Separation and Purification Technology 372 (2025) 133507

Contents lists available at ScienceDirect

Separation and Purification Technology

journal homepage: www.elsevier.com/locate/seppur

Assessing modified fouling index of ultrafiltration process in urban sewage treatment

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ARTICLE INFO

Editor: V. Tarabara

Keywords:
Ultrafiltration
Sewage
Municipal wastewater treatment plant
Modified fouling index

ABSTRACT

Membrane fouling remains a significant challenge in the ultrafiltration (UF) process, restricting the widespread application of UF membranes. Despite extensive research, more intuitive early warnings for membrane fouling and predictions of operating trends remain scarce. This study investigates the application of the modified fouling index (MFI) in the UF process for urban sewage treatment. The changing trend of transmembrane pressure difference in the UF process is consistent with the measured MFI results, and MFI also has a significant correlation with influent turbidity. This predictive capacity offers practical value for industrial process optimization, allowing operators to anticipate fouling risks and adjust pretreatment strategies before operational cycles commence. Key water quality parameters, including chemical oxygen demand (COD), total organic carbon, turbidity, MFI, ultraviolet absorbance at 254 nm, and three-dimensional fluorescence, were systematically analyzed. After treatment by the UF membrane, the effluent COD and turbidity were less than 30 mg/L and 1 NTU, respectively, meeting the Class IV surface water standard. Furthermore, the tested MFI trend aligns closely with theoretically calculated fouling index values, confirming that MFI can serve as a predictive indicator of membrane fouling potential in full-scale operations. These findings underscore the MFI's significance as a robust parameter for influent water quality evaluation in UF systems. To enhance process reliability, we propose integrating real-time MFI monitoring into control strategies to dynamically optimize pretreatment protocols. This approach offers critical operational guidance for improving the long-term hydraulic stability and fouling mitigation efficacy of UF in municipal wastewater treatment applications.

1. Introduction

Addressing the issue of water scarcity and demand for safe water has intensified in response to the rapid development of the economy and society [1–3]. Treating and reusing wastewater is one of the key approaches to enhancing water management and alleviating water stress [4,5]. Enhancing the safety and quality of effluent from municipal wastewater treatment plants (MWTPs) is therefore of critical importance [6,7]. Currently, most wastewater treatment concludes with secondary treatment, where effluent is discharged into rivers or repurposed as industrial water. The inadequate treatment of discharge effluent poses significant environmental risks, particularly to aquatic ecosystems and downstream drinking water facilities [8,9]. To mitigate these risks, advanced treatment processes have been integrated to further remove suspended solids, pollutants, bacteria, and chromaticity, thereby ensuring the safety and quality of treated wastewater [10,11].

The membrane separation technique has attracted significant attention due to its high efficiency in reducing sewage turbidity and removing organic matter without secondary pollution to the environment [12,13], UF advanced treatment technology, as tertiary treatment in a water reclamation plant, plays a significant role in the production process [14,15]. However, membrane fouling remains a significant challenge, limiting the economic viability of the UF process in wastewater treatment [16,17]. Extensive research has been conducted using humic acids and sodium alginate as model foulants, which are widely utilized in laboratory studies to investigate UF membrane fouling

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https://doi.org/10.1016/j.seppur.2025.133507
Received 19 March 2025; Received in revised form 30 April 2025; Accepted 10 May 2025
Available online 11 May 2025
1383-5866/

Table 1
Properties of UF membrane.

Manufacturer	Types	Membrane area/m^2	Average pore diameter/nm	Pressure types	Technologies	inlet pressure/ kPa	operating temperature/°C
A	PVDF	40	100	EP	NIPS	<300	<45
B	PVDF	50	100	EP	TIPS	<300	<40

characteristics [18–20]. Beyond standalone UF operation, hybrid treatment processes, such as the integration of flocculation with UF, have been shown to enhance effluent quality [21,22]. However, in practical applications, membrane fouling behavior varies due to differences in water quality and the specific treatment processes employed in MWTPs. Several fouling prediction tools are available to assess the fouling propensity of feedwater, including turbidity [23], silt density index (SDI) [24], and membrane fouling index (FI) [25–27]. Despite their significance, comprehensive evaluations of these fouling indices remain scarce. The SDI serves as an industry-standard metric to assess the fouling propensity of suspended/colloidal substances in membrane systems. Manufacturers commonly incorporate SDI as a key criterion alongside physicochemical parameters in design specifications and performance warranties. The SDI test is known to suffer from poor reproducibility and accuracy due to inherent limitations such as inconsistent membrane properties (e.g., pore size, porosity, hydrophilicity), variable testing conditions (e.g., temperature fluctuations where $\Delta T = 1\ ^\circ C$ alters SDI by 0.13), and operational artifacts like air bubbles or operator errors, all of which frequently lead to disputes over results [28,29]. To address these challenges, the Modified Fouling Index (MFI) has been developed as a more reliable and accurate alternative, which mitigates the aforementioned errors through standardized corrections and improved measurement methodologies, thereby providing a robust indicator for predicting membrane fouling tendencies in water treatment systems [28,30]. There are few reports on the application of MFI in guiding practical production. Mohanad et al. discussed the application and effectiveness of the MFI-UF method in predicting the particulate fouling rate in RO plants [31]. MFIs were measured to evaluate the fouling potential of the feed water with size fractionation [32].

This study investigates the correlations between MFI and turbidity, as well as between MFI and FI, and aims to provide insights into the assessment of UF treatment loads and to guide the operation optimization in wastewater treatment. The “Biological filter – Ultrafiltration” system using MWTP is employed. In this system, the effluent from the biological filter serves as the feedwater for the UF process, and the impact of the UF membrane on sewage quality is examined. Meanwhile, the UF membrane operates at a constant flux while monitoring the influent pressure, permeate pressure, and concentrate pressure. To comprehensively assess membrane performance, essential metrics for water quality assessment encompassing total organic carbon (TOC), chemical oxygen demand (COD), turbidity, MFI, ultraviolet absorbance at 254 nm (UV_{254}), and excitation-emission matrices (EEM) are analyzed. The MFI results provide a discussion to evaluate the effectiveness of UF in improving sewage quality and provide a scientific reference for optimizing UF technologies in municipal wastewater treatment.

2. Materials and methods

2.1. Chemical and materials

The UF membranes used in this study were supplied by commercial manufacturers A and B (product details cannot be revealed due to the confidential agreement), to evaluate the robustness of the MFI as a predictive tool across membranes with differing manufacturing methods and physical characteristics. Both product A and product B are PVDF (polyvinylidene fluoride) external pressure (EP) type UF membranes with an average pore size of 100 nm, the maximum inlet water pressure

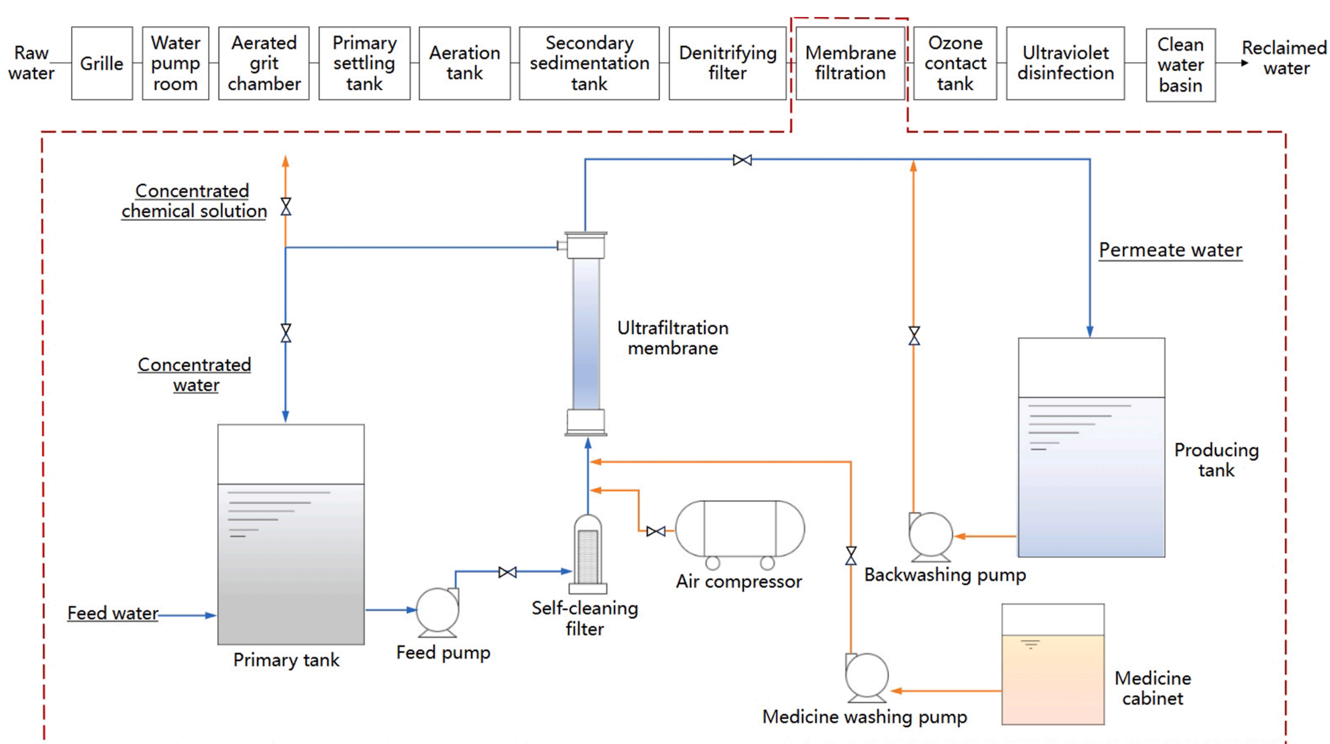

Fig. 1. Process of mobile UF container.

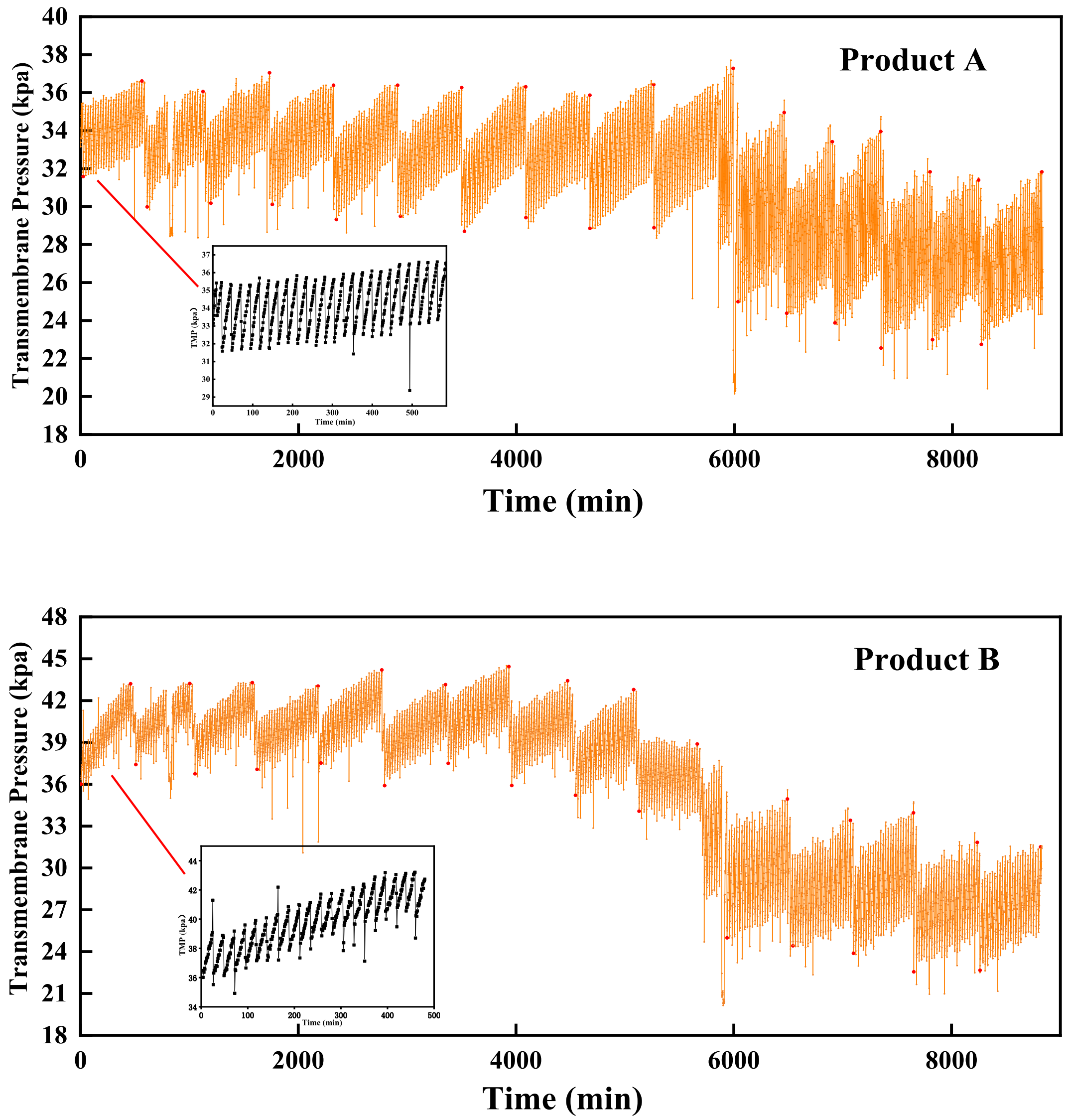

Fig. 2. Transmembrane pressure of manufacturers A and B.

for both is 300 kPa. The effective membrane area of Product A is 40 m^2, and it is fabricated by the nonsolvent-induced phase separation (NIPS) method, the operating water temperature requirement is less than 45 ℃. The effective membrane area of Product B is 50 m^2, and it is manufactured by the thermally induced phase separation (TIPS) method, the operating water temperature requirement is less than 40 ℃. The detailed membrane characteristics are presented in Table 1. Sodium hydroxide (10 wt%) was purchased from the SINOPHARM group, China.

2.2. UF process and raw water

The UF testing apparatus is illustrated in Fig. 1. The effluent from the biofilter is first passed through a self-cleaning filter (200-μm precision) before feeding into the UF membrane column. The denitrifying filter produced water from a MWTP in Beijing was selected as the feedwater for the UF process. The study evaluated the operational performance of UF membranes supplied by Manufacturer A, maintaining an operating flux of 50 L/(m^2·h). To mitigate membrane fouling and ensure stable performance, the UF membranes underwent air–water backwash (AWB) every 24 min. During this period, it was washed with water for 40 s, washed with a combination of air and water for 40 s, and emptied for 40 s, and chemical-enhanced backwash (CEB) cleaning every 25 AWB filtration cycles, during CEB treatment, a 1500 mg/L concentration of NaClO was applied as the cleaning agent for 63 min

2.3. Analytical methods

Analytical instrumentation comprised a SHIMADZU, TOC-VCPH for TOC quantification and a Hitachi U-2900 system for UV–vis spectral analysis, both manufactured in Japan. MFI tester (SDI Attache, Netherlands) [33], turbidimeter analyzer (2100Q, Hitachi, Japan) and a three-dimensional fluorescence excitation-emission matrices analyzer (3-D-EEM, F-7000, Hitachi, Japan) were utilized to characterize the UF membrane properties and analyze the distribution of organic constituents. While there is no universal standard for FI calculation in ultrafiltration systems, the method provides a robust, peer-reviewed framework that aligns with common practices in the field. The membrane FI is calculated as:

$$FI = \frac{\frac{\Delta p_s}{\Delta p_0} - 1}{V}$$

where ΔP_0 (kPa)is the initial transmembrane pressure (TMP) within a CEB cycle, ΔP_s (kPa) is the final TMP, and V (L·m^{-2}) represents the amount of water passing through the unit membrane area within one CEB cycle.

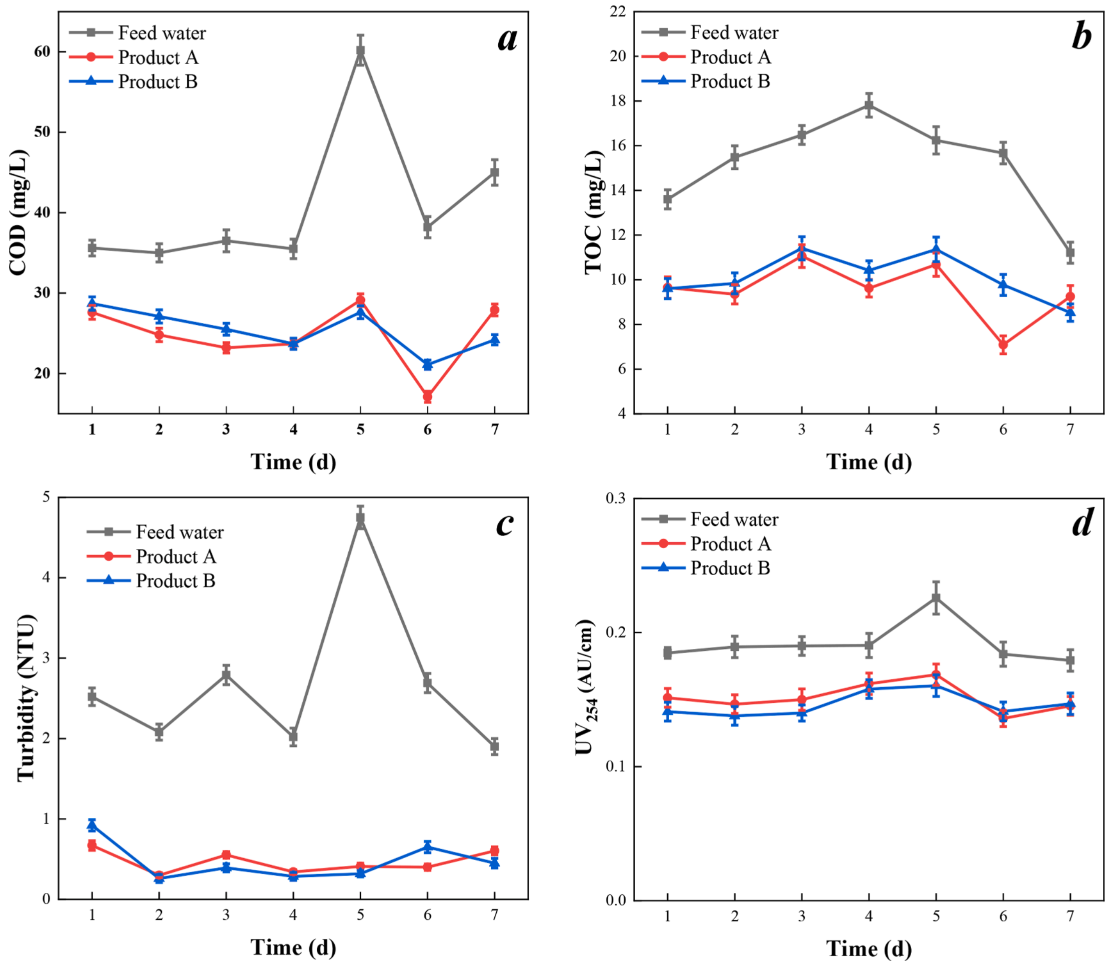

Fig. 3. The water quality of UF membrane inlet and outlet: (a) COD analysis; (b) TOC analysis; (c) turbidity analysis; (d) UV $_{254}$ analysis.

3. Results and discussion

3.1. Pressure analysis of UF membrane in the treatment of effluent from biological filter

The TMP of the UF membrane is defined as the pressure difference across the membrane, which refers to the half-sum of the inlet and outlet water pressure minus the permeate pressure. TMP is a key parameter for assessing the operational performance and fouling behavior of the UF membrane process (Not including the cleaning process). Fig. 2 illustrates the variations in TMP over time, demonstrating a gradual increase as membrane fouling progresses. Take the seventh CEB cycle as an example. During a single filtration cycle, following gas–water cleaning, the TMP of Product A was restored to 28.93 kPa, and that of Product B returned to 37.84 kPa, after initial increases from 28.71 kPa to 33.58 kPa and from 37.50 kPa to 41.88 kPa, respectively. The application of AWB effectively mitigated membrane fouling by reducing the cake layer and gel layer [34]. Furthermore, during a single filtration cycle incorporating CEB, the TMP increase rate of product A was 7.6 kPa, and product B was 6.93 kPa. After CEB, the TMP of Product A decreased from 36.31 kPa to 29.42 kPa, while that of Product B reduced from 44.43 kPa to 35.91 kPa, which suggested that CEB treatment successfully restored TMP, primarily by removing the cake layer, gel layer, and pore blockages, thereby enhancing membrane performance and extending operational stability. The operational performance exhibited a slowly rising trend followed by a gradual decline, which can be attributed to fluctuations in influent water quality characteristics.

3.2. Analysis of effluent quality in UF membrane operation processes

Suspended matter and partially dissolved organic compounds in water can be effectively removed by UF membranes through physical retention and adsorption processes. To evaluate the impact of the UF membrane on water quality, both the feedwater and effluent from the UF membrane were analyzed, as shown in Fig. 3. The water quality of the biological filter effluent exhibited fluctuations, reflecting variations in the biological treatment process. For the COD parameter (Fig. 3a), significant fluctuations were observed in the influent COD (peaking at 60.2 mg/L). Both membrane systems achieved effective organic removal, with the effluent COD consistently maintained below 29.12 mg/L even under high organic shock loading conditions (Day 5). For the TOC parameter (Fig. 3b), the influent concentration peaked at 17.81 mg/L. Following UF treatment, effluent TOC was consistently maintained below 11.41 mg/L. Product A demonstrated superior overall removal efficiency compared to Product B, which may be attributed to differences in membrane pore size distribution or surface hydrophilic modification characteristics, suggesting the UF membrane treatment process is effective in organic removal and water quality improvement. The feedwater had turbidity levels (Fig. 3c) of 4.75 NTU (nephelometric turbidity units) and the effluent was reduced to under 0.92 NTU after treatment with a UF membrane, which suggests that the UF membrane effectively removed pollutants through the interception process, resulting in a significant decrease in turbidity and an improvement in water clarity. In addition, UV_{254} is an optical technology that utilizes ultraviolet light at a wavelength of 254 nm and can detect the content of humus macromolecular organics and aromatic compounds containing

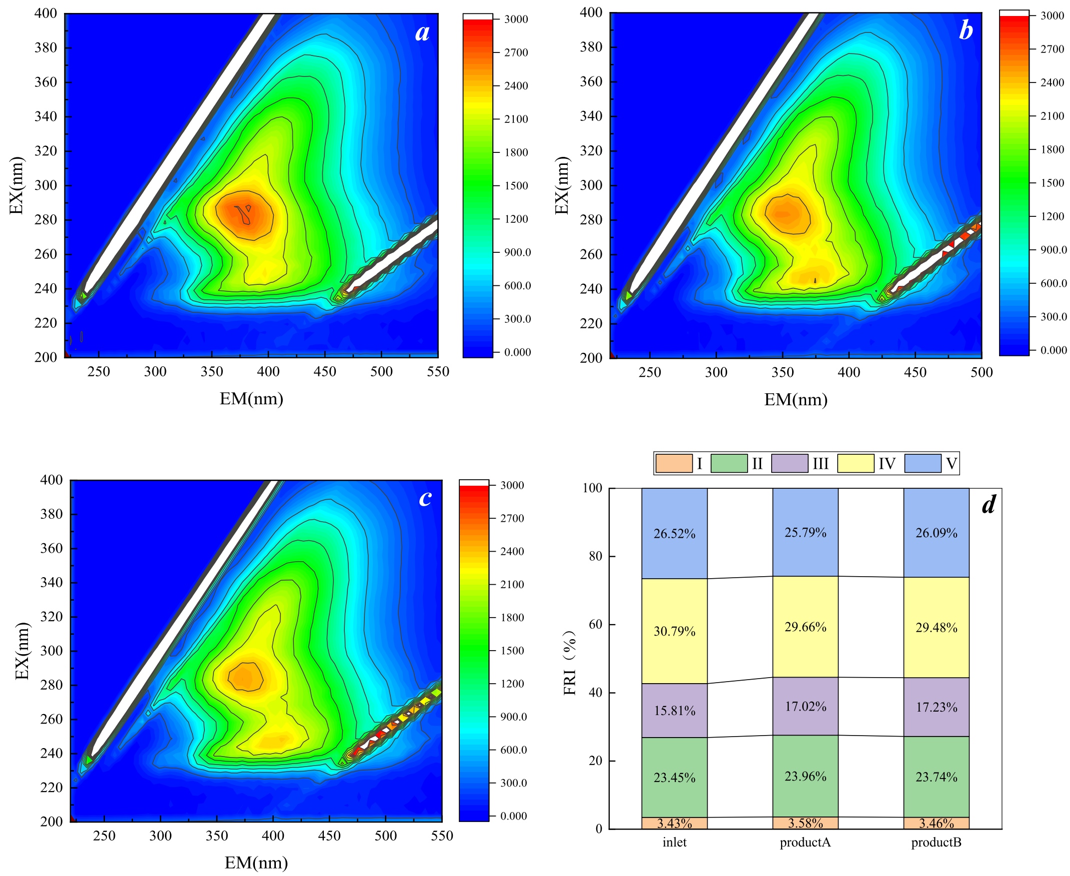

Fig. 4. The three-dimensional fluorescence of the UF membrane inlet and outlet. (a) Feedwater; (b) Product A; (c) Product B; (d) The proportion of each component in EEM.

C=C double bond and C=O double bond in water. As shown in Fig. 3**d**, the UV_{254} of the feedwater from biological filtration was 0.18 AU/cm, dropping to 0.15 AU/cm after UF membrane treatment, indicating a reduction in organic pollutants. The treated water quality consistently met Class IV surface water quality standards (GB 3838–2002), demonstrating full compliance with effluent requirements for membrane-based processes in water reclamation plants. COD, turbidity, and UV $_{254}$ exhibited fluctuating trends, all reaching their peak values on Day 5. TOC concentration gradually increased, peaked on Day 4, and subsequently declined.

In the EEM spectra, fluorescence peaks of extracellular polymeric substances (EPS) were assigned as the following [35]: Region I (220–250/280–330 nm, tyrosine-like proteins), II (220–250/330–380 nm, tryptophan-like proteins), III (220–250/380–550 nm, fulvic acid-like substances), IV (250–280/280–380 nm, microbial byproducts), and V (250–400/380–550 nm, humic acid-like compounds). Validated through MATLAB-based algorithms, this standardized method enables semi-quantitative organic matter characterization and has become a benchmark in environmental research. As shown in Fig. 4, the fluorescence peak (excitation/emission wavelengths = 365/280) was primarily associated with microbial byproducts in the water, following UF membrane treatment, the fluorescence intensity of soluble microbial products was reduced from 2669(Fig. 4**a**) a.u. to 2580 a.u. (Fig. 4**b**) and 2467 a.u. (Fig. 4**c**), indicating a reduction in the concentration of soluble microbial products. This suggests that the UF membranes effectively removed soluble microbial products through the interception process, which could cause gel layer contamination on the membrane surface. Furthermore, the gel layer contamination can be minimized by the AWB process, demonstrating that membrane fouling could be mitigated by controlling microbial metabolites in the influent, thus improving the overall performance and robustness of the UF membrane. As shown in Fig. 4**d**, the microbial byproduct content in UF effluent decreased compared to the feedwater, while fulvic acid-like substances slightly increased. The overall proportional distribution of components remained similar, attributed to the UF membrane's larger molecular weight cutoff, which balances the retention of macromolecules (e.g., proteins) and penetration of small hydrophilic substances.

3.3. Analysis of MFI during the operation of the UF membrane

MFI was employed to evaluate variations in the quality of feedwater for the UF process, providing a novel monitoring parameter for UF membrane technology. Fig. 5**a** presents the variations of MFI in both feedwater and UF effluent. It was observed that the MFI of the biofilter effluent was up to 581.94 s/L^2, while the MFI of the effluent after UF treatment was significantly reduced to below 12.83 s/L^2. Turbidity is an important factor affecting the operation of the membrane. High turbidity levels correlate with increased particulate loading, which promotes the formation of a dense cake layer on the membrane surface. This layer restricts pore accessibility, elevates TMP, and accelerates fouling. For instance, the UF in treating the surface water with high turbidity could result in a reduction in water production due to the severe membrane fouling [36]. Reducing turbidity through pretreatment has been proven to significantly decrease membrane fouling [37,38]. However, conventional turbidity testing can only quantify the amount of suspended solids, and may not fully capture the potential for fouling caused by suspended particles, colloids, and partially dissolved organic matter. During the experiment, it was observed that the variation trend of the MFI value was analogous to that of the water quality turbidity change value. Subsequently, a fitting operation was performed on the turbidity and the MFI value. As shown in Fig. 5**b, a** robust linear correlation between MFI and turbidity was established, with a correlation

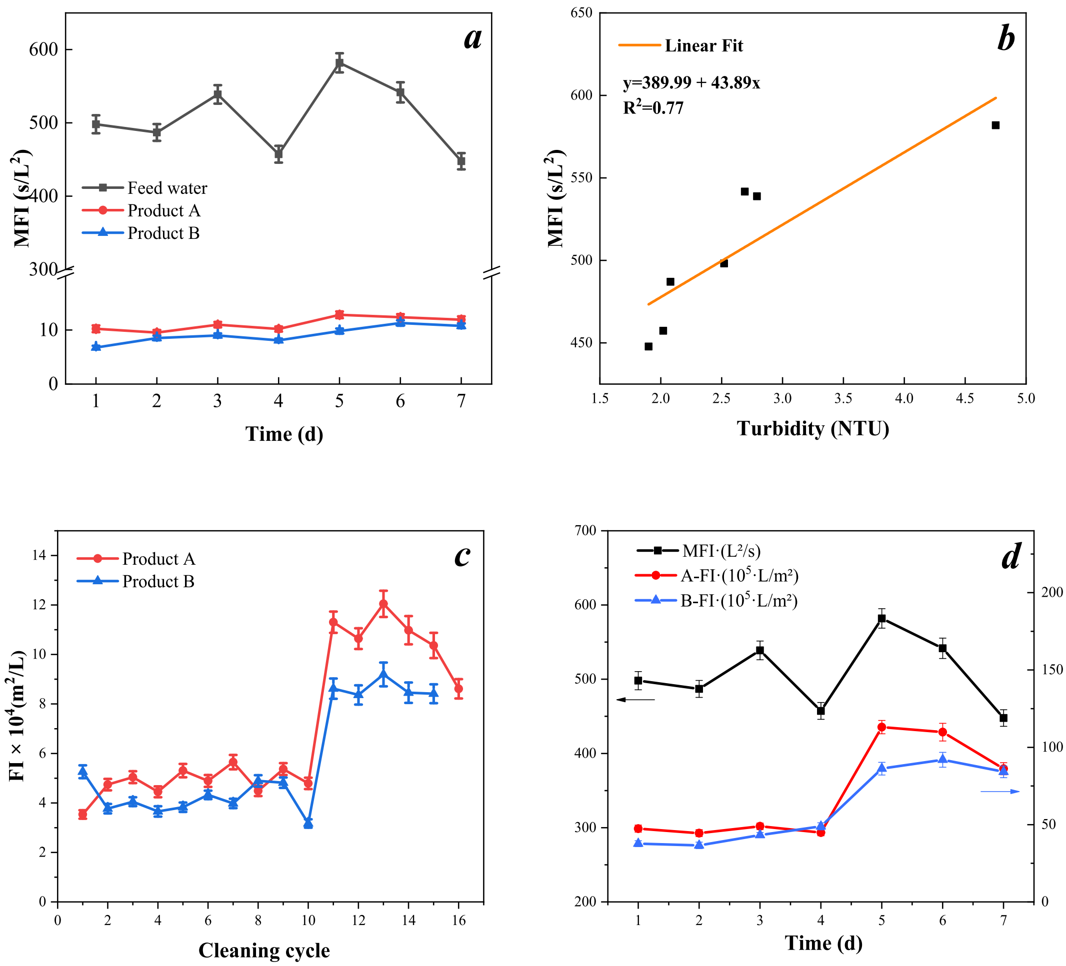

Fig. 5. Membrane FI of water inlet and outlet of UF membrane: (a) MFI test value of membrane inlet and outlet; (b) the relation between MFI and turbidity. (c) FI calculated the value of product A and product B; (d) The MFI test value and the FI calculated value corresponding to the cleaning cycle.

coefficient reaching as high as 0.77, validating that MFI effectively captures particulate-related fouling risks, providing a reliable indicator of fouling potential under varying turbidity conditions. Therefore, the MFI value can serve as a crucial parameter for assessing influent water quality in the UF process of MWTP, offering valuable guidance for the operation and management of the UF process, enabling proactive adjustments (e.g., backwash frequency or pretreatment optimization) to mitigate fouling.

The membrane fouling model is also a method that can, to a certain extent, describe the fouling trend during the membrane filtration process. Based on the FI determined by Nguyen et al. [39], the fouling behavior during the UF process is calculated. When the flux remains constant, the membrane FI directly determines the final head loss. The FI value can be obtained through changes in the TMP difference. Fig. 5**(C)** shows the FI values corresponding to each CEB cycle. Although the FI reflects membrane fouling status, following the 10th cleaning cycle, the FI exhibited an abrupt surge, followed by a gradual decline after three subsequent cleaning cycles. This pattern was temporally correlated with the water quality fluctuations observed on Day 5. The FI calculated values of 2–3 cleaning cycles per day were averaged and compared with the measured MFI values. In Fig. 5**(d)**, the FI (units of m^2/L) was converted to a dimensionless constant by multiplication with L/m^2 and normalized by a factor of 10^5 for graphical clarity. The MFI (units of s/L^2) was analogously scaled by L^2/s to generate dimensionless values. It was found that the three trends were similar. Although the Pearson correlation coefficients do not indicate a strong linear relationship, the consistency in trends validates the predictive potential of MFI for membrane fouling. The primary reasons for this discrepancy may lie in the mechanistic differences: MFI is based on the prediction of initial fouling potential, while FI reflects the actual accumulation of TMP during operation. Additionally, short-term fluctuations in water quality (e.g., sudden high-load events on Day 5) may introduce localized deviations. Nevertheless, MFI and FI show strong alignments with synchronized peaks and periodic fluctuations (Fig. 5d). This confirms that MFI can serve as an early warning indicator for FI, providing a critical time window for optimizing pretreatment strategies. Such practical utility is particularly valuable in industrial applications, where proactive fouling mitigation is essential for operational efficiency and cost-effectiveness.

4. Conclusions

The study investigated the effects of UF treatment in wastewater, and the following conclusions were drawn: (1) TMP gradually varies with water quality fluctuations over time. (2) During the municipal wastewater UF process, the COD and turbidity of effluent were consistently below 30 mg/L and 1 NTU, respectively, indicating that the effluent quality met the surface IV class water standard. (3) A robust and statistically significant correlation between MFI values and water turbidity levels has been identified, underscoring the critical role of particulate and colloidal matter in governing membrane fouling dynamics. (4) In industrial membrane systems, maintaining constant water production flux necessitates dynamic adjustment of operating pressure. Membrane fouling triggers pressure compensation to sustain output, causing progressive TMP escalation. This accelerates energy consumption and risks surpassing membrane pressure thresholds, potentially inducing structural failures. Implementing an MFI-based early-warning system becomes critical for risk mitigation. Quantitative assessment of feedwater quality impacts through MFI enables pretreatment optimization, such as controlling turbidity breakthrough in ultrafiltration systems to decelerate TMP rise, prolong chemical cleaning intervals, and reduce operating expenses. By integrating MFI monitoring into process control strategies, operators can proactively mitigate membrane fouling risks and optimize feedwater pre-treatment protocols (e.g., coagulation-flocculation, media filtration, or pH conditioning) to stabilize membrane performance. This approach not only extends membrane lifespan but also reduces energy consumption and downtime, thereby enhancing operational efficiency and cost-effectiveness in large-scale wastewater treatment applications.

CRediT authorship contribution statement

Lian Yang: Conceptualization, Writing – review & editing, Supervision, Resources, Funding acquisition, Methodology, Validation, Formal analysis, Investigation, Writing – original draft. **Guoliang Chen:** Methodology, Validation, Formal analysis, Investigation, Writing – original draft. **Guoliang Liu:** Methodology, Validation, Formal analysis, Investigation, Writing – original draft. **Lijun Zhao:** Data curation, Formal analysis. **Hao Wang:** Data curation, Formal analysis. **Jiang Chang:** Review, Funding acquisition. **Yibin Zhou:** Data curation, Formal analysis. **Lei Ge:** Review & editing, Software, Data curation, Visualization. **Quan-fu An:** Review & editing, Software, Data curation, Visualization

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgement

This study greatly appreciates the support from Beijing Engineering Research Center for Wastewater Reuse research and development fund, China.

Data availability

Data will be made available on request.

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