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Influence of the Backwash Cleaning Water Temperature on the Membrane Performance in a Pilot SMBR Unit

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Received: 5 January 2018; Accepted: 22 February 2018; Published: 25 February 2018

Abstract: In this work, different backwash (BW) schemes were applied on identical hollow fiber (HF) membranes in a membrane bioreactor (MBR) treating municipal wastewater. The effect of BW duration (1 min, 3 min and 8 min) and water temperature (8 °C, 18 °C, 28 °C and 38 °C) on membrane fouling were investigated. Specifically, the transmembrane pressure (TMP) drop and the membrane permeability increase caused by the BW was investigated. Furthermore, the time required for the membrane to return to the state just before each BW experiment, was also examined. It was found that membranes presented better operating performance, as the BW temperature and the backwash duration were increased. Specifically, for 1 min backwash duration at the BW temperatures of 8 °C, 18 °C, 28 °C and 38 °C, TMP decreased by 7.1%, 8.7%, 11.2% and 14.2% respectively. For 8 min BW duration at 8 °C, 18 °C, 28 °C and 38 °C, TMP values decreased by 12%, 17.5%, 23.7% and 30.2% respectively. Increased BW water temperature and duration also improved the membrane permeability. Using higher BW water temperatures, more hours were required to return the membranes to the condition just before cleaning. The selected BW water temperatures did not adversely affect the permeate quality.

Keywords: Membrane Bioreactor; hollow fiber membranes; TMP; backwash duration; temperature; membrane fouling

1. Introduction

Membrane bioreactor (MBR) systems are now a mature technology for wastewater treatment. The importance of membrane technology, is growing in the field of environmental protection. In 2008, a 22.4% compound annual growth rate (CAGR) was predicted for the world MBR market for the period 2008–2018 [1,2]. The global MBR market was worth $838.2 million in 2011 and is expected to witness positive growth and revenue sales through 2018 [3]. According to the recent report from BCC Research, the global market for MBRs was $425.7 million in 2014 and is projected to approach $777.7 million by 2019, registering a CAGR of 12.8% in the period 2014–2019 [4].

Although MBR technology has many advantages over the conventional activated sludge process, membrane fouling and the increased energy consumption are a major barrier to further use of this technology [5,6]. Membrane fouling is a severe problem and affects operating cost due to the frequent membrane cleaning and the increased aeration demands [7,8]. The degree of fouling in submerged membrane systems is a complex function of feed characteristics, membrane properties but more importantly of biomass characteristics and operating conditions [9,10]. To address the problem of membrane fouling, several measures are undertaken, including, wastewater pretreatment, hydraulic and chemical cleaning of the membranes, membrane modification and operation under conservative fluxes [11].

One of the most common hydraulic membrane cleaning methods, especially in hollow fiber (HF) submerged MBR is backwash (BW) cleaning. Membranes require periodical backwash to control fouling [12]. During the BW cleaning procedure, the filtration process is reversed so that permeate is sent back through the membranes. BW cleaning is particularly effective in the removal of accumulated particles over the membrane surface, which mainly constitute the reversible fouling, dislodging loosely adherent aggregates sludge from the membrane's surface [13,14]. BW is applied in both ultrafiltration (UF) and microfiltration (MF) hollow fiber and also in specific flat sheet membranes. The above procedures are performed in immersed MBR systems. After the BW process, the membrane recovers part of its initial permeability. However, over time, an irreversible loss of membranes productivity is observed, using the above cleaning procedures particularly when the system operates at high membrane flux [15]. The BW frequency, the duration and the BW to filtration flux ratio, are key operating parameters for the design of an effective backwashing procedure [16]. The optimization of backwashing is necessary for energy and permeate consumption [17]. The optimal duration of a backwash cycle is related to the effective removal of reversible foulants from the membrane's surface [11]. In the literature there are several studies which investigate the effect of BW on the mitigation of membrane fouling. The fouling deposition and removal during filtration with short periodical backwash by direct observation coupled with hydraulic resistance measurement in hollow fiber membranes was investigated [18]. Other work [19] stress that the intermittent backwashing and relaxation are mandatory in the MBR for its effective operation; also examined different relaxation and BW scenarios and found that the provision of relaxation or backwashing at small intervals prolonged the MBR operation by reducing fouling rates. There is a lack of experimental data on the influence of water temperature on the efficiency of BW cleaning. Moreover, the influence of BW water temperature is considered important in patent No WO2015198080 A1 in which it claims that, water's or permeate water's temperature is foreseen as adjustable [20].

Research works have also focused on the effect of the duration of BW. The effect of BW duration, on the membrane fouling of a pilot pressurized hollow fiber membrane module applied for the pre-treatment of seawater was investigated [21]. The BW duration is one of the most significant parameters in order to minimize the specific energy consumption. It was shown by other work [22] that were able to prolong the time constant TMP operation by 50% when BW together with air scouring during BW was implemented compared to simple dead end filtration without BW. The effect of filtration duration on membrane fouling of real seawater filtration while other operation parameters were kept constant was investigated [18]. There are also works in which demonstrating the importance of backwash duration in MBR systems. It was pointed that backwashing conditions (i.e., duration, interval, strength) considerably affected the fouling rate in membrane bioreactor systems [23]. In addition were presented various combinations in duration of filtration and backwash in MBR systems in order to achieve better results with respect to membrane fouling and the lowest fouling rates were found for 15 s in each 5 min of filtration [24]. In this work, the impact of BW water temperature and duration on TMP and permeability was investigated in a MBR treating municipal wastewater. Specifically, four different temperatures and three different backwash cleaning time periods were investigated.

2. Materials and Methods

2.1. MBR Operation

The MBR consists of a 60 L aeration tank fed with synthetic wastewater which simulates municipal wastewater (Figure 1). To test the impact of BW water temperature and duration, three identical HF type Khong membranes were used. The HF membrane were immersed in the aeration tank of the pilot MBR which was fed with synthetic municipal wastewater. The HF membrane modules characteristics are given in Table 1. The MBR was operated continuously with repeating cycles of filtration followed by relaxation. During the normal MBR operation, suction was applied to each HF module using a peristaltic, suction pump (0.975 L/h–9.750 L/h). There were two effluent lines which allow to conduct two parallel experimental cycles. At each effluent line a glycerin pressure indicator and an analog vacuum pressure transducer (−1/0 bar) in series with an analogue flow meter (FM) were installed. The filtration (8 min) and relaxation (2 min) time of the suction pump were adjusted according to the manufacturer for the protection of HF membrane elements. The operating conditions of the MBR process are listed in Table 2.

Table 1. HF Membrane Characteristics.

Membrane Type	Filtration Type	Membrane Material	Pore Size (µm)	Membrane Area (m^2)	Frame Dimensions (mm)	Critical Flux (L/m^2·h)
HF	UF	R-PVDF	0.1	0.05	24 × 22	25

Table 2. Experimental conditions.

Operating Parameter	Value
Working Time/Cycle (min)	8
Relaxing Time/Cycle (min)	2
Gross Flux (L/m^2·h)	24
pH	7–8
Aeration type	Coarse bubble
Max TMP (mbar)	220
MLSS (mg/L)	7450–11250
Backwash period/frequency	see experimental procedure
Backwash recommended flow (L/m^2·h)	30
Max Backwash Pressure (mbar)	<50

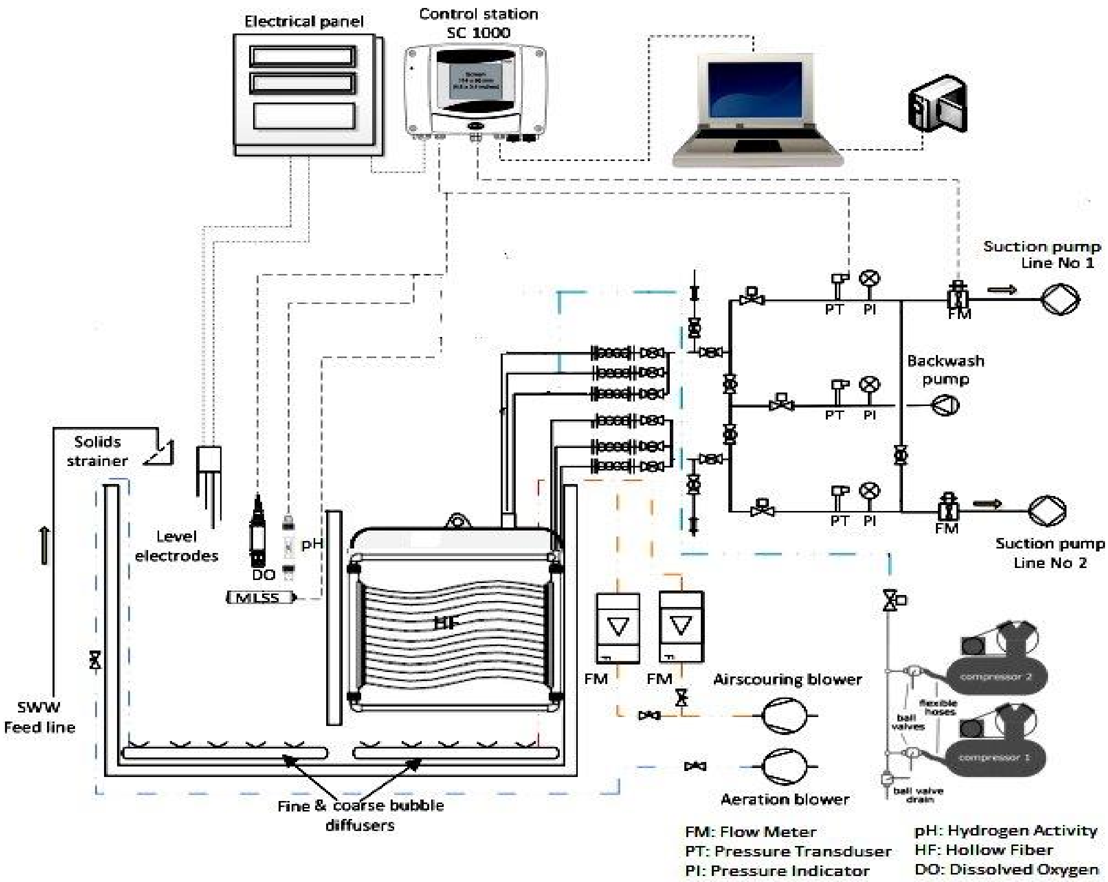

Figure 1. MBR pilot plant and backwashing layout.

The BW procedure was applied each time the membranes presented significant fouling, by monitoring the TMP value which was chosen not to exceed 210 mbar. The range of BW water temperature was in the permitted limits of manufacturers and did not exceed 40 °C. In the backwash line the following equipment was placed in series: a flow control solenoid valve, a glycerin pressure indicator and an analog pressure transducer (0/1 bar). The backwash pump was connected to a volume calibrated water container which was equipped with a thermometer, a regulated thermostat and an immersed heater. The backwash pump was manually calibrated to provide the recommended flow of backwash cleaning water. As seen in Figure 1, the BW was partly performed in a separate line compared to the permeate collection line. The dead volume of water in the BW tubes is considered to be negligible compared to the total amount of BW water. The MBR pilot unit was continuously working, for a period of 12 months. The air scouring amount was maintained constant but lower than manufactures suggest for faster membrane fouling simulation. More extensive description of the MBR pilot plant and backwashing equipment also presented elsewhere [25].

2.2. Backwashing Experimental Procedure

A consistent number of backwashing experimental cycles was performed to confirm the accuracy and repeatability of the working method. In each backwashing experimental cycle, an HF membrane (Khong) was used, working continuously at an operational scheme of 8 min filtration and 2 min relaxation period. Each cycle was carried out once the TMP had reached close to 210 mbar so that the membrane was considerably fouled. At the first period, three experimental cycles were implemented: the backwash water temperature was set at 8 °C and three different backwashing durations of 1 min, 3 min and 8 min were applied. At the second period, three BW cycles were carried out: the backwash water temperature was set at 18 °C which was near the ambient mixed liquor temperature. The above water temperature was tested for three different backwashing durations of 1 min, 3 min and 8 min. The same procedure repeated using backwash water temperature of 28 °C and 38 °C for BW duration of 1 min, 3 min and 8 min. In all cases, each backwash experimental cycle was repeated three times, in each selected membrane for repeatability reasons.

The TMP and permeability experimental data are mean values of each backwash scheme. All the values are normalized to a standard temperature of 20 °C. An adequate number of treated effluent samples were collected for physicochemical analyses after an hour of each cleaning procedure. For all BW cleaning cycles, tap water instead of the effluent was chosen, so as to assure potential external factors as internal clogging from solids or biofouling from microorganisms.

3. Results and Discussion

In Figure 2 the effect of the BW water temperature on TMP decrease is shown for a BW duration of 1 min, 3 min and 8 min. The TMP decrease was calculated as a percentage decrease of the TMP value using the following equation $(TMP_{\text{before BW}} - TMP_{\text{after BW}})/(TMP_{\text{before BW}} - TMP_{\text{clean membrane}})$. The clean membrane's TMP was 2.5 mbar at the flux of 24 $L/m^2 \cdot h$. The membranes which were treated for 1min by BW water at 8 °C resulted in a TMP decrease of about 7.1%. As the backwash water temperature was increased to 18 °C, 28 °C and 38 °C, TMP values showed a decrease of about 8.7%, 11.2% and 14.2% respectively. Consequently, the BW water temperature increase from 8 °C to 38 °C caused the doubling of the TMP reduction.

In the same figure, the impact of water temperature on the decrease of TMP is shown for BW duration of 3 min. The membranes which were fed with backwash water at 8 °C resulted in TMP decrease of 8.2%. As in the case of 1 min BW, by increasing the backwash water temperature, the TMP decrease was higher. Specifically as the BW water temperature increased at 18 °C, 28 °C and 38 °C, the TMP showed a decrease of about 12.2%, 17.1% and 20.3% respectively.

The percent TMP decrease for the four different water temperatures for BW duration of 8 min is also presented in Figure 2. The BW cleaning procedure using water at 8 °C and 18 °C have much lower improvement in terms of membrane TMP and permeability with respect to the cleaning procedure using water at 28 °C and 38 °C. Specifically the membranes which were treated by BW water at 8 °C and 18 °C, resulted in TMP decrease of about 12% and 17.5% respectively. By increasing the BW water temperature at 28 °C and 38 °C the TMP showed a decrease of about 23.7% and 30.2% respectively. Consequently, in all the experimental cycles which were performed, the increase of temperature and/or of the duration resulted in an improvement of the membrane TMP.

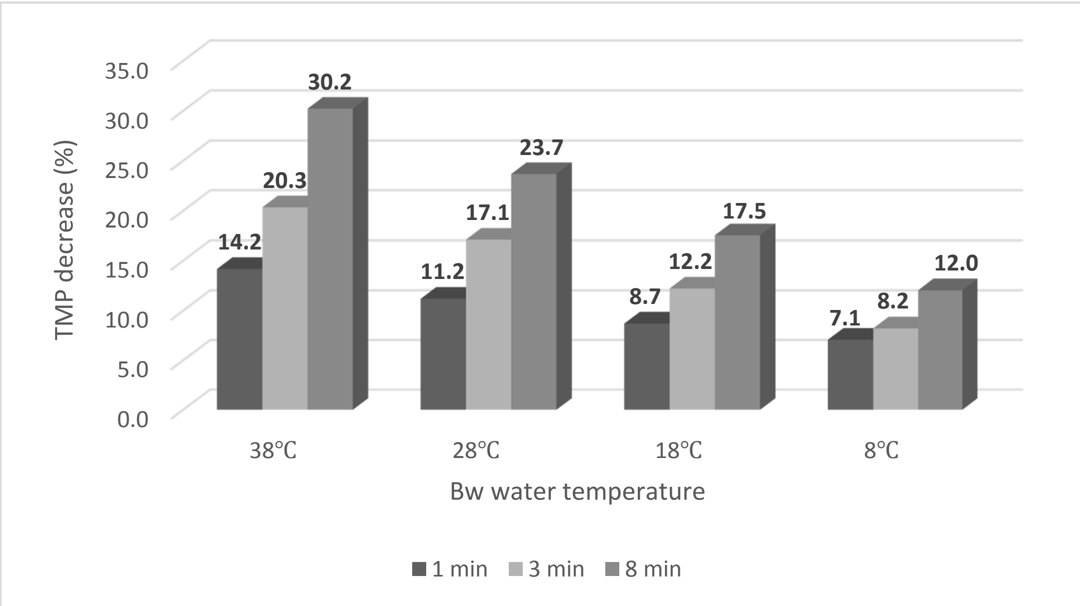

Figure 2. Impact of water temperature on TMP decrease for the BW durations of 1 min, 3 min and 8 min.

Figure 3a shows the monitored TMP values of the MBR before and after the backwash cleaning procedure with water at 8 °C, 18 °C, 28 °C and 38 °C for BW duration of 1 min. In this experimental scheme, only 1 h of MBR operation was required just after the BW to reach approximately the TMP value which was observed just before the BW process was applied (~210 mbar). As the BW water temperature increased to 18 °C, 28 °C and 38 °C the membrane modules operated more hours before the max TMP was reached. Specifically 3h, 9h and 18 h were required respectively.

Figure 3b presents the monitored TMP values before and after the BW cleaning procedure with BW water temperature at 8 °C, 18 °C, 28 °C and 38 °C using BW duration of 3 min. In this case, the time needed to reach the same TMP as the one recorded before the BW was 4 h (~210 mbar). The increase of backwash water temperature to 18 °C and 28 °C prolonged the time taken to reach 210 mbar to 10 h and 24 h acordingly. Finally, the membrane module which was cleaned with water at th temperature of 38 °C needed 56 h to reach a TMP above 200 mbar.

In Figure 3c the recorded TMP values before and after the BW cleaning procedure with water at 8 °C, 18 °C, 28 °C and 38 °C by applying a BW duration of 8 min. It is found that the membrane module which was cleaned with water at 8 °C needed 10 h to restore the TMP values. Apparently the BW water temperature increase to 18 °C, 28 °C and 38 °C maintained significantly increased the elapsed time which was required to reach the max TMP. Therefore, the temperature increase from 8 °C to 38 °C resulted in sixteen times more time to reach the max TMP. The utility of the above method was perceived both in short as in longer backwash period. Consequently, the increase of water temperature results in much fewer BW cycles during the operation of the MBR process and has a positive impact on membrane fouling.

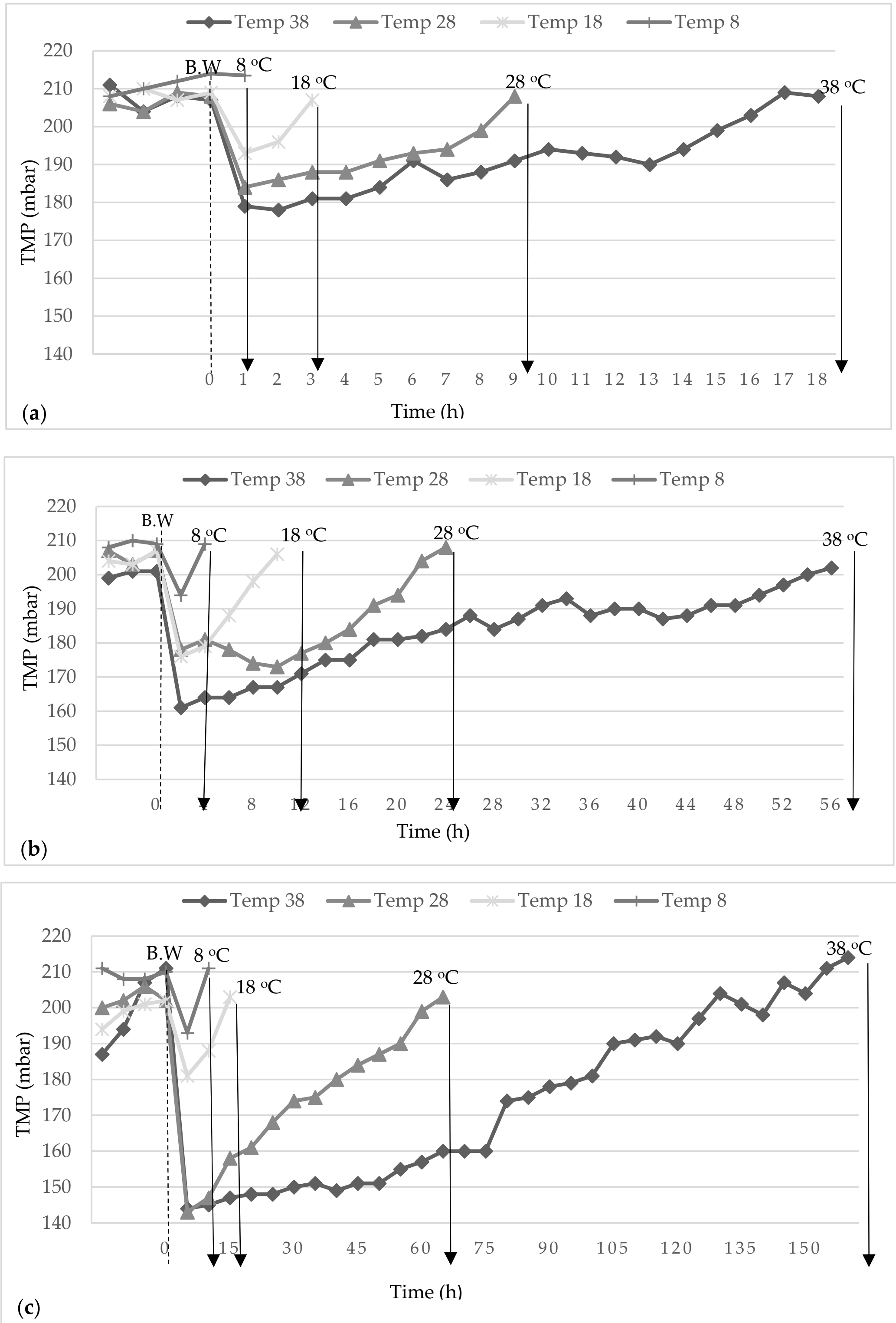

Figure 3. Mean TMP monitored values for the continuous operation of the MBR following BW at all examined water temperatures for BW duration of (**a**) 1 min, (**b**) 3 min and (**c**) 8 min.

Figure 4 presents the BW cleaning steps that are required in a period of a week (168 h) with 1 min, 3 min and 8 min BW period of each step. It is noticed that the increase of BW water temperature leads to decrement of BW steps. Specifically, the backwash of 1 min duration with water of 8 °C required 168 cleaning steps in order to keep TMP within the required limits. The increase of temperature at

18 °C, 28 °C and 38 °C leads to decrement of BW steps to 56, 18 and 11 accordingly. That gives a high energy and flow rate profit.

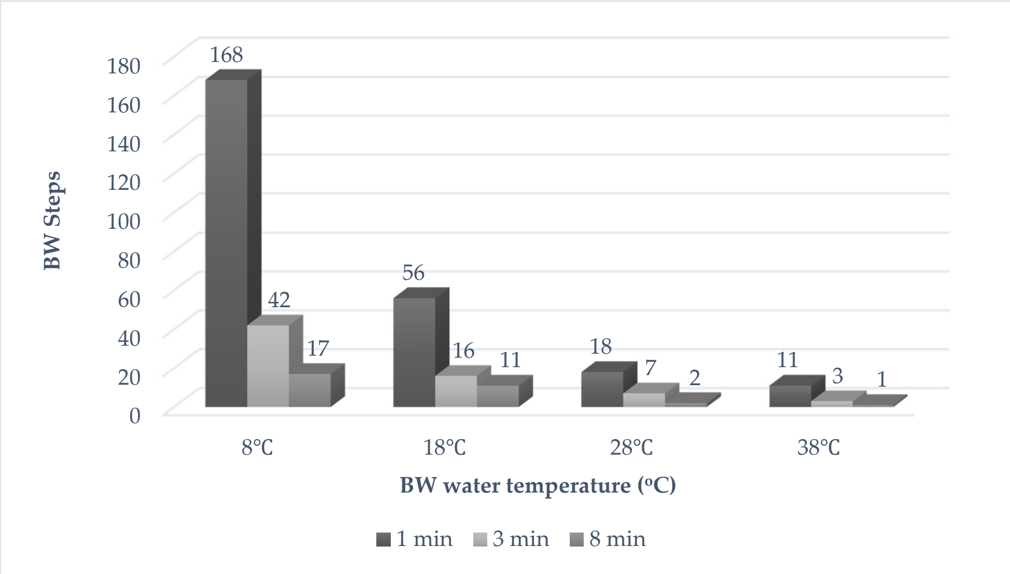

Figure 4. Number of BW steps required for the different water temperature in a period of a week (168 h), for BW duration of 1 min, 3 min and 8 min.

Similar results are observed in both cases of 3 min and 8 min of BW period. Specifically in the case of 8 °C the required BW steps were 42 for 3 min BW period and 17 for 8 min BW period. For 18 °C, 28 °C the respective steps were, 16 and 11 for 3 min BW period and 7 and 2 for 8 min BW period accordingly. At last, in the case of 38 °C the required steps were just 3 in the case of 3 min BW period and only one in all over the week in the case of 8 min BW duration. These results confirm the importance of the method as the decrease of required number of BW steps offer a great profit in energy consumption and a higher effluent productivity.

Table 3 shows the net flux of all the tested BW schemes for a weekly operation. It is observed that increasing the BW temperature leads to higher net flux in all the examined cases. However, in the case of lower temperatures (8 °C–18 °C) the highest flux is obtained for the 3 min BW duration. The positive impact in fouling resistance can be also observed by examining the rate of permeability decrease (Figure 5a–c). The permeability of the membrane module which was cleaned with the higher water temperature presented lower rate of permeability decrease with time and therefore required less frequent BW and chemical cleaning.

Table 3. Net flux (L/m^2·h) of all the different BW scheme for a weekly operation.

BW Scheme	Net Flux (L/m^2·h)
8 °C for 1 min	18.28
8 °C for 3 min	18.51
8 °C for 8 min	18.46
18 °C for 1 min	18.89
18 °C for 3 min	18.93
18 °C for 8 min	18.83
28 °C for 1 min	19.10
28 °C for 3 min	19.09
28 °C for 8 min	19.11
38 °C for 1 min	19.13
38 °C for 3 min	19.15
38 °C for 8 min	19.16

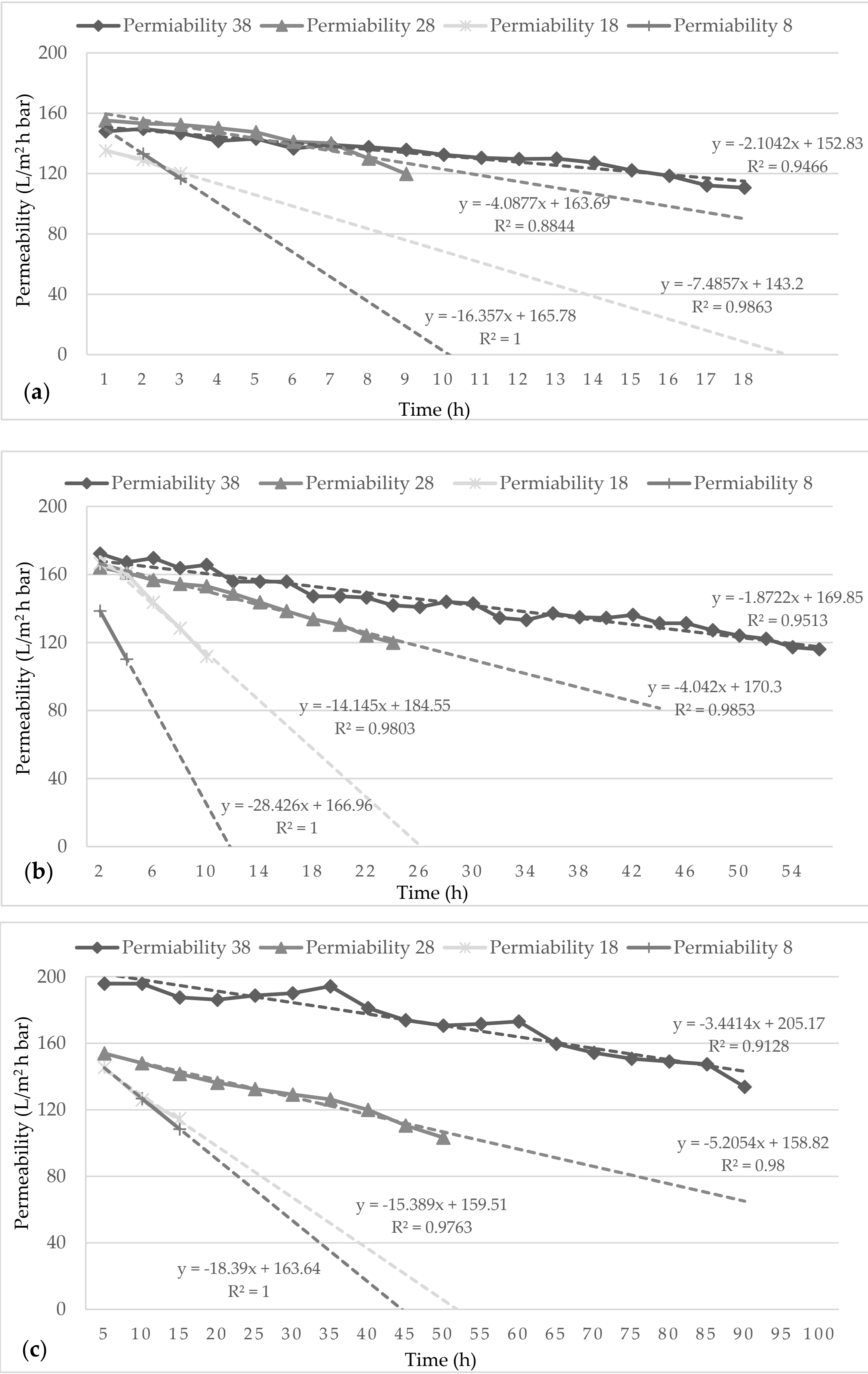

Figure 5. Mean membrane permeability with time for BW duration of (**a**) 1 min, (**b**) 3 min and (°) 8 min.

In Figure 6, the average values of selected physicochemical parameters (conductivity - turbidity) of the treated effluent are presented just before and after the cleaning backwash procedure for all the experimental cycles are presented.

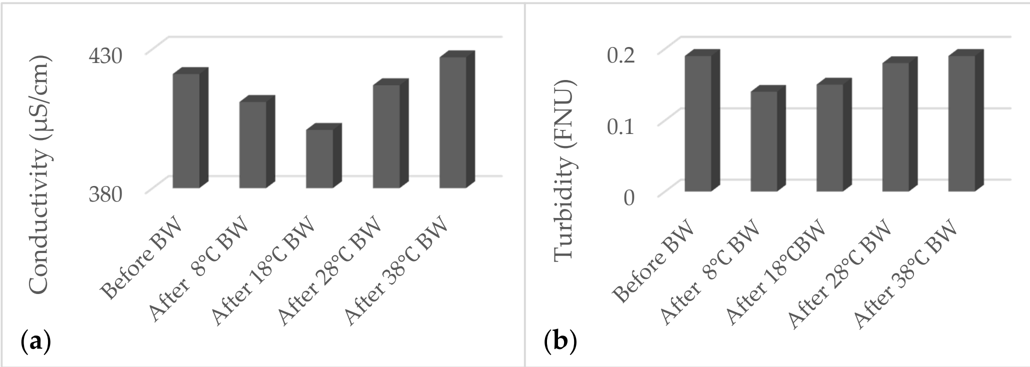

Figure 6. Treated effluent physicochemical parameters of (**a**) conductivity and (**b**) before and after water backwash at temperatures of 8 °C, 18 °C, 28 °C and 38 °C. Each mean value is derived from 6–10 repetitions.

From the results of Figure 6 it is observed that the BW water temperature does not influence significantly the quality of the treated effluent.

4. Conclusions

It was found that membranes presented better operating performance as the BW temperature water was increased. Furthermore, the increasing duration of the BW leads to better membrane performance. The increase of BW water temperature also entails an increase of the operating period before the next BW cycle is required. Increasing the BW temperature resulted in higher net flux in all the examined cases. However, in the case of lower temperatures (8 °C–18 °C) the highest flux was observed for the 3 min BW duration. In addition, the rate of membrane permeability decrease with time was much lower when the membrane was cleaned with high BW water temperature. In addition, it was found in all examined cases that the treated effluent quality is not influenced using the above cleaning procedure, by measuring certain indicative physicochemical parameters. These results are considered encouraging to the direction of the use of environmental friendly cleaning procedures in MBR units.

Author Contributions: L.L, K.C. and N.T. conceived and designed the experiments; L.L. performed the experiments; L.L, S.M. and K.C. analyzed the data; K.C. and S.M. contributed reagents/materials/analysis tools; L.L., S.M, K.C. and N.T wrote the paper.

Conflicts of Interest: The authors declare no conflict of interest.

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