



Effect of coagulant dose and backflush pressure on NOM membrane fouling in inline coagulation–ultrafiltration

Gabriela Kamińska^{a,*}, Wouter Pronk^b, Jacqueline Traber^b

^a*Institute of Water and Wastewater Engineering, Silesian University of Technology, Konarskiego 18, 44-100, Gliwice, Poland, email: gabriela.kaminska@polsl.pl (G. Kamińska)*

^b*Department of Process Engineering, Eawag, Swiss Federal Institute of Aquatic Science and Technology, Dübendorf, Switzerland, emails: jacqueline.traber@eawag.ch (W. Pronk), wouter.pronk@livinguard.com (J. Traber)*

Received 19 October 2019; Accepted 4 February 2020

ABSTRACT

One of the major concerns for the successful application of ultrafiltration in drinking water production is membrane fouling due to NOM occurring in water resources. Coagulation as a prior step before ultrafiltration enhance membrane permeability and its general lifetime. The main objective of this work was to determine the impact of various coagulant dosage and backflush pressure on fouling behavior and cake layer formation in a lab-scale inline coagulation–ultrafiltration system treating surface water spiked with humics. Permeability loss and the irreversible fouling resistance were the most serious in the system without coagulation. As the coagulant dosage increased, permeability drifted toward lower values suggesting a higher degree of fouling. It was also pronounced by higher compressibility of cake layer under higher coagulant dosage. A strong correlation was found for backflush pressure and fouling resistance. The most serious fouling attributed to the highest value of irreversible resistance was observed for the lowest backflush pressure (0.35 bar). Backflushing under 0.65 bar resulted in complete removal of cake layer with no need of forward flushing. Mass balance calculation suggested that the irreversible fouling was an effect of the internal blocking of pores by adsorption of humic substances.

Keywords: Coagulation; Ultrafiltration; Fouling; NOM; OCT

1. Introduction

Natural organic matter (NOM) is defined as a mixture of organic substances, which widely occurs in surface waters. Concentration, fractions, and properties of NOM vary significantly in water resources and depend on biogeochemical cycles of surrounding environment [1]. The dominant fraction (50%–90%) of NOM is humic substances (HS), that have been considered as the most serious disinfection by-products [2]. Moreover, HS are the most difficult fraction to remove [3]. NOM in drinking water sources impairs quality of water and makes water treatment process more complicated [4].

Over the past few years, ultrafiltration has been commonly used as technique for drinking water production [5–8]. Nevertheless, NOM membrane fouling is one of the most significant difficulty affecting permeability of ultrafiltration membranes in water treatment plants [9,10]. In that context, the most serious fraction is humic substances causing irreversible fouling. Hence coagulation pretreatment prior to membrane filtration has been widely implemented to control fouling and improve membrane permeability [11]. One approach of coagulation pretreatment is inline coagulation–ultrafiltration (C–UF), in which the coagulant is added just before the ultrafiltration step, with contact time usually shorter than 1 min. It yields that C–UF is less

* Corresponding author.

complicated and requires less coagulant dosage and shorter coagulation time comparing with conventional C–UF [12].

During inline C–UF, colloids and dissolved organic matters are bonded in larger flocs, which form the cake layer. This layer is suggested to protect membrane surface from pore clogging by smaller than membrane pore size foulants and should exhibit detachability by backflushing [13]. Therefore, the structural properties of cake layer such as compressibility, porosity, and thickness are considered as a key parameter to control membrane fouling. Many authors reported cake layer structure is influenced by floc properties such as size, fractal dimension, charge, and shape [9,14,15].

Floc size and consequently structure of cake layer are affected by coagulant dosage, type, and coagulation regime. In view of the pore size of UF membranes (around 10–100 nm), the floc size does not need to be very large to prevent fouling by internal clogging. Therefore, inline coagulation at underdose conditions yields similar results to inline coagulation at sweep floc conditions [16,17]. Thus, while reducing the coagulant addition and controlling membrane fouling, coagulation at underdose conditions is beneficial for operation costs of ultrafiltration plants. Both iron- and aluminum-based salts can be used as a coagulant. For the inline-coagulation process, FeCl_3 was found to be more suitable than polyaluminum chloride (PACl) due to the formation of a more permeable cake layer [18].

NOM foulants that are not removed with cake layer during backflushing are responsible for irreversible fouling. When the accumulation of irreversible fouling gains a critical level, backflushing is no longer effective to recover the membrane permeability and chemical cleaning is required [19]. However, chemical cleaning significantly increases costs and generates waste chemicals [20]. Therefore, optimization of C–UF conditions with regards to process conditions providing permeable and easy to remove cake layer is very important.

Both the effect of coagulant dose on floc size as well clear relation that higher backflush pressure provides higher force to remove cake layer is well-known [21,22]. However, these data do not visualize the compressibility and detachability of deposited cake in dependence of process conditions, which are crucial to reduce irreversible fouling and restore membrane permeability. Currently, available data do not image the impact of backflush pressure on cake layer removal.

The aim of this study was to determine an effect of coagulant dosage and backflush pressure on fouling behavior and cake layer removal. For this purpose, this study used *in-situ* observation of the fouling cake layer by optical coherence tomography (OCT).

2. Materials and methods

2.1. Feed water

Experiments were conducted at creek water (Chriesbach, Dübendorf, Switzerland). Due to low content of NOM in creek water as taken, this water was spiked with technical grade humic acid (Sigma-Aldrich, Poznań, Poland, 14 ppm). It allowed to provoke a considerable fouling and at the same time reflect a real conditions of surface water. The NOM composition of feed water, as analyzed by liquid chroma-

tography-organic carbon detection (LC-OCD), is presented in Table 1.

2.2. Experimental setup and membrane

A schematic diagram of the lab scale inline C–UF configuration used in this study is presented in Fig. 1. Flat sheet polysulfone membrane US100 with the MWCO (molecular weight cut-off) of 100 kDa was provided by Microdyn Nadir (Germany). Before each experiment the membranes were soaked in nanopure water for 24 h and the clean water flux was determined using ultrapure water. Membrane flow cells with a membrane surface area of 0.0023 m² were used, as described in previous investigations [23]. The coagulant solution was introduced to the feed water stream providing a residence time of 40 s in the tubing between the water/coagulant mixing point and the membrane module. The process was operated at a constant flux of around 100 L/m² h and a constant temperature of 22°C ± 1°C. Initial feed pressure was 0.15 bar. The transmembrane pressure and the weight of permeate were monitored in order to determine the flux, permeability, and resistance values. A specific design of membrane flow cells was used in which the flat membranes are clamped using screws and O-rings. These modules are suitable for *in-situ* observation of the fouling layer by OCT.

2.3. Coagulant dosage testing

Inline C–UF tests were carried out with 2, 5, and 10 ppm of iron chloride as coagulant. In initial studies, iron chloride dosage of 1 ppm was also tested, due to almost identical permeability loss to filtration without coagulation, the further studies with 1 ppm were not continued. Coagulant solution was dosed continuously during ultrafiltration. Each C–UF run consisted of three cycles including 60 min of filtration followed by hydraulic backflushing carried out during 60 s at 0.65 bar, and a forward flush during 60 s at a flow rate of 0.3 L/min. Comparatively, filtration test without coagulant was conducted.

2.4. Backflushing experiment

In order to determine the effect of backflush pressure on fouling behavior and unsticking of cake layer by

Table 1
Composition of the feed water used, as analyzed by LC-OCD

NOM fractions	Chriesbach water spiked with humic acid
TOC, ppb-C	3,909
DOC, ppb-C	3,454
Biopolymers, ppb-C	36
Humic substances, ppb-C	1,782
Building blocks, ppb-C	569
Low molecular weight-organics ppb-C	135
Neutrals, ppb-C	511

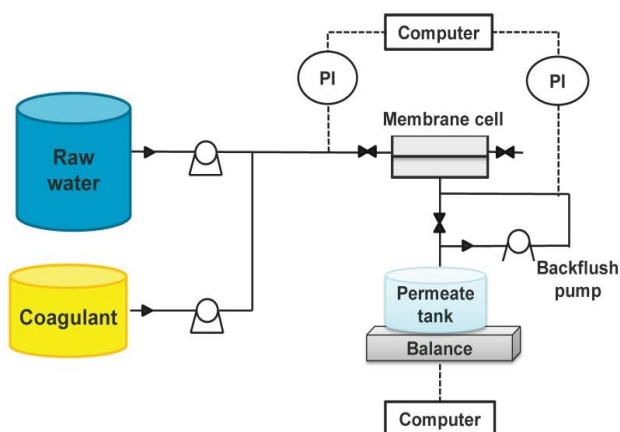


Fig. 1. Schematic diagram of the experimental setup.

backflushing, three experiments with different backflush pressures were carried out. Each C–UF run consisted of three filtration cycles including 90 min of filtration followed by hydraulic backflushing carried out at 0.35, 0.55, or 0.65 bar during 60 s and a forward flush during 60 s at a flow rate of 0.3 L/min. Continuous dosing of 5 ppm of iron chloride was used.

2.5. Ultrafiltration performance and membrane fouling characterization

Performance of ultrafiltration was evaluated by permeability according to the Eq. (1):

$$L_p = \frac{V \cdot A^{-1} \cdot t^{-1}}{\Delta P} \quad (1)$$

where: L_p is permeability ($\text{L m}^{-2} \text{h}^{-1} \text{bar}^{-1}$) in short (LMHB), V is permeate volume (L), A is membrane surface area (m^2), t is permeate time collection (h), and ΔP is transmembrane pressure (bar).

In this study, hydraulic resistances were used to characterize the fouling behaviour of UF membranes treating surface water. Hydraulic resistances of membrane and fouling layer were calculated using the resistance in series model and Darcy's law using Eqs. (2)–(4) [24]:

$$k_{\text{tot}} = k_m + k_f \quad (2)$$

$$k_f = k_{\text{irr}} + k_{\text{rev}} \quad (3)$$

$$k = \frac{\Delta P}{\mu \cdot J} \quad (4)$$

where: k is hydraulic resistance, where subscripts m , f , irr, rev, tot relate to membrane, fouling, hydraulically irreversible fouling, hydraulically reversible fouling and total (m^{-1}), respectively, J is the flux ($\text{m}^3 \text{m}^{-2} \text{s}^{-1}$), ΔP is the transmembrane pressure ($\text{kg s}^{-2} \text{m}^{-1}$), μ is the dynamic viscosity of water at given temperature ($\text{kg m}^{-1} \text{s}^{-1}$). Membrane resistance (k_m) was measured for the clean membrane with

ultrapure water prior to feed water filtration. Hydraulically irreversible resistance was determined from the flux after backflushing, while hydraulically reversible resistance was determined from the difference in fouling and irreversible resistances.

The OCT (model 930 nm Spectral Domain, Thorlabs GmbH, Dachau, Germany) with a light-source wavelength of 930 nm was used to investigate the morphology (in the mesoscale) of fouling layer by direct imaging through the cover glass of the flow cells. In order to determine the cake layer thickness and floc size, the OCT pictures were analyzed using Fiji software.

2.6. NOM characterization by LC-OCD-OND and mass balance

NOM characterization and quantification was carried out using LC-OCD-OND, enabling the fractionation of NOM in representative fraction as described previously [25]. Carbon-free sample vials were used (muffle furnace 450°C for 4.5 h) and great care was taken to avoid any other source of carbon contamination during the sample collection and analysis procedure.

For the calculation of the NOM mass balance, samples of feed water (F), backflush water (BF), and forward flush water (FF) were analyzed by LC-OCD-OND and the fraction of deposited material (A) of each NOM fraction was calculated from the Eq. (5):

$$A = \left(1 - \frac{C_{\text{BF}}V_{\text{BF}} + C_{\text{P}}V_{\text{P}} + C_{\text{FF}}V_{\text{FF}}}{C_{\text{F}}V_{\text{F}}} \right) \times 100\% \quad (5)$$

where V denotes the total volume of the respective stream (L), accumulated over all filtration cycles and C denotes the concentration of the respective NOM fraction (ppb).

3. Results

3.1. Effect of coagulant dose on membrane fouling during C–UF process

A hydraulic performance of all C–UF processes was evaluated by permeability loss as a function of time. As shown in Fig. 2, the permeability decreased rapidly in the first cycle for all studied configurations. It was an effect of a rapid adsorption/deposition of the feed components on the membrane surface [26]. In sequential cycles, the permeability loss was slighter due to establishment of steady state. Look et al. [27] also reported that permeability decreased sharply at the beginning of permeation and then reached a relatively steady state.

Importantly, the final permeability in the processes enhanced by inline coagulation was all higher than it was for filtration itself. More specifically, the final permeability was 263 LMHB for filtration without coagulation. However, inline C–UF processes with 2, 5, or 10 ppm of FeCl_3 exhibited higher final permeability of 440, 391, and 392 LMHB, respectively. It means that membrane hydraulic performance was significantly improved by coagulation. Probably, organic ingredients of raw water blocked membrane pores and caused higher fouling [28]. When they coagulated, they formed bigger aggregates creating semipermeable layer.

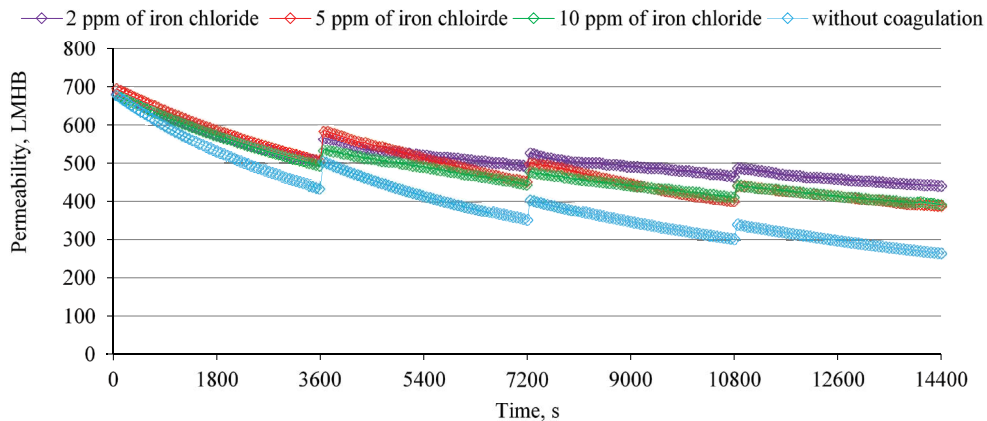


Fig. 2. Permeability loss as a function of time for inline C-UF processes and filtration without coagulation.

Comparing permeability loss in C-UF with different coagulant dosage, the highest performance was observed for 2 ppm and the lowest for 10 ppm. The impact on coagulant dose has previously been described by several authors, showing an optimum coagulation dose dependent on the feed water composition, and an increasing fouling behavior at higher doses [16,17,29,30].

The performance of inline C-UF processes was also evaluated by portion of reversible and irreversible resistances. As seen in Fig. 3, significant proportion of the increase in resistance during both inline C-UF and UF without coagulation was irreversible in nature. Irreversibility of fouling can be a consequence of high content of humic substances that adsorb easily in membrane pores and are not removed by backflushing [31]. In filtration without coagulation, irreversible fouling was much more serious than in C-UF processes. This suggested positive effect of coagulation since some part of humic substances formed bigger aggregates which did not block the internal pores due to steric hindrance. The results for inline C-UF showed similar reversible and irreversible fouling resistance values for doses of 5 and 10 ppm, but lower irreversible fouling occurred at a dose of 2 ppm. It can be explained by the formation of a thicker and more compressed cake layer at doses above the optimal dose [18]. As seen in Fig. 4, a distinct cake layer was formed on the membrane, which is known to consist of complexes of Fe, NOM, and particulate/

dispersed matter present. From OCT pictures and Table 2, it is clear that coagulant dosage influences on thickness and compressibility of cake layer. Both cake layer thickness and floc size increased with coagulant dosage. Thin and loose cake observed for 2 ppm seemed to be more prone to be removed by backflushing while the more compact cake formed under 10 ppm was harder to detach.

3.2. Effect of backflush pressure on fouling behavior

As seen in Figs. 5 and 6, a higher backflush pressure resulted in better permeability recovery and lower fouling resistance, especially with regard to the hydraulically irreversible fouling. It is because of backflushing at higher pressure removes not only cake layer deposited on the membrane but also fragmentarily particles from pores [32].

It was also found that reversible resistance exhibited relatively similar value in cycles 1–3, while irreversible fouling increased greatly cycle by cycle. It suggested that under given conditions (feed compositions and backflushing conditions) reversibility of fouling did not change greatly. Oppositely, the irreversible resistance tended to increase since foulants in pores accumulate over time [33]. Katsou et al. [34] also reported that rapid irreversible fouling occurs when internal pore adsorption takes place for a long time. Obtained results correspond well with OCT pictures

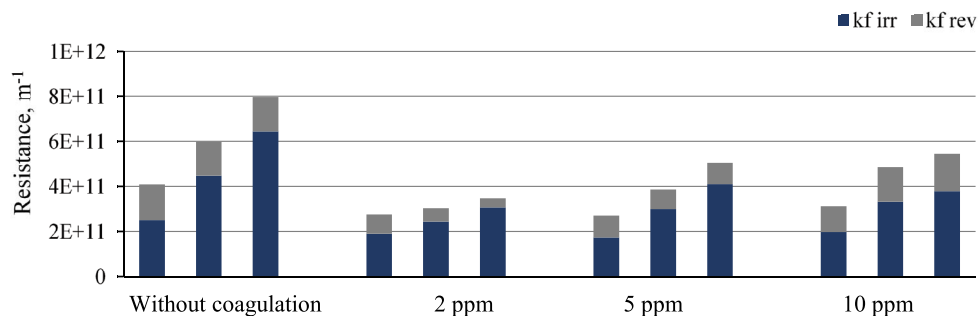


Fig. 3. Irreversible and reversible fouling resistances of in-line C-UF processes and filtration without coagulation. Each bar corresponds to the filtration cycle 1–3.

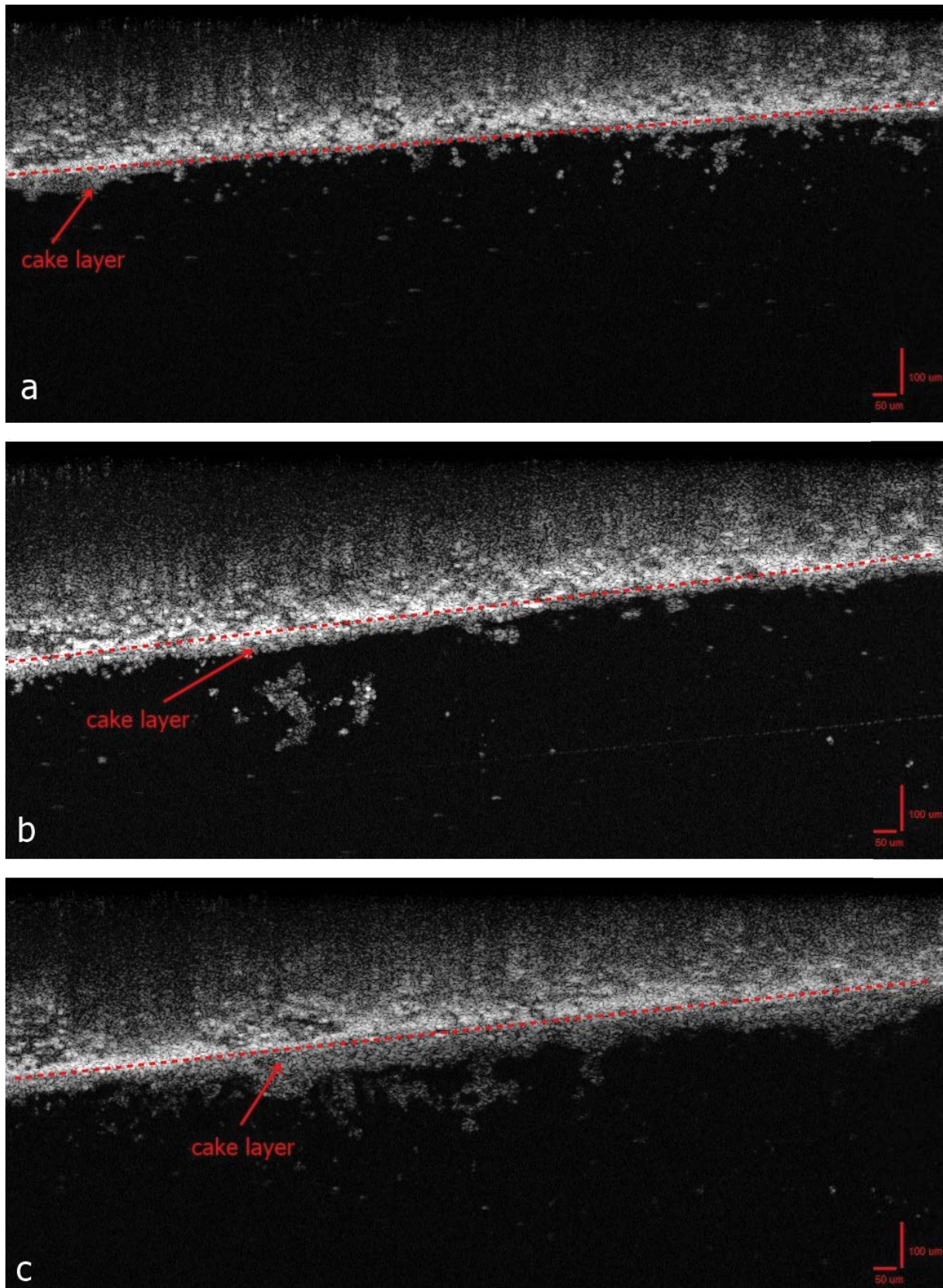


Fig. 4. (a–c) Effect of coagulant dosage of formation of cake layer under coagulant dose 2, 5, and 10 ppm, respectively. Pictures represent the cake layer after the first filtration cycle. Three-dimensional OCT projections represent membrane (top) and fouling layer (bottom). Interface of membrane and cake layer is marked by the red dashed line.

Table 2
Effect of coagulant dosage on cake layer thickness and floc size

Coagulant dosage	Cake layer thickness			Floc size		
	Average, μm	Min., μm	Max., μm	Average, μm	Min., μm	Max., μm
2 ppm	27.9	10.8	48.9	44.9	23.5	87.3
5 ppm	29.0	20.8	47.9	59.9	15.6	102.7
10 ppm	57.9	27.5	98.0	90.0	53.0	122.2

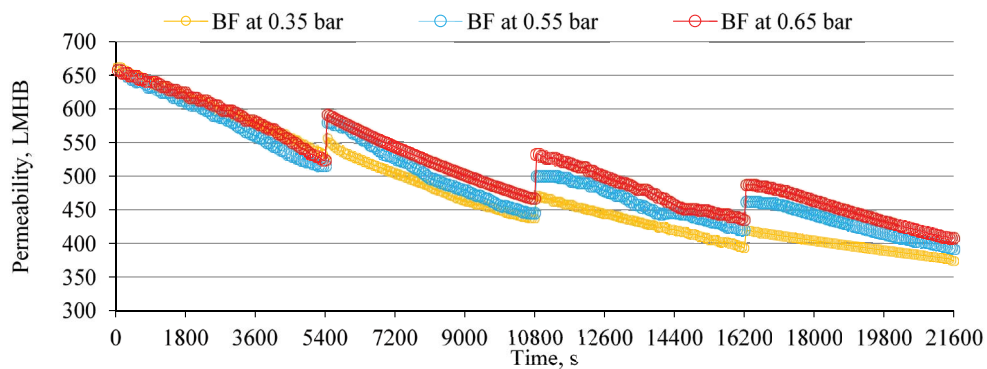


Fig. 5. Permeability loss as a function of time for inline C-UF processes under various backflush pressures.

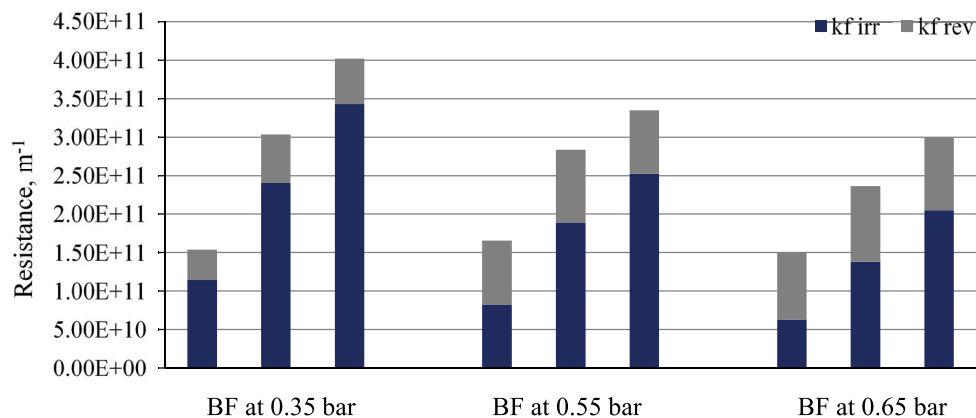


Fig. 6. Effect of backflush pressure on irreversible and reversible fouling resistances of in-line C-UF processes. Each bar corresponds to the filtration cycle.

(Fig. 7) and Table 3 presenting an increase in cake layer thickness within cycle 1–3.

Fig. 8 furthermore showed that the increase in backflush pressure from 0.35 to 0.55 bar led to the increased detachment of the fouling layer, which could be removed to a great by forward flushing. These results showed that backflushing at a pressure of 0.35 bar only resulted in a partial removal of the cake layer, while complete removal was observed at backflushing with 0.65 bar and after combined backflushing (0.55 bar) and forward flushing. Nevertheless, a further reduction of fouling resistances was observed when increasing the backflush pressure from 0.55 to 0.65 bar, as shown in Fig. 6.

In order to investigate this further, the organic composition of membrane deposits was investigated. The results

Table 3
Cake layer thickness in cycles 1–3

Cycle number	Cake layer thickness		
	Average, μm	Min., μm	Max., μm
1	42.9	32.6	51.0
2	56.7	42.9	65.3
3	100.8	64.6	152.0

(Fig. 9) showed that biopolymers, humic substances and building blocks were all deposited at the membrane and still present after back- and forward-flushing. The accumulation of the total amount of NOM dissolved organic carbon

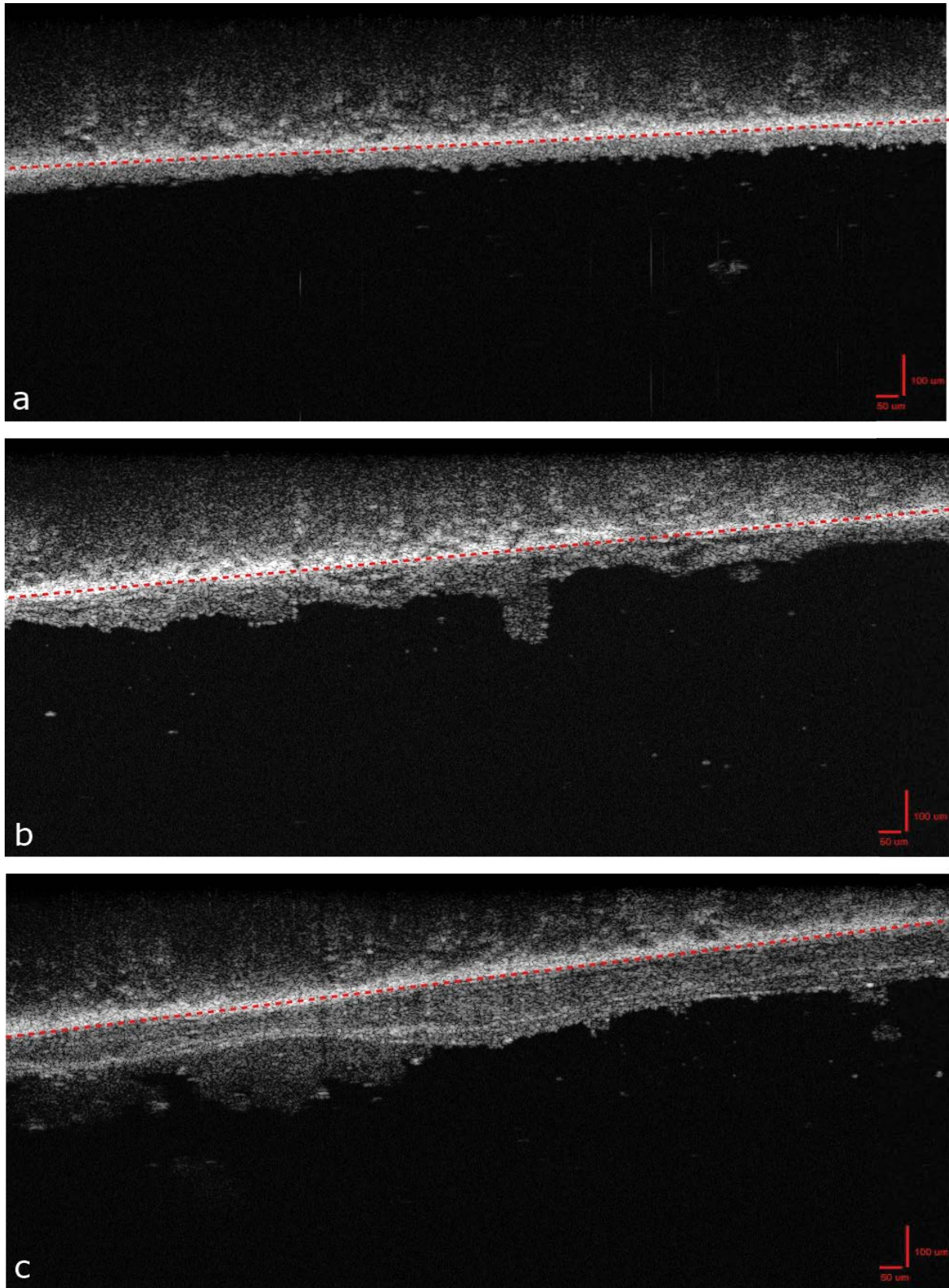


Fig. 7. (a–c) OCT images of membrane (top) and fouling layer (bottom) after first, second, and third filtration cycle, respectively. Coagulant dosage was 5 ppm, backflushing between cycles were conducted under 0.65 bar. The red dashed line represents the membrane/fouling layer interface.

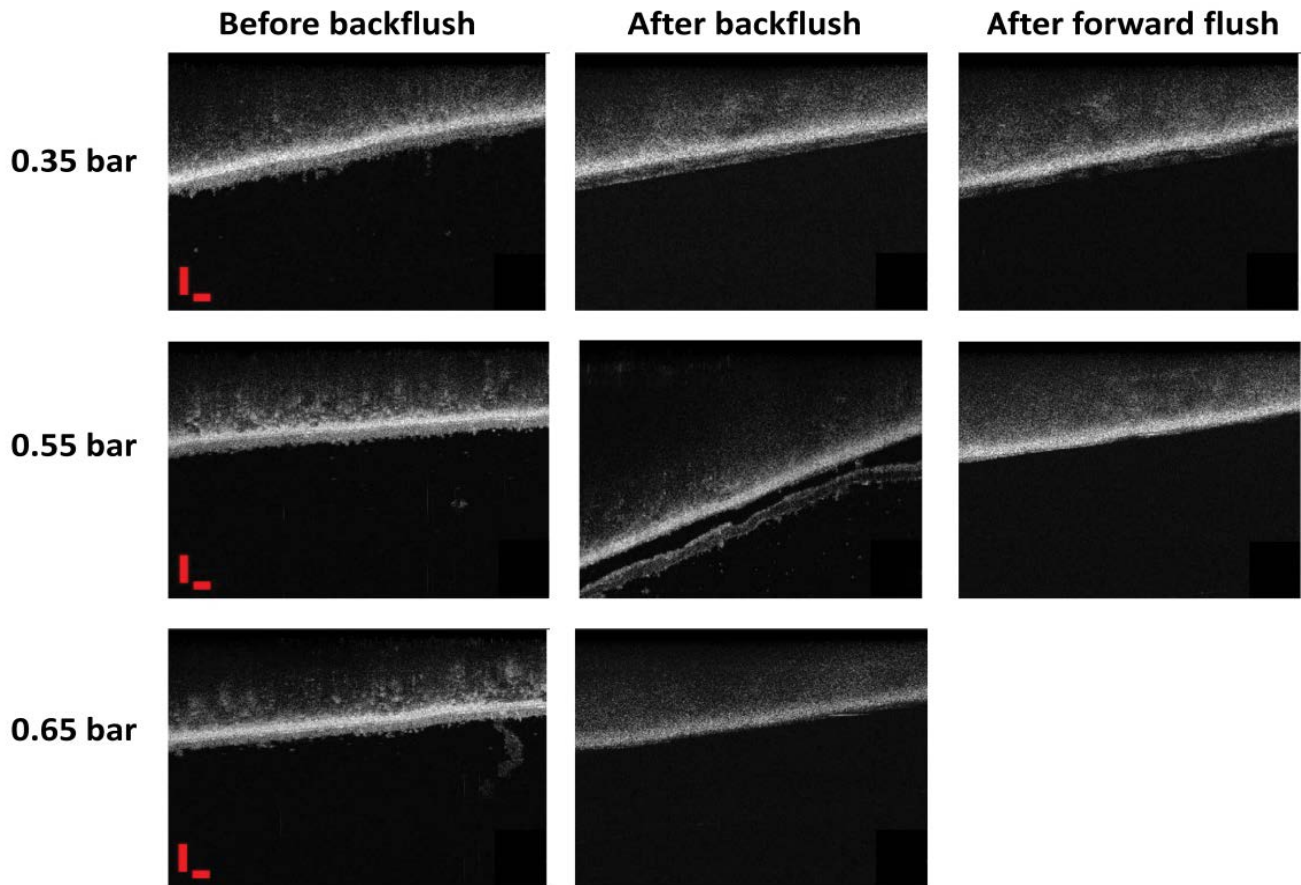


Fig. 8. OCT images of membrane (top) and fouling layer (bottom) before and after backflushing as well as after forward flush at different backflush pressures—cycle 1. The scale bars indicate 100 μm .

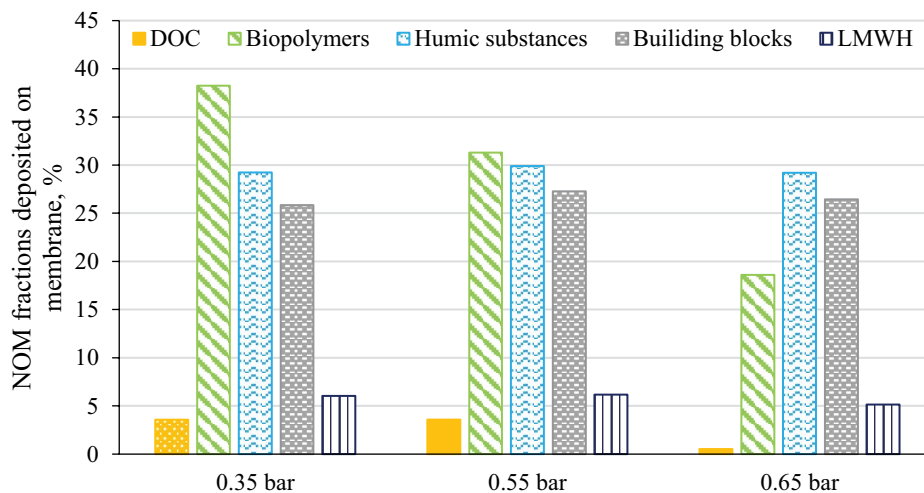


Fig. 9. NOM fractions deposited on the membrane after backflushing at different pressures, as calculated by the mass balance of feed, permeate, and backflush water determined by LC-OCD (expressed as % of the total NOM fraction in the feed solution).

(DOC) decreased with increasing backflush pressure, while specifically an amount of deposited biopolymers decreased significantly with increasing pressure. While the cake layer is practically completely removed at pressures above

0.55 bar, it can be assumed that the dominant fouling mechanism is internal fouling (pore blocking) and adsorption. Pore blocking is likely to be related to humic substances, while biopolymers are known to adsorb to membranes [35].

By increasing the backflush pressure, material deposited on membrane surface can in principle be removed, while adsorbed in pores humics can only be removed by chemical cleaning measures. Our results confirm the importance of humic substances as a fouling (pore-blocking) compound, since its deposition is significantly reduced at increasing backflush pressure. Irreversible fouling by inorganic particles humic substances has been described extensively in the literature for different types of waters [28,36], which corresponds with the results presented here. The application of in-line coagulation can minimize the fouling effects of NOM but cannot completely prevent it, presumably since a part of the NOM molecules do not aggregate and can lead to irreversible fouling due to adsorption and pore blocking.

4. Conclusions

This study examined the performance of inline coagulation–UF–NF process treating surface water containing NOM. The main findings are as follows:

- For the C–UF processes treating creek water, a dominant portion of fouling was irreversible. The irreversible resistance increased over time due to incremental foulants accumulation, while reversible resistances did not change greatly in cycles 1–3.
- Under the optimal iron chloride dosage of 2 ppm, UF membrane permeability loss was reduced by 60%. In C–UF processes irreversible fouling was less serious than in ultrafiltration without coagulation. Owing to coagulation, bigger particles were created that did not block pores irreversibly. Cake layer created under coagulant dosage of 2 ppm was less compressed and easier to remove by backflushing.
- As backflush pressure increased, higher permeability recovery was observed. Higher backflush pressure reduced the membrane fouling, mainly with respect to the irreversible fouling component. It was attributed to the combined effect of cake layer removal and removal of internal fouling. It was found that, the biopolymers deposition on the membrane decreased with increasing backflush pressure, which is especially important to reduce internal pore blocking.
- From OCT pictures was concluded that, complete removal of the cake layer was observed for backflushing at 0.65 bar and combined backflushing (0.55 bar) and forward flushing, while the cake was only partially removed at 0.35 bar.

Acknowledgments

Author Gabriela Kamińska received funding from National Science Centre (Poland) for preparing Ph.D. thesis under grant number DEC-2014/12/T/ST8/00668. Publication supported by the Rector's habilitation grant. Silesian University of Technology, No. 08/040/RGH19/0126.

References

- [1] A. Matilainen, M. Vepsäläinen, M. Sillanpää, Natural organic matter removal by coagulation during drinking water treatment: a review, *Adv. Colloid Interfaces*, 159 (2010) 189–197.

- [2] A.R. Costa, M.N. Pinho, Effect of membrane pore size and solution chemistry on the ultrafiltration of humic substances, *J. Membr. Sci.*, 255 (2005) 49–56.
- [3] J. Wang, S. Pan, D. Luo, Characterization of cake layer structure on the microfiltration membrane permeability by iron pre-coagulation, *J. Environ. Sci.*, 25 (2013) 308–315.
- [4] S. Zhao, B. Gao, Q. Yue, W. Song, R. Jia, P. Liu, Evaluation of floc properties and membrane fouling in coagulation ultrafiltration system: the role of enteromorpha polysaccharides, *Desalination*, 367 (2015) 126–133.
- [5] H. Dong, B. Gao, Q. Yue, Y. Wang, Q. Li, Effect of pH on floc properties and membrane fouling in coagulation – Ultrafiltration process with ferric chloride and polyferric chloride, *Chemosphere*, 130 (2015) 90–97.
- [6] M. Zupančič, D. Nowak, J. Diaci, I. Golobčič, An evaluation of industrial ultrafiltration systems for surface water using fouling indices as a performance indicator, *Desalination*, 344 (2014) 321–328.
- [7] M. Rajca, The role of microfiltration and ultrafiltration in hybrid treatment systems for NOM removal from water, *Procedia Eng.*, 44 (2012) 1527–1529.
- [8] K. Konieczny, D. Szałol, J. Płonka, M. Rajca, M. Bodzek, Coagulation–ultrafiltration system for river water treatment, *Desalination*, 240 (2009) 151–159.
- [9] X.-D. Chen, H.-W. Yang, W. Liu, X.-M. Wang, Y. Xie, Filterability and structure of the fouling layers of biopolymer coexisting with ferric iron in ultrafiltration membranes, *J. Membr. Sci.*, 495 (2015) 81–90.
- [10] H. Dong, W. Zhou, Q. Yue, H. Rong, S. Sun, S. Zhao, Effect of Fe(III) species in polyferric chloride on floc properties and membrane fouling in coagulation–ultrafiltration process, *Desalination*, 335 (2014) 102–107.
- [11] H. Huang, K. Schwab, J.G. Jacangelo, Pretreatment for low pressure membranes in water treatment: a review, *Environ. Sci. Technol.*, 43 (2009) 3011–3019.
- [12] W. Jin, W. Xiao-Chang, Ultrafiltration with in-line coagulation for the removal of natural humic acid and membrane fouling mechanism, *J. Environ. Sci.*, 18 (2006) 880–884.
- [13] K. Li, T. Huang, F. Qu, X. Du, A. Ding, G. Li, H. Liang, Performance of adsorption pretreatment in mitigating humic acid fouling of ultrafiltration membrane under environmentally relevant ionic conditions, *Desalination*, 377 (2016) 91–98.
- [14] M. Yao, J. Nan, T. Chen, D. Zhan, Q. Li, Z. Wang, H. Li, Influence of flocs breakage process on membrane fouling in coagulation/ ultrafiltration process – effect of additional coagulant of poly-aluminum chloride and polyacrylamide, *J. Membr. Sci.*, 491 (2015) 63–72.
- [15] L. Ehrl, M. Soos, M. Morbidell, Dependence of aggregate, strength, structure and light scattering properties on primary particle size under turbulent conditions in stirred tank, *Langmuir*, 24 (2008) 3070–3081.
- [16] K.Y.J. Choi, B.A. Dempsay, Inline coagulation with low pressure membrane filtration, *Water Res.*, 38 (2004) 4271–4281.
- [17] C. Guigui, J.C. Rouch, L. Durand-Bourlier, V. Bonneye, P. Aptel, Impact of coagulation conditions on the inline coagulation/ UF process for drinking water production, *Desalination*, 147 (2002) 95–100.
- [18] P. Park, C. Lee, S. Choi, K. Choo, S. Kim, C. Yoon, Effect of the removal of DOMs on the performance of a coagulation–UF membrane system for drinking water production, *Desalination*, 145 (2002) 237–245.
- [19] O. Ferrer, B. Lefevre, G. Prats, X. Bernat, O. Gibert, M. Paraira, Reversibility of fouling on ultrafiltration membrane by backwashing and chemical cleaning: differences in organic fractions behavior, *Desal. Water Treat.*, 59 (2015) 1–15.
- [20] C.H. Lee, Y.-H. Kim, M.J. Jeon, A. Jang, J. Kim, H. Kim, The effects of physical cleaning and chemical backwashing on foulant formation in a microfiltration membrane intended for the reuse of wastewater, *Desal. Water Treat.*, 57 (2016) 26586–26594.
- [21] S.S. Yoo, Operating cost reduction of in-line coagulation/ ultrafiltration membrane process attributed to coagulation condition optimization for irreversible fouling control, *Water*, 10 (2018) 1076–1093.

- [22] Y. Gaio, J. Qin, Z. Wang, S.W. Østerhus, Backpulsing technology applied in MF and UF processes for membrane fouling mitigation: a review, *J. Membr. Sci.*, 584 (2019) 1–20.
- [23] T. Klein, D. Zihlmann, N. Derlon, C. Isaacson, I. Szivak, D.G. Weissbrodt, W. Pronk, Biological control of biofilms on membranes by metazoans, *Water Res.*, 88 (2016) 20–29.
- [24] J.C. Crittenden, R.R. Trussell, D.W. Hand, K.J. Howe, J. Tchobanoglous, *Water Treatment: Principles and Design*, John Wiley & Sons, Hoboken, 2005.
- [25] S.A. Huber, A. Balz, M. Abert, W. Pronk, Characterisation of aquatic humic and non-humic matter with size-exclusion chromatography - organic carbon detection - organic nitrogen detection (LC-OCD-OND), *Water Res.*, 45 (2011) 879–885.
- [26] X. Shen, B. Gao, X. Huang, F. Bu, Q. Yue, R. Li, B. Jin, Effect of the dosage ratio and the viscosity of PAC/PDMDAAC on coagulation performance and membrane fouling in a hybrid coagulation-ultrafiltration process, *Chemosphere*, 173 (2017) 288–298.
- [27] A. Look, H. Wray, P. Bérubé, R.C. Andrews, Optimization of air sparging and in-line coagulation for ultrafiltration fouling control, *Sep. Purif. Technol.*, 188 (2017) 60–66.
- [28] H.-C. Kim, B.A. Dempsay, Membrane fouling due to alginate, SMP, EfOM, humic acid, and NOM, *J. Membr. Sci.*, 428 (2013) 190–197.
- [29] H. Paar, J. Benecke, M. Ernst, M. Jekel, Pre-coagulation and ultrafiltration of effluent impaired surface water for phosphorus removal and fouling control, *Water Sci. Technol.* 11 (2011) 211–218.
- [30] M. Dixon, C. Staaks, R. Fabris, V. Vimonses, C.W.K. Chow, S. Panglisch, J. van Leeuwen, M. Drikas, The impact of optimised coagulation on membrane fouling for coagulation/ultrafiltration process, *Desal. Water Treat.*, 51 (2013) 2718–2725.
- [31] C. Combe, E. Molis, P. Lucas, R. Riley, M. Clark, The effect of CA membrane properties on adsorptive fouling by humic acid, *J. Membr. Sci.*, 154 (1999) 73–87.
- [32] H.-G. Kim, C. Park, J. Yang, B. Lee, S.-S. Kim, S. Kim, Optimization of backflushing conditions for ceramic ultrafiltration membrane of disperse dye solutions, *Desalination*, 202 (2007) 150–155.
- [33] A. Broeckmann, J. Busch, T. Wintgens, W. Marquardt, Modeling of pore blocking and cake layer formation in membrane filtration for wastewater treatment, *Desalination*, 189 (2006) 97–109.
- [34] K. Katsou, S.G. Yiantsios, A.J. Karabelas, A study of ultrafiltration membrane fouling by humic acids and flux recovery by backwashing: experiments and modeling, *J. Membr. Sci.*, 266 (2005) 40–50.
- [35] D. Jermann, W. Pronk, S. Meylan, M. Boller, Interplay of different NOM fouling mechanisms during ultrafiltration for drinking water production, *Water Res.*, 41 (2007) 1713–1722.
- [36] D. Jermann, W. Pronk, M. Boller, Mutual influences between natural organic matter and inorganic particles and their combined effect on ultrafiltration membrane fouling, *Environ. Sci. Technol.*, 42 (2008) 9129–9136.