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Enhancing the membrane bioreactor efficiency: The impact of rotating membrane modules and aeration strategies on the transmembrane pressure

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ABSTRACT

The study analyses the performance of a pilot plant using a rotating hollow fibre (HF) membrane bioreactor system. The experiments evaluated the effect of operational parameters such as rotational speed, aeration strategies, and maintenance cleaning (MC) procedures on the efficiency of the system, in particular transmembrane pressure (TMP) and filtrate quality. The results indicate that the rotating membrane module reduces TMP increase and can operate for 48 days with satisfactory performance, even without aeration. This has the potential to significantly improve efficiency, resulting in significant energy savings. In addition, two MC methods, clean in air and clean in place, were tested and found to be efficient for weekly MC. It was observed that operating without aeration during colder seasons may not be effective. Therefore, adaptive strategies are needed to address seasonal temperature variations.

Key words: membrane bioreactor, membrane maintenance cleaning, rotating hollow fibre membrane, transmembrane pressure

HIGHLIGHTS

- Different membrane rotational speeds, aeration strategies, and maintenance cleaning methods were evaluated.
- Membrane rotation played a significant role in maintaining the optimal transmembrane pressure, outperforming aeration.
- The pilot plant operated continuously for 48 days without pre-screening and aeration.
- There is significant potential for energy savings by reducing or eliminating aeration.

1. INTRODUCTION

The membrane bioreactor (MBR) system, integrating biological processes with membrane filtration, provides a robust approach to wastewater treatment (Judd 2016). Its compact design, achieved by eliminating the need for a secondary settling tank, confers a distinct advantage over conventional activated sludge (CAS) systems. The MBR process offers additional benefits, including the capability to operate at higher mixed liquor suspended solid (MLSS) concentrations, an extended sludge age, and reduced sludge production compared to CAS methods (Visvanathan *et al.* 2000; Pollice *et al.* 2008; Barreto *et al.* 2017). These benefits have encouraged the adoption of MBR technology across 200 countries by 2016, with the global market for MBR systems experiencing an annual growth rate of 15% (Judd 2016).

Nevertheless, fouling is a significant challenge associated with MBR systems, which is characterized by the accumulation of disruptive deposits on the membrane surface or within the pores. These deposits originate from retained salts, macromolecules, colloids, and particles (Ladewig & Al-Shaeli 2017). To deal with fouling, operational strategies such as chemical and mechanical cleaning strategies are necessary to prevent the membrane from fouling. However, these countermeasures add complexity to the system, resulting in increased capital and operational costs. The main cost drivers are the periodic need to replace membrane modules and the implementation of anti-fouling strategies, which collectively raise the financial burden of utilizing MBR technology (Judd 2011; Rahman *et al.* 2023).

The phenomenon of fouling represents the primary challenge encountered in an MBR system. As a result, solving or reducing the problem has the greatest impact on the efficiency of an MBR plant (Al-Asheh *et al.* 2021). Thereby, fouling is a process by which the membrane experiences a loss of performance due to the deposition of dissolved and/or suspended matter on the membrane surface, openings, or within the pores (Iorhemen *et al.* 2016). This leads to a decrease in flux, which is the quantity of material passing through a unit area of membrane per unit time, measured in litres per m^2 per hour (or LMH) (Judd 2011). The fouling depends on a large number of factors such as the cleaning strategy, the operating conditions, the specific properties of the wastewater, and the membrane used (Al-Asheh *et al.* 2021). A common strategy to reduce membrane fouling is by using coarse bubble (CB) aeration under the membrane module. Yet the increased oxygenation leads to increased foam formation and increased ongoing energy requirements, which can be almost double that of the CAS process (Iorhemen *et al.* 2016; Judd 2016; Al-Asheh *et al.* 2021). The use of CB aeration compromises oxygen transfer efficiency, which could be significantly improved by using fine bubble (FB) aeration (Henkel *et al.* 2009; Mahdariza *et al.* 2023; Zuo *et al.* 2024).

Another possibility is to increase the shear force to prevent the attachment of biofilm to the membrane surface. A potential solution is to introduce a rotational membrane, which can minimize the formation of reversible fouling (Rector *et al.* 2006; Wu *et al.* 2008; Zuo *et al.* 2010; Jiang *et al.* 2012). Furthermore, a novel pilot-plant scale prototype of rotating hollow fibre (HF) MBR modules was built and studied in the batch process (Mahdariza *et al.* 2022, 2023). In contrast to conventional HF MBR modules, the new concept applies a continuing sheer force by rotation to the new arrangement of HF membrane modules. The results showed that the additional energy required for rotation can be overcompensated by the improved oxygen transfer efficiency driven by rotation.

In this study, a series of experiments was conducted with the rotating HF membrane module in operation. The objective was to evaluate the performance of the pilot plant under various operational parameters, with a focus on transmembrane pressure (TMP) and filtrate quality.

2. MATERIAL AND METHODS

The rotating HF membrane module discussed in this study is the same as the one utilized in prior research by Mahdariza *et al.* (2022, 2023). The module (Figure 1) comprises 1,950 HF membranes constructed from polyvinylidene fluoride, each with a pore size of 0.3 μm. Every individual fibre is sealed at one end and attached at the other end to the permeate tube, arranged

Figure 1 | The rotatable HF membrane module.

horizontally. The total membrane area of the module is 2.25 m^2, yielding a packing density of 81 m^2/m^3. The unique feature of this setup is the rotation of the HF membrane module, coupled with the horizontal positioning of the membranes, which ensure that air bubbles effectively contact all fibres during the aeration process.

The experiments were carried out at the wastewater treatment plant (WWTP) of Kassel, Germany (340,000 PE), utilizing return sludge as the inflow source. The MLSS concentration of the return sludge ranged from 5 to 7 g/L, with an average solid retention time of 15 days. This sludge was introduced into the pilot plant without additional screening at a flowrate of 1 L/s. The 1 m^3 capacity tank typically held 0.9 m^3 of sludge until it reached two designated overflow channels. Filtration was achieved using a membrane module, which was facilitated by a positive displacement pump (Flojet, Xylem Water Solutions Deutschland GmbH, Langenhagen, Germany). An identical pump model was employed for the backwashing process. For aeration, a Flexnorm 500 diffuser (OTT System GmbH & Co. KG, Langenhagen, Germany), was employed to generate FBs, while a custom-built CB diffuser, constructed from PVC piping with three 3-mm holes, served for coarse aeration. The rotation of the HF membrane module was powered by a motor (MSF-Vathauer Antriebstechnik GmbH & Co KG, Detmold, Germany). The setup of the pilot plant is depicted in Figure 2.

The research explored a range of operational variables, such as diverse module rotational speeds and aeration systems, to assess their impact on system performance. After each experimental session, the system underwent maintenance cleaning (MC), which involved chemically enhanced backflush with 20 L of sodium hypochlorite (NaOCl). This procedure was essential for maintaining the efficiency of the system.

In the first phase of the experiment, two different ratios of filtering to backflushing processes and fluxes were examined. The outcomes of this phase guided the subsequent experimentation during the second phase, which focused on testing different aeration strategies and membrane module rotations. Each experimental set was scheduled to run for approximately 1 week (6–7 days), after which the MC of the membrane module was conducted. This phase also aimed to evaluate the effectiveness of MC by exploring different concentrations of NaOCl. Following the methodologies outlined by Judd (2011) and Wang *et al.* (2014), two distinct approaches were compared: cleaning in air (CIA), involving emptying the reactor, and cleaning in place

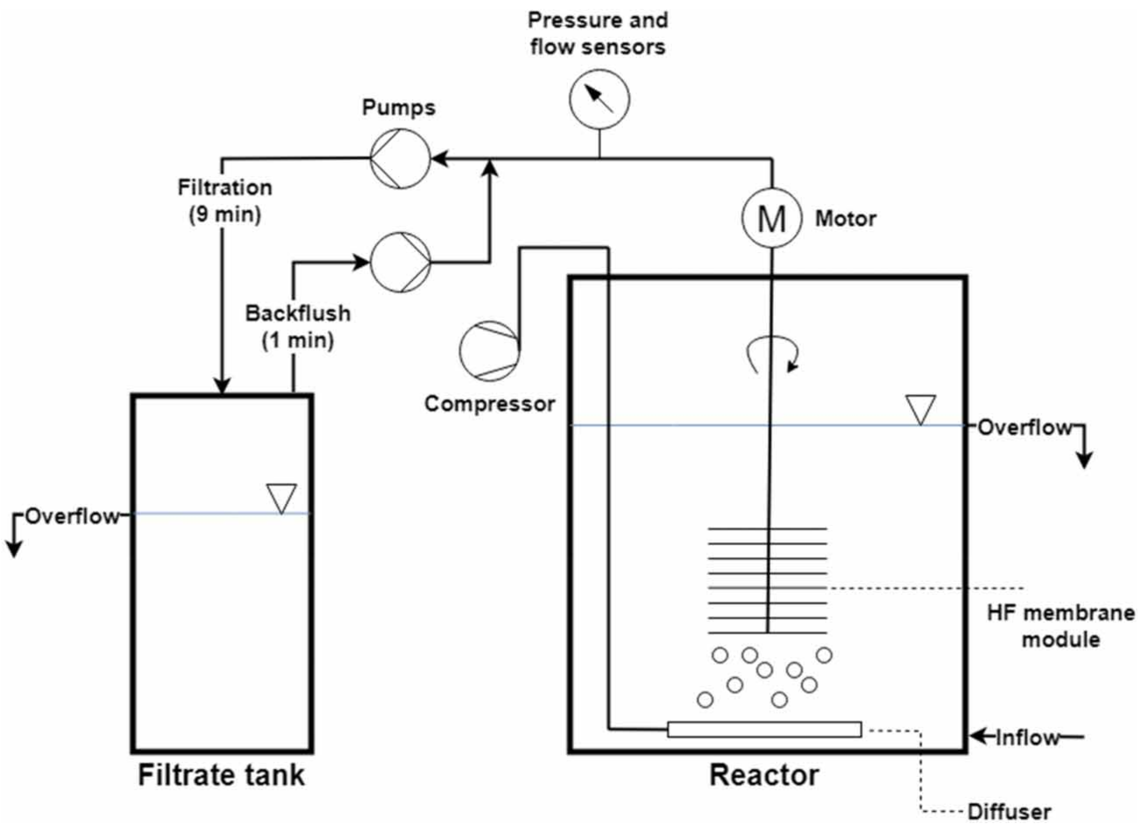

Figure 2 | Setup of the pilot plant (Mahdariza *et al.* 2024).

(CIP), where the reactor remained filled with wastewater. The final phase extended over 7 weeks, during which the pilot plant operated to assess the feasibility of the MBR module in practical applications.

3. RESULTS AND DISCUSSIONS

3.1. The measurement of the quality of sludge and filtrate

A series of parameters were subjected to periodic laboratory sampling during all experiments conducted within this study. In addition to monitoring the quality of the input sludge, it was necessary to observe any changes in the filtrate quality that may have occurred when different operational setups were applied during the operational period of the pilot plant.

As illustrated in Table 1, the pilot plant demonstrated effective performance in terms of soluble chemical oxygen demand (sCOD) removal and filtrate turbidity even in the absence of pre-screening. Despite the MLSS concentration exceeding 8 g/L on several occasions during the 48-day operation period (third phase), the turbidity of the filtrate remained consistently below 1 NTU. Furthermore, the pilot plant demonstrated the ability to maintain an average sCOD removal rate of 54%, which aligns with reported values for microfiltration MBR systems from other studies, which range between 25 and 98% (Ahn & Song 1999; Baek & Pagilla 2006; You *et al.* 2007; Lin *et al.* 2012; Deowan *et al.* 2019; Kabuba *et al.* 2023).

3.2. The impact of filtration-to-backflush time ratio and flux on TMP

In the initial phase of the experiment, the investigation focused on the impact of the filtration-to-backflush ratio and the flux on the increase of TMP. The objective was to achieve a TMP increase that would allow stable operation with one MC per week.

Setting the filtration flux to 26.7 LMH (filtration flowrate 1 L/min) with CB aeration and 20 rpm module rotation, the results indicated that with a filtration backwash ratio of 9:1 min, the TMP increase was too steep to achieve the desired outcome, as shown in Figure 3. A reduction in filtration time and an increase in backwash time improved the performance. Finally, the desired outcome was achieved by employing a filtration backwash ratio of 9:1 min at a flux of 24 LMH (filtration flowrate 0.9 L/min). In support of this, Jiang *et al.* (2005) also demonstrated that operating the MBR system at a flux of less than 25 LMH resulted in more stable long-term performance. This flux value is commonly observed in MBR systems (Judd 2016).

3.3. The impact of aeration strategies and module rotation on TMP

In the subsequent stage of the investigation, the focus shifted to assessing the impact of three different aeration strategies: without aeration, FB aeration, and CB aeration. This assessment was further enhanced by adjusting the rotational speeds of the membrane module to 0, 20, and 30 rpm. The limitation to 30 rpm was based on insights from a previous study on the same membrane system conducted by Mahdariza *et al.* (2022). The study identified that standard aeration efficiency peaked at this speed, with efficiency declining at higher rotation speeds.

To mitigate the influence of sludge temperature on the outcomes, the experiments for this second phase were scheduled within the same season during spring. This approach ensured comparable results. Figure 4 illustrates that two out of six experiments experienced early termination when membrane rotation was not employed due to a rapid increase in TMP exceeding anticipated levels. In the experiment without aeration and without module rotation, this occurrence was somewhat expected, given that the interaction between the foulant and the membrane surface was not disrupted. In another experiment, in which only aeration was applied without module rotation, only a portion of the membrane module was scoured, as the design of the membrane module did not allow for all membrane fibres to interact with air bubbles in the absence of rotation. However,

Table 1 | The characteristic of sludge and the filtrate during the experiment

	First phase		Second phase		Third phase	
Parameters	**Sludge**	**Filtrate**	**Sludge**	**Filtrate**	**Sludge**	**Filtrate**
MLSS concentration (g/L)	5.9 (±0.4)	–	6.2 (±0.4)	–	7.0 (±2.2)	–
Turbidity (NTU)	–	0.6 (±0.1)	–	0.8 (±0.2)	–	0.4 (±0.1)
pH	6.9 (±0.1)	7.0 (±0.0)	6.9 (±0.1)	7.0 (±0.1)	6.8 (±0.1)	6.8 (±0.1)
Conductivity (μS/cm)	1,203 (±54)	1,230 (±58)	1,165 (±153)	1,206 (±146)	734 (±211)	849 (±215)
sCOD (mg/L)	50.0 (±3.5)	21.6 (±2.6)	48.8 (±2.4)	21.0 (±1.8)	24.8 (±8.1)	14.5 (±3.9)

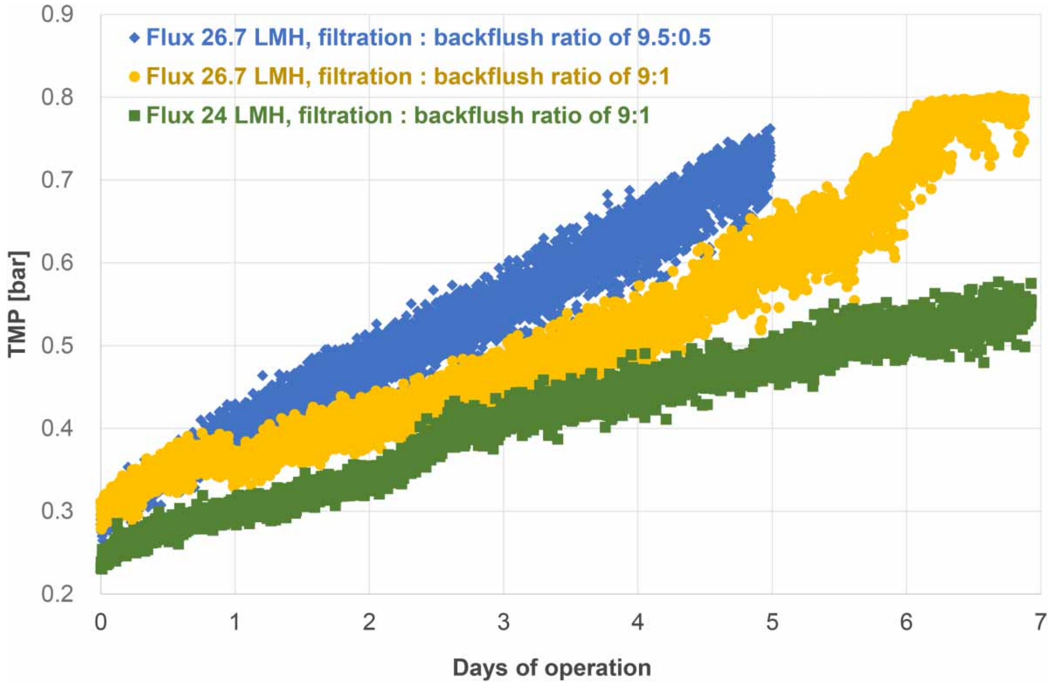

Figure 3 | TMP increase across varied filtration-to-backflush time ratios and filtration fluxes.

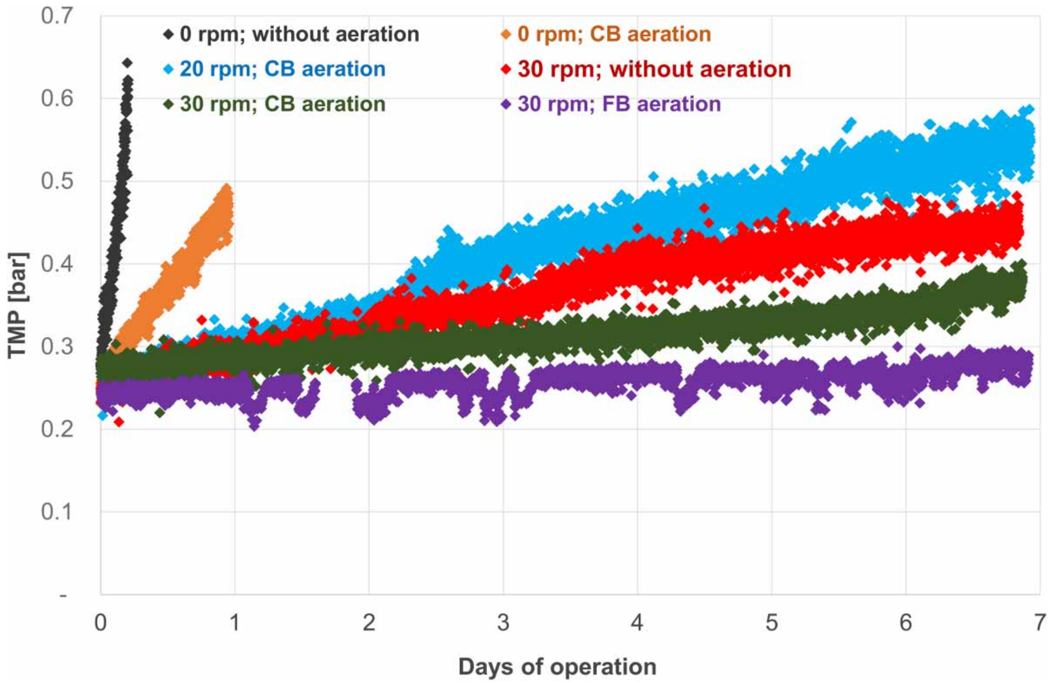

Figure 4 | TMP increase across varied aeration strategies and membrane rotational speeds (Mahdariza *et al.* 2024).

after the implementation of membrane rotation, the rise of TMP was effectively controlled even in scenarios without any aeration.

A number of studies have highlighted the enhanced physical cleaning benefits of CB aeration. These include studies by Judd (2005), Phattaranawik *et al.* (2007), Braak *et al.* (2017), and Zhao *et al.* (2021). Furthermore, a study conducted by

Jones (2017) demonstrated that the rotational mechanisms in a rotating MBR system contributed to a mere 12% of fouling prevention by removing the cake, with the majority of the removal achieved through air scouring. However, the findings from this study revealed no substantial differences in the increase of TMP among the various aeration strategies when membrane rotation was implemented. This indicates that the efficacy of membrane cleaning and fouling prevention may not be significantly influenced by the type of aeration employed as assumed. This thereby emphasizes the pivotal role of membrane rotation in maintaining optimal membrane performance. In addition to facilitating oxygen transfer, membrane rotation has been demonstrated to increase shear force, thereby limiting the build-up of a cake layer on the surface of the membrane. This finding is consistent with previous research on this specific rotating HF membrane module (Mahdariza *et al.* 2022, 2023).

3.4. MC strategy

Furthermore, the influence of MC on TMP reduction was inspected through experiments employing three different concentrations of NaOCl solution while maintaining the solution temperature between 30 and 38 °C. In each cleaning cycle, a 5 L volume of NaOCl solution was introduced to the membrane module four times, each followed by a 5-min soaking period.

Table 2 demonstrates that increasing the concentration of NaOCl did not result in a proportional decrease in TMP within the CIP approach. In contrast, the CIA approach demonstrated a direct correlation between increased NaOCl concentration and TMP reduction, highlighting its effectiveness. It is important to note the variation in initial TMP values prior to MC in different experimental setups. Despite the observed variations, the data obtained suggest that the CIA method is more effective in reducing TMP when compared to the CIP method.

This finding is consistent with the results from Brepols *et al.* (2008), which demonstrated that CIA achieved twice the permeability recovery compared to CIP with the same NaOCl dosage. However, it is noteworthy that the overall CIA process in this pilot plant required an additional hour compared to CIP, which was attributed to the time necessary for emptying and refilling the tank. Therefore, the CIP method is considered to be sufficiently effective for routine weekly MC.

3.5. Further experiment without aeration

Based on these results, a longer period of the experiment was conducted without aeration and relying solely on membrane rotation to increase the shear force. The pilot plant was successfully operated for 48 days as shown in Figure 5. In addition, the pilot plant was operated without any chemical cleaning for 2 weeks during the second experiment of this phase. This finding demonstrates the potential for energy savings by avoiding the need to increase aeration and potentially eliminating it entirely without compromising filtrate quality.

In terms of MC, the pilot plant was effectively operated with four times CIP and one time CIA over the course of this period. An operational pause on the 26th day, necessitated by pump repairs at the WWTP, briefly halted inflow to the MBR pilot plant. As seasonal temperatures began to fall, leading to cooler wastewater, there was a noticeable acceleration in the increase of the TMP after the 28th day of operation. The experiment showed that a higher concentration of NaOCl for CIP was necessary due to this condition. By the end of the experiment, TMP levels had risen to over 0.6 bar. This result emphasizes the need for increased NaOCl concentrations and more frequent MCs during colder months, which is particularly important for operations without aeration.

3.6. The impact of sludge temperature on membrane fouling

Several studies have found a correlation between decreasing temperatures and increased membrane fouling. This is attributed to the enhanced release of soluble microbial products and extracellular polymeric substances by filamentous bacteria (van

Table 2 | TMP before and after MC (Mahdariza *et al.* 2024)

	CIA			CIP		
NaOCl solution concentration (ppm)	**TMP before cleaning (bar)**	**TMP after cleaning (bar)**	**TMP reduction (bar)**	**TMP before cleaning (bar)**	**TMP after cleaning (bar)**	**TMP reduction (bar)**
250	0.58	0.32	0.26	0.55	0.36	0.19
500	0.56	0.30	0.26	0.54	0.41	0.13
1,000	0.69	0.33	0.36	0.37	0.30	0.07

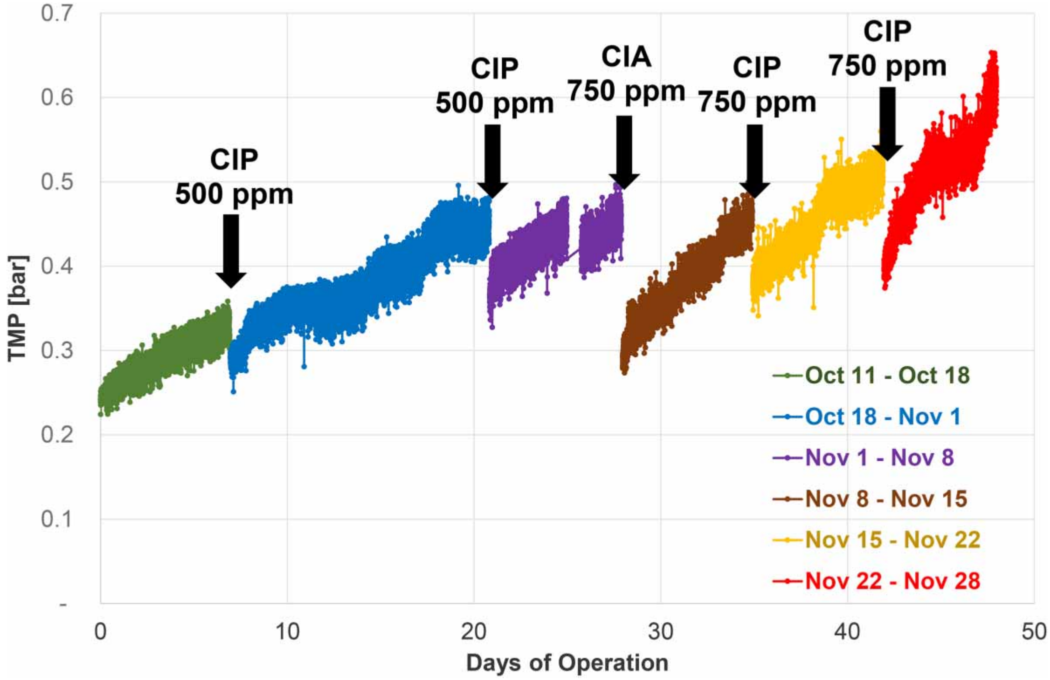

Figure 5 | TMP increase for 48 days of operation with membrane rotation and without aeration.

den Brink *et al.* 2011; Ma *et al.* 2013; Iorhemen *et al.* 2016). Therefore, temperature differentials are considered a significant factor that could either exacerbate or alleviate fouling during filtration and backwash operations. To investigate this hypothesis, the study repeated two experiments under varying sludge temperatures caused by seasonal changes. Figure 6 illustrates the comparison of these experiments, demonstrating the effect of temperature on TMP increase.

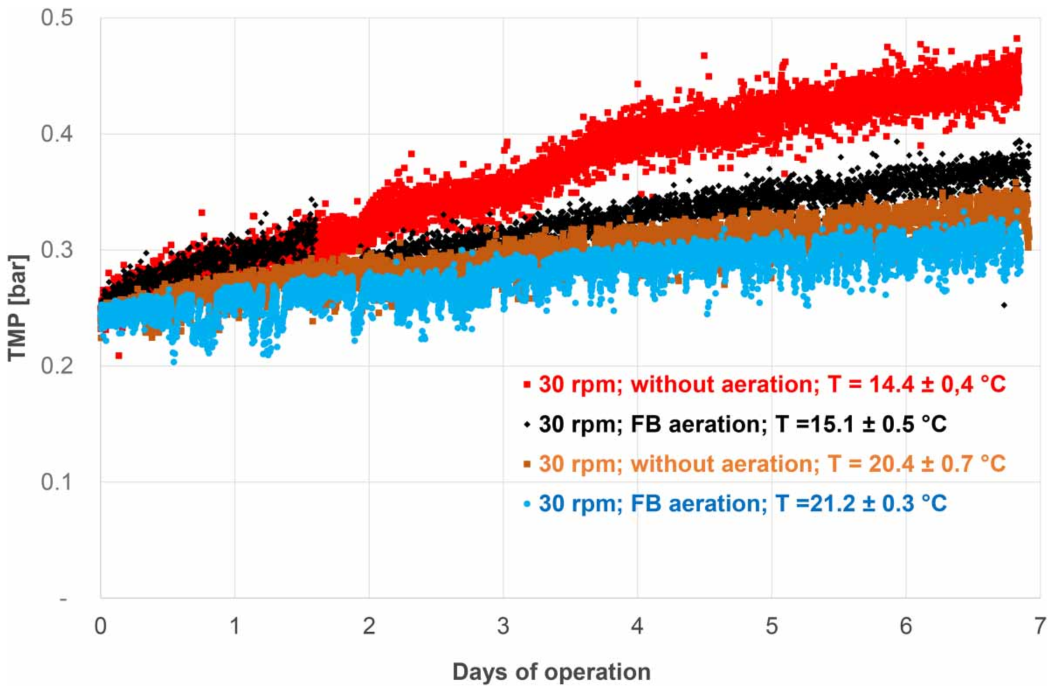

Figure 6 | TMP increase for different sludge temperature.

This outcome demonstrates that experiments conducted with sludge at a temperature 6 °C lower resulted in a faster increase in TMP. Hence, for this specific rotating membrane module configuration, it is not recommended to use a configuration without aeration during colder seasons. To overcome the challenges posed by lower temperatures, it is suggested to adopt one or more alternative strategies. Itokawa *et al.* (2008) recommended doubling the frequency of MC in colder months compared to summer. Other strategies, such as the use of aeration systems, reducing operational flux, and applying higher concentrations of NaOCl for MC, can also significantly mitigate fouling rates and ensure optimal membrane system performance during colder months.

4. CONCLUSIONS

This study evaluated the performance of a pilot plant MBR system utilizing a rotating HF membrane module by measuring the increase in TMP and the quality of the filtrate during the filtration operation. The operational variables of filtration flux, filtration-to-backflush time ratio, aeration strategies, and membrane rotational speeds were found to exert an influence on the dynamics of TMP during membrane filtration. Furthermore, two distinct methodologies for conducting MC were employed, and their efficacy in reducing TMP was evaluated. The most significant findings of this study are as follows:

(a) Based on the initial phase of the experimental series, the optimal configuration for the pilot plant to operate for 7 days of filtration was a flux of 24 LMH and a filtration-to-backflush time ratio of 9:1 min. The pilot plant also demonstrated the capacity to operate at elevated filtration flux; however, it is not recommended for extended periods of operation.
(b) The pilot plant exhibited the ability to operate and achieve the desired level of TMP increase through membrane module rotation even in the absence of aeration. This was corroborated by a subsequent extended period of operation utilizing this configuration. The results indicated that membrane rotation had a more pronounced effect on the control of fouling than the type of aeration employed.
(c) Both FB and CB aerations performed in the same manner for the TMP increase behaviour during the experiments. This suggests that FB aeration can be used to enhance oxygen transfer without compromising fouling mitigation and should the membrane module be integrated as a submerged MBR system into an existing aeration tank of a CAS system.
(d) Temperature effects on fouling dynamics are correlated with an accelerated TMP increase at lower temperatures. Consequently, it is recommended that MC protocols and operating strategies be adjusted during colder seasons.

Further research could be directed towards optimizing the operating parameters, such as varying the membrane rotational speeds and applying relaxation, to improve the performance of this rotating HF MBR module for its application in wastewater treatment.

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DATA AVAILABILITY STATEMENT

All relevant data are included in the paper or its Supplementary Information.

CONFLICT OF INTEREST

The authors declare there is no conflict.

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