, C=O and N≡N, on the membrane surface. The detection of functional groups is
 249 also supported by XPS analysis. Four different functional groups containing carbon
 250 element are clearly recognizable in Table 2: C–(C/H), C–OH, C=O and C=OO.
 251 Interestingly, one of them (C=OO) vanishes on the membrane surface of I-MBR, as
 252 shown in Fig. 8(b). We cannot detect the amount variation of these functional groups
 253 by this comparison because of the complex source for XPS peak intensity. One may
 254 ask that its disappearance could be correlated to its weak peak intensity, but this
 255 possibility could be eliminated as that the other peaks (such as the highest peak at
 256 284.8 eV) are even stronger for the scenario of I-MBR. Hence the analysis reflects
 257 that the hydrophilic group such as C=OO on the membrane surface evidently
 258 vanished.

259 **3.3.3 Inorganic membrane fouling**

260 Inorganic elements analysis of the membrane surface matters by EDS was finally
261 explored and the results have been recorded in Table 3. The deposition of inorganic
262 element Na (1.2%), Ca (0.82%), S (1.38%), P (0.66%) and Mg (0.38%) which was
263 added for the cultivation of anammox bacteria was much lower in I-MBR than that in
264 MBR (Na 3.25%, Ca 1.87%, S 1.44%, P 1.23%, Mg 1.48%). This result demonstrates
265 that the inorganic membrane fouling of MBR could also be reduced by
266 microbiological immobilization.

267 Discussion

268 Anammox is an effective and novel process for the removal of nitrogen from
269 wastewater (Abma et al., 2010). MBR as a kind of effective reactor for the enrichment
270 and retention of anammox bacteria has been studied previously (Wang et al., 2009;
271 Tao et al., 2012). However, membrane fouling is an obstacle for the extensive
272 application of MBR. In this study, it is illustrated that anaerobic MBR employed for
273 anammox process could easily produce the membrane fouling, which arise from three
274 sources: the high bacteria adsorption on membrane surface, organic matter produced
275 by anammox sludge, and high concentration inorganic ion in the influent. The
276 differences in characteristics of organic matter attached to the membrane are obvious
277 between anammox MBRs and typical aerobic MBRs in which heterotrophic bacteria
278 are dominant. In typical aerobic MBRs, polysaccharides tend to dominate among the
279 organic matter causing membrane fouling (Okamura et al., 2009). Such difference
280 may be useful information when further considering strategies for controlling
281 membrane fouling when anammox MBRs are employed.

282 Microbiological immobilization is beneficial for anammox MBR for mitigating
283 membrane fouling without affecting the performance of anammox bacteria, which is
284 useful for the application of MBR for anammox process. Previously, the methods for
285 reducing membrane fouling always only reduce one of foul sources, organic matters
286 or inorganic compounds (Choo et al., 2000; Wei et al., 2014; Li et al., 2014). It is
287 noteworthy that the present strategy provides an effective way to reduce organic,
288 inorganic, and biological membrane fouling simultaneously in MBR applied in
289 anammox process.

290 Several investigations on the effect of introducing granular or carrier for mitigating
291 membrane fouling have been reported (Yang et al., 2006; Hu et al., 2012). However,
292 most of them relied on physical contact between carrier and membrane surface. In this
293 study, the carrier introduced to the reactor did not directly contact with the membrane
294 surface. Former works reported the reduced membrane fouling in anammox MBR by
295 rotating membrane material (Jiang et al., 2013). By applying this method, the TMP of
296 anammox MBR was 3 kPa, which was much less than the conventional MBR that the
297 TMP reached to 16 kPa when the operation time was 60 day. In this study, the TMP of
298 I-MBR only reaches 3 kPa after 50 days' operation, which is much lower than that of
299 MBR with the high TMP value of 22 kPa on the 50th day. Therefore microbiological
300 immobilization could mitigate membrane fouling in a larger extent.

301 The origin of mitigating membrane fouling is focused on the layer formed on the
302 surface of membrane material (Jiang et al., 2013; Discart et al., 2015). EPS released
303 by anammox bacteria was also the factors for influencing membrane fouling (Jiang et

304 al., 2013). Actually, other factors causing membrane fouling for anammox MBR, such
305 as organic fouling and inorganic fouling in anammox MBR have not been studied
306 formerly (Mairal et al., 1999; Tang et al., 2014). The present results indicate that
307 carriers could reduce the existence of the hydrophobic groups including CH₃ of fat,
308 CH₂ and CH on the membrane surface, compared to the hydrophilic groups. At the
309 same time, from the result of XPS, carriers can also reduce the existence of organic
310 matters containing C=OO on the membrane surface. Very recently, it is reported that
311 the soluble microbial products released by anammox culture contained a lot of
312 hydrophobic groups revealed by FTIR analysis, which is the main reason for the
313 easily deposition of anammox bacteria on membrane to cause the membrane fouling
314 (Xiao et al., 2014).

315 Our study demonstrated that carrier could reduce the polysaccharide and protein
316 content in the supernatant and DOM in the reactors. This could well explain the
317 reason why I-MBR had less membrane fouling. SEM showed that less anammox
318 bacteria deposited on the I-MBR membrane surface for lots of bacteria joining into
319 the carriers, which mitigated bio-fouling fundamentally. I-MBR had less membrane
320 fouling than that of MBR, also because there were fewer bacteria producing
321 polymeric substances on the membrane. In addition, it is verified that carriers do not
322 decrease the operation performance of anammox bacteria. Instead, they increase the
323 operation performance of anammox bacteria in a small extent. As reported by Tang et
324 al., the anammox granules have higher pollutant removal performance than the
325 suspended anammox sludge. The biomass aggregation to achieve high cell density is

326 beneficial to improve bacteria activity (Tang et al., 2011). In this study, the application
327 of carriers is useful for the formation of anammox biofilm with high cell density.
328 Therefore, it could result in the slight enhancement of reactor performance of I-MBR,
329 compared to MBR. The study also showed other functions of carriers introduced to
330 MBR besides the supplement of microenvironment (Wu et al., 2004).

331 The application of microbiological immobilization by carrier not only increased
332 bacteria retention in the reactors, but also effectively reduced membrane fouling.
333 Mitigating membrane fouling was vital for MBR operation, which could reduce the
334 cost of MBR operation cost. This would open a new window to operate anammox
335 MBR, which was much important for the real use of applying MBR for anammox
336 process for treating wastewater.

337 **Conclusion**

338 Anaerobic MBR employed for anammox process was verified to easily produce the
339 membrane fouling in this study. The application of microbiological immobilization
340 not only increased bacteria retention in the reactors, but also played an important role
341 on mitigating membrane fouling. It could efficiently reduce the membrane biological,
342 organic and inorganic fouling. Our work opens a different way to explore a suitable
343 reactor type for anammox process operation, which is beneficial for the real use of
344 MBR for anammox process.

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446 Table 1 The peak locations and corresponding constitutes of membrane surface

447 deposition by FTIR analysis

Waves	Vibration types	Corresponding groups	Relative transmittance*	
			MBR	I-MBR
3445	O-H stretching	Hydroxyl	1	0.58
2924	C-H stretching	Lipid-carbon chain	0.05	0.03
2366	N≡N stretching	Protein	0.03	—
1636	C=O stretching	Amidel(protein peptide bond)	0.42	0.23
1549	C-H stretching N-H bending	Amidell(protein peptide bond)	0.13	0.12
1448	CH ₃ bending	Methyl	0.27	—
	CH ₂ stretching	Methylene		
1403	C=OO stretching	Carboxyl	0.16	—
1385	CH ₃ stetching	Methyl	0.23	1
1234	C-OH	Polysaccharide	0.02	0.14
1054	C-H bending	Polysaccharide	0.13	0.13
<1000	fingerprint region	Sulfurandphosphorus groups	—	—

448 * In order to compare the content of each functional group, we set the maximum peak in each
 449 group to be 1.0. Then the relative transmittances of other peaks are represented as the ratio to
 450 the maximum peak.

451 Table 2 Element content of membrane surface deposition by XPS spectra analysis

Element content (%)								
	O	C	N	Na	Ca	S	P	Mg
MBR	30.95	54.05	3.82	3.25	1.87	1.44	1.23	1.48
I-MBR	23.19	68.07	4.3	1.2	0.82	1.38	0.66	0.38

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455 Table 3 Corresponding constitute of C atomic by high-resolution C 1s XPS spectra

456 analysis

Peak	Position	Assignment	C atomic content (%)	
			MBR	I-MBR
1	284.8	C-C,C-H	59.67	61.74
2	286.3	C-OH	24.97	27.43
3	288.06	C=O	10.2	10.83
4	289.63	COO-	5.16	-

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463 **Figure Captions**

464 Fig.1 $\text{NH}_4^+\text{-N}$, $\text{NO}_2^- \text{N}$ and $\text{NO}_3^- \text{-N}$ concentrations in the influent and effluent of (a)
465 MBR and (b) I-MBR

466 Fig.2 TMP profiles of (a) MBR (b) I-MBR

467 Fig.3 EEM spectra of the organic matter contained in supernatant of (a) MBR and (b)
468 I-MBR

469 Fig.4 Protein and polysaccharide concentrations in the reactor supernatant and DOM
470 obtained from (a) MBR and (b) I-MBR

471 Fig.5 Amounts of protein and polysaccharide deposited on surfaces of membrane used
472 in (a) MBR and (b)I- MBR

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483 Fig.1

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485 Fig.2

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489 Fig.3

Fig.4

Fig.5

Abstract figure