Chemical Papers
https://doi.org/10.1007/s11696-026-04847-w

ORIGINAL PAPER

Enhanced treatment of high-COD MDF wastewater using hybrid coagulation-membrane distillation process: Coagulation efficiency and membrane performance

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Received: 19 November 2024 / Accepted: 24 March 2026

Abstract

The treatment of medium density fiberboard (MDF) wastewater presents a significant challenge due to its complex composition and elevated temperature, which limit the effectiveness of conventional treatment methods. This study investigates the applicability of a hybrid coagulation–membrane distillation (MD) process for the treatment of high-strength MDF wastewater. Poly-aluminum chloride hydroxide (PACS) was employed as a pretreatment to reduce fouling potential, followed by MD using a hydrophobic polytetrafluoroethylene (PTFE) membrane operated at different feed temperatures (50–80 °C). The optimal operating condition was obtained at a feed temperature of 50 °C, where the PTFE membrane exhibited a stable flux of 9.45 L/m^2.h and achieved a COD removal efficiency of 95.02%, together with over 95% reduction of conductivity, turbidity, color, and total suspended solids. Increasing feed temperature enhanced membrane flux but led to membrane wetting and deterioration of permeate quality. Membrane wetting was mainly attributed to elevated operating temperature, organic fouling, and inorganic scaling, as confirmed by contact angle measurements, scanning electron microscopy-energy dispersive spectroscopy (SEM–EDS), and attenuated total reflectance Fourier transform infrared spectroscopy (ATR–FTIR) analyses. The results demonstrate that MD, when combined with effective pretreatment, is a promising and energy-efficient approach for MDF wastewater treatment, provided that operating conditions are carefully optimized to minimize membrane wetting.

Keywords MDF wastewater · Membrane distillation · Membrane wetting · Coagulation pretreatment · PACS · PTFE membrane

Introduction

The expanding scope of industrial activities, technological advancements, and evolving consumer preferences has led to a continuous increase in the global production of wood-based panels, particularly MDF. Consequently, MDF production has increased significantly over the past decade, intensifying concerns related to water consumption, wastewater generation, and environmental pollution. (Badve et al. 2013; Balcik-Canbolat et al. 2016). The MDF manufacturing process is characterized by intensive water consumption and the generation of wastewater with high pollutant loads, mainly originating from chip washing and steam pretreatment stages. This wastewater typically contains high concentrations of suspended solids, chemical oxygen demand (COD), turbidity, and color, and may cause significant environmental impacts if discharged without adequate treatment (Navas-Cárdenas et al. 2022; Khonakdar Dazmiri et al. 2019; Amat et al. 2005; Kaczala et al. 2010).

Untreated discharge of wastewater may result in significant harm to the aquatic environments. The MDF wastewater exhibits a significant concentration of pollutants, as well as the presence of resins and fibers. Additionally, the temperature of the wastewater exceeds 40 °C. This creates

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Published online: 11 April 2026

unique solid/liquid separation challenges if the wastewater is allowed to stand (Navas-Cárdenas et al. 2022; Khonakdar Dazmiri et al. 2019; Galehdar et al. 2009; Song et al. 2008). The effluent is also contaminated with highly harmful chemicals as a result of the wood preservatives that are employed to combat fungi and insects. Consequently, MDF wastewater is not permitted to be discharged into the sewerage system prior to treatment (Munoz et al. 2014).

Several techniques have been used to treat industrial wastewaters with high pollutant concentrations. The conventional and easily applicable methods are coagulation, flocculation, and chemical precipitation, which involve the use of large quantities of coagulants in the effluent (De los Santos Ramos et al. 2009; Renault et al. 2009; Zhang et al. 1999; Ghorbannezhad et al. 2016). However, this technique has drawbacks including inadequate effectiveness, high chemical expenses, and the generation of a large amount of sludge. Although coagulation–flocculation is widely applied as a primary or pretreatment method, it alone is generally insufficient to achieve high-quality effluent suitable for discharge or reuse, particularly when stringent effluent standards are imposed. Activated carbon and ion exchange resins are alternate treatment options; nevertheless, they might have regeneration issues and quick clogging or blocking in highly polluted industrial wastewaters (Quesada et al. 2020; Kansara et al. 2016). Among other treatment methods, biological treatment may lack effectiveness owing to operational challenges, whereas advanced oxidation processes (AOP) may pose cost-related issues (Balcik-Canbolat et al. 2016; Bay et al. 2021; Leiviskä et al. 2009). Furthermore, membranes, which have recently emerged as the dominant technology in industrial treatment applications, may encounter issues related to clogging and operational costs. MD is a third generation treatment technology that has been developed for desalination purposes and has recently also been used in the treatment of industrial wastewater. It is a distinct type of membrane process that effectively removes ions, particles, and non-volatile materials (Turk et al. 2024; Türk et al. 2022a; Zoungrana et al. 2020; Souhaimi and Matsuura 2011). While MD may accomplish high-quality water production, the wettability of the membrane and the expense of heating may impose limitations on this process (Wang and Chung 2015; Tijing et al. 2015; Norman et al. 2008). However, industries that generate waste heat or hot wastewater might benefit from the cost-effectiveness of MD (Ghaffour et al. 2019; Alkhudhiri et al. 2012a; Zarasvand Asadi et al. 2012; Chang et al. 2010). Nevertheless, MD performance is often limited by membrane fouling, scaling, and wetting, especially when treating wastewaters containing high concentrations of suspended solids, colloids, and organic matter. To overcome these limitations, hybrid MD-based treatment systems incorporating appropriate pretreatment steps have been increasingly proposed in the literature (Alkhatib et al. 2021; Türk et al. 2022b).

Despite the increasing interest in MD for the treatment of industrial wastewaters, research focusing specifically on MDF wastewater remains very limited. MDF wastewater is characterized by elevated concentrations of non-volatile organic and inorganic contaminants, together with an inherently elevated discharge temperature, which pose considerable challenges for conventional treatment technologies. However, these same characteristics make MDF wastewater particularly suitable for thermally driven separation processes such as MD. In this context, integrating coagulation as a pretreatment step with MD represents a promising hybrid treatment strategy, as coagulation effectively removes suspended solids, colloidal particles, and high-molecular-weight organic compounds that would otherwise accelerate membrane fouling and wetting during MD operation. By reducing the fouling load of the feed stream, coagulation enhances MD performance, improves permeate quality, and contributes to flux stability. Moreover, the relatively high temperature of freshly discharged MDF wastewater enables the direct utilization of inherent waste heat to drive the MD process, thereby minimizing external energy demand. Therefore, this study systematically investigates a hybrid coagulation–MD process for the treatment of high-strength MDF wastewater under realistic industrial conditions, with a particular focus on pollutant removal efficiency, temperature-dependent membrane flux, fouling behavior, and membrane wetting mechanisms.

Materials and methods

Source and characterization of the feed solution

The wastewater used in this study was collected from an MDF production factory located in Turkey and characterized by pH, conductivity, COD, sulfate, turbidity, color, TSS, and total hardness. The characteristics of the wastewater are presented in Table 1.

Table 1 Characteristics of wastewater used in the study

Parameter	Value
pH	4.61
Conductivity, µS/cm	823
COD, mg/L	58,900
Sulfate, mg/L	362
Turbidity, NTU	19,690
Color, Pt-Co	32,565
TSS, mg/L	16,510
Total Hardness, mg $CaCO_3$/L	720
Temperature, °C	50

Pretreatment procedure

Conventional coagulation–flocculation pretreatment of MDF wastewater was performed using a standard jar test apparatus. PACS was selected as the coagulant due to its high basicity and low sulfate content, which minimizes the contribution of residual sulfate to the treated water. It is widely used as a coagulant in drinking water and wastewater treatment processes. Coagulant dosing was conducted using a PACS stock solution with a concentration of 1.273 g/L.

Jar test experiments were carried out to determine the optimum coagulant dosage and operational conditions. Rapid mixing was applied for 5 min at a velocity gradient of 100 s^{-1}, followed by slow mixing for 25 min at 20 s^{-1} to promote floc formation. Sedimentation was subsequently conducted in beakers for settling times of 30, 60, and 90 min. PACS dosages of 100, 500, 1,000, and 2,500 mg/L were investigated to evaluate coagulation efficiency.

Following sedimentation, the clarified supernatant was subjected to centrifugation to enhance solid–liquid separation. Centrifugation was performed at 3000 rpm for centrifugation times of 2, 3, 4, and 5 min. For each jar test, a working volume of 500 mL was used. The pH of the samples was adjusted to the range of 6–7 prior to coagulation using 1 N NaOH or 1 N H_2SO_4. After the coagulation–flocculation process, 100 mL of supernatant was collected and transferred into two 50 mL Falcon tubes for centrifugation.

MD experimental setup and procedure

The MD experiments were conducted using a lab-scale direct contact membrane distillation (DCMD) setup. Figure 1 illustrates a schematic diagram of the lab-scale DCMD setup, highlighting the membrane module, feed and cooling streams, and the stainless-steel condensation plate responsible for vapor condensation and permeate collection.

A commercial hydrophobic PTFE flat-sheet membrane, supplied by Membrane Solutions (China), was employed in all MD experiments and operated in a DCMD configuration under cross-flow conditions. The detailed physicochemical properties of the membrane are provided in Table 2.

The experimental setup consisted of a wastewater feed tank, a cooling water tank, a custom-modified DCMD module, feed and cooling water pumps, a precision balance, and a data acquisition system. In the DCMD module, the hydrophobic PTFE membrane was positioned over the hot feed chamber, into which the wastewater was circulated using a centrifugal pump. Cooling water was circulated through the upper chamber by a peristaltic pump. The two chambers were separated by a stainless-steel condensation plate with a thickness of 1 mm, which facilitated heat transfer and condensation upon contact with the cooling water.

Water vapor transported through the hydrophobic membrane condensed on the stainless-steel plate and was collected as permeate. The effective membrane area of the DCMD module was 0.015 m^2. The wastewater feed tank had a capacity of 10 L and was constructed from stainless steel. Feed heating was achieved using a water jacket system surrounding the tank. The feed temperature was continuously monitored by a temperature sensor and regulated using a control panel to maintain the desired operating temperature. The heating system automatically deactivated upon reaching the target temperature and reactivated upon temperature drop..

The freshly discharged MDF wastewater had an average temperature of approximately 50 °C. In the MD experiments, the feed temperature was adjusted to 50, 60, 70, and 80 °C to systematically investigate the effect of temperature on membrane flux, permeate quality, and membrane wetting behavior. Although the wastewater inherently contained sufficient thermal energy to directly drive the MD process, controlled temperature adjustment was applied to simulate various operational scenarios and to identify both optimal and limiting operating conditions for the hybrid coagulation–MD process. The cooling water temperature was maintained at 10 °C in all experiments to maximize the vapor pressure gradient across the membrane, thereby enhancing vapor transport and ensuring effective condensation during the MD process. Each experiment was conducted for 2 h, and permeate production was continuously recorded using a precision balance for the calculation of membrane flux.

The hybrid coagulation–MD process was conducted sequentially. First, coagulation–flocculation and solid–liquid separation were applied as a pretreatment step to reduce suspended solids, colloidal matter, and fouling precursors. The clarified supernatant obtained under optimal coagulation conditions was then directly used as the feed solution for the MD experiments. This sequential configuration ensured that the impact of coagulation on MD performance, membrane wetting, and permeate quality could be systematically evaluated.

Performance evaluation and removal efficiency calculation

The removal efficiencies of the coagulation pretreatment and MD processes were calculated to evaluate treatment performance. Removal efficiency was determined based on the change in pollutant concentration before and after treatment using the following equation:

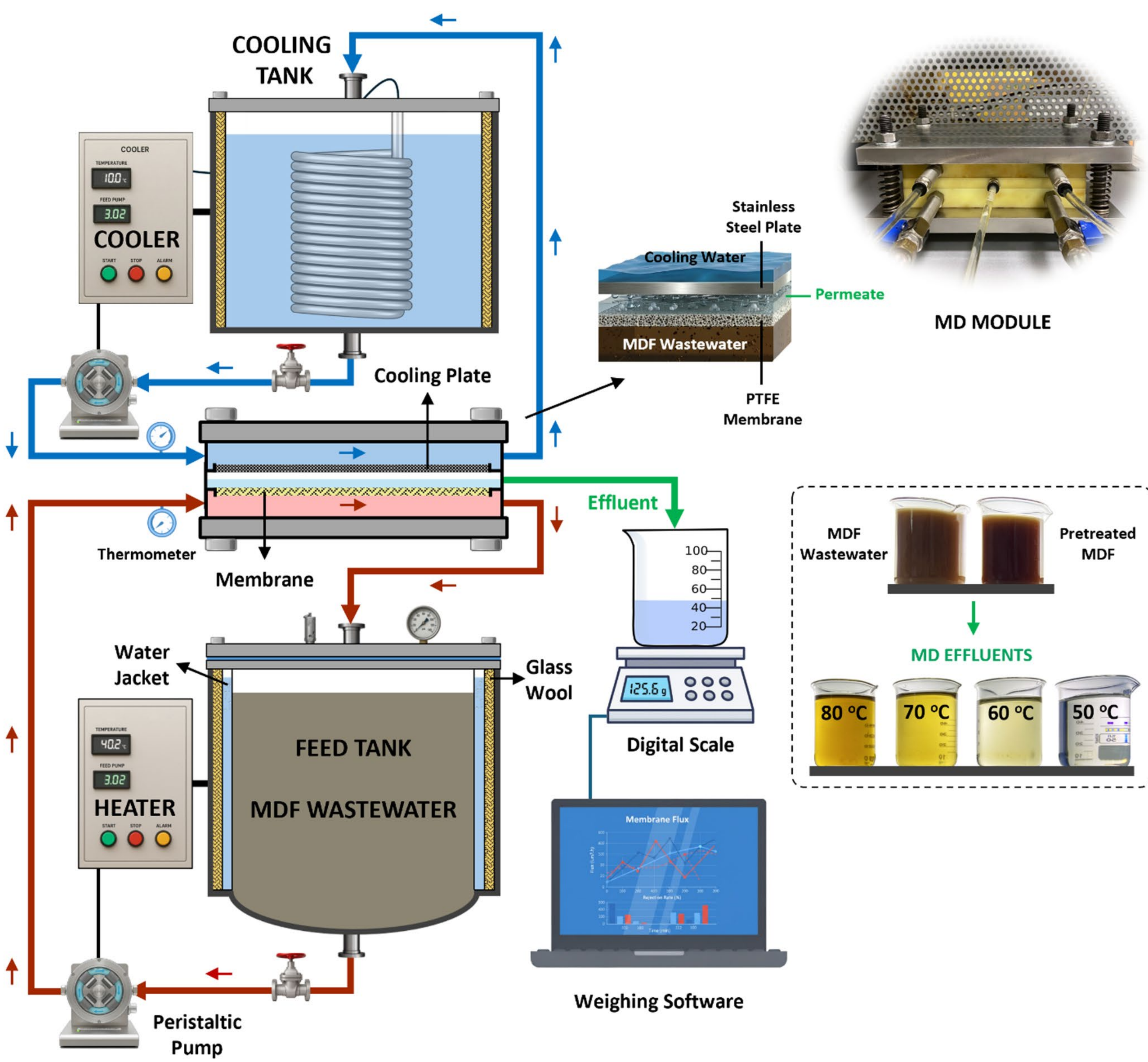

Fig. 1 Schematic diagram of the lab scale MD unit

Table 2 The properties of the membranes used in the study

Membrane material	Pore size (μm)	Thickness (μm)	Flow rate (mL/min/cm^2)	Bubble point (bar)	LEP (bar)	Contact angle (°)
PTFE	0.45	170–220	63–74	0.5-1	4–5	140.49

$$\text{Removal Efficiency }(\%) = \frac{C_o - C_t}{C_o} \times 100$$

where C_o and C_t represent the initial and treated concentrations of the target parameter, respectively.

The membrane flux was calculated to evaluate the performance of the MD process. The flux was determined based on the mass of permeate collected over a specific time interval and the effective membrane area, as expressed in the following equation:

$$J = \frac{\Delta m}{A \times \Delta t}$$

Table 3 Water quality analysis conducted in the study

Analysis	Method	Material
COD	Standard Methods, 5220 C	Closed reflux
Conductivity	Standard Methods, 2510	Conductivity probe
pH	Standard Methods, 4500 H^+	pH probe
Sulfate	Standard Methods, 4500 $SO4^{2-}$	Spectrophotometric
Total hardness	Standard Methods, 2340 C	Titration
TSS	Standard Methods, 2540 D	Filtration setup
Turbidity	Standard Methods, 2130 B	Spectrophotometric

where J is the membrane flux ($L/m^2.h$), Δm is the mass of permeate collected (kg), A is the effective membrane area (m^2), and Δt is the operation time (h).

Analysis

Water quality analyses were conducted to characterize of raw MDF wastewater and the permeate obtained after MD. The specific water quality parameters analyzed are presented in Table 3. These analyses were performed using standard methods to ensure accurate and reliable results.

Results and discussion

Pretreatment performance

The initial characterization of MDF wastewater (Table 1) revealed extremely high pollutant concentrations, with COD reaching 58,900 mg/L and TSS reaching 16,510 mg/L, indicating the presence of a highly polluted and stable colloidal suspension. Such characteristics highlight the necessity of an effective pretreatment step to reduce the fouling potential of the feed solution prior to the MD process. Coagulation–flocculation experiments were conducted using PACS as the coagulant, while the effects of coagulant dosage, settling time, and centrifugation time were systematically investigated. The detailed experimental results obtained under different operational conditions are presented in Supplementary Tables S1–S3.

The effect of PACS dosage on COD removal efficiency is presented in Fig. 2. Increasing the PACS dosage from 100 to 1,000 mg/L led to a gradual increase in COD removal efficiency, which can be attributed to enhanced charge neutralization and aggregation of organic colloidal particles during the coagulation process. However, a slight decrease

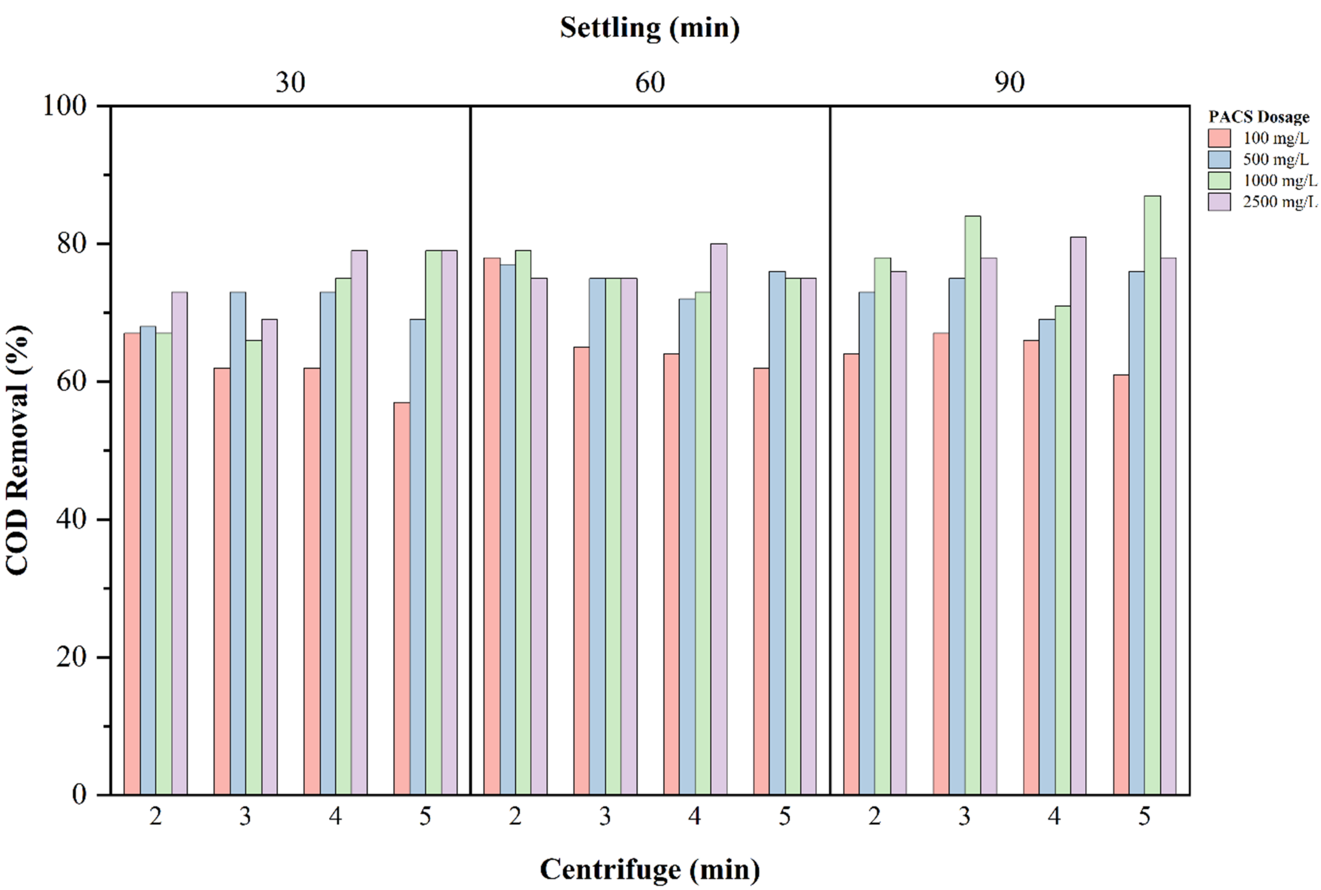

Fig. 2 Effect of PACS dosage, centrifugation time, and settling time on COD removal efficiency during the coagulation pretreatment of MDF wastewater

in COD removal was observed at 2,500 mg/L. This observation suggests that increasing the coagulant dosage beyond a certain level does not significantly improve the removal of dissolved organic compounds, which constitute a considerable fraction of the COD in MDF wastewater.

The effect of PACS dosage on turbidity removal efficiency is shown in Fig. 3. Turbidity removal increased significantly with increasing PACS dosage, approaching complete removal at 2,500 mg/L. This behavior indicates that turbidity in MDF wastewater is primarily associated with suspended and colloidal particles that can be effectively removed through coagulation and flocculation mechanisms.

The effect of PACS dosage on color removal is illustrated in Fig. 4. Similar to turbidity removal, color removal increased significantly with PACS dosage. The pronounced increase observed between 500 and 2,500 mg/L suggests that the chromophoric compounds in MDF wastewater are largely associated with colloidal organic structures that can be efficiently removed via sweep flocculation.

The effect of PACS dosage on sulfate removal efficiency is presented in Fig. 5. Sulfate removal showed a moderate increase with coagulant dosage, reaching approximately 60% at higher PACS dosages. This indicates that sulfate removal is partially associated with adsorption onto aluminum hydroxide flocs rather than direct precipitation. The removal efficiency of suspended solids is shown in Fig. 6. TSS removal remained consistently high across all PACS dosages, exceeding 80%, confirming the strong capability of PACS coagulation to remove particulate pollutants present in MDF wastewater.

Settling time also influenced the separation efficiency of formed flocs. Increasing the settling time from 30 to 90 min generally enhanced the removal of particulate pollutants by allowing larger flocs to aggregate and settle more effectively. However, sedimentation alone was insufficient to remove fine suspended particles, particularly low-density organic flocs. Therefore, centrifugation was applied as an additional clarification step to enhance solid–liquid separation. Centrifugation times of 3–4 min provided the most effective clarification performance. A slight decrease in removal efficiency was observed at longer centrifugation

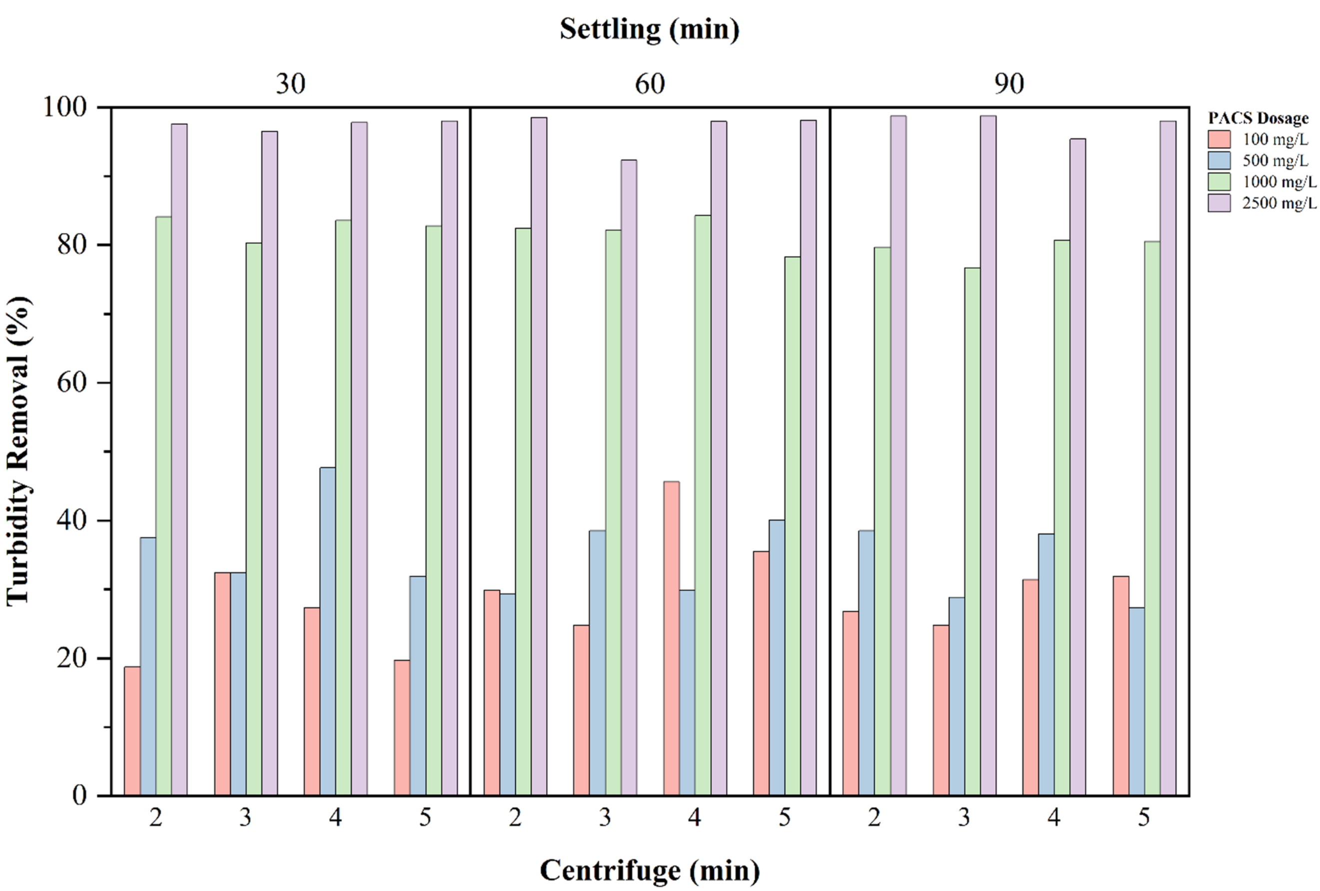

Fig. 3 Effect of PACS dosage, centrifugation time, and settling time on turbidity removal efficiency during the coagulation pretreatment of MDF wastewater

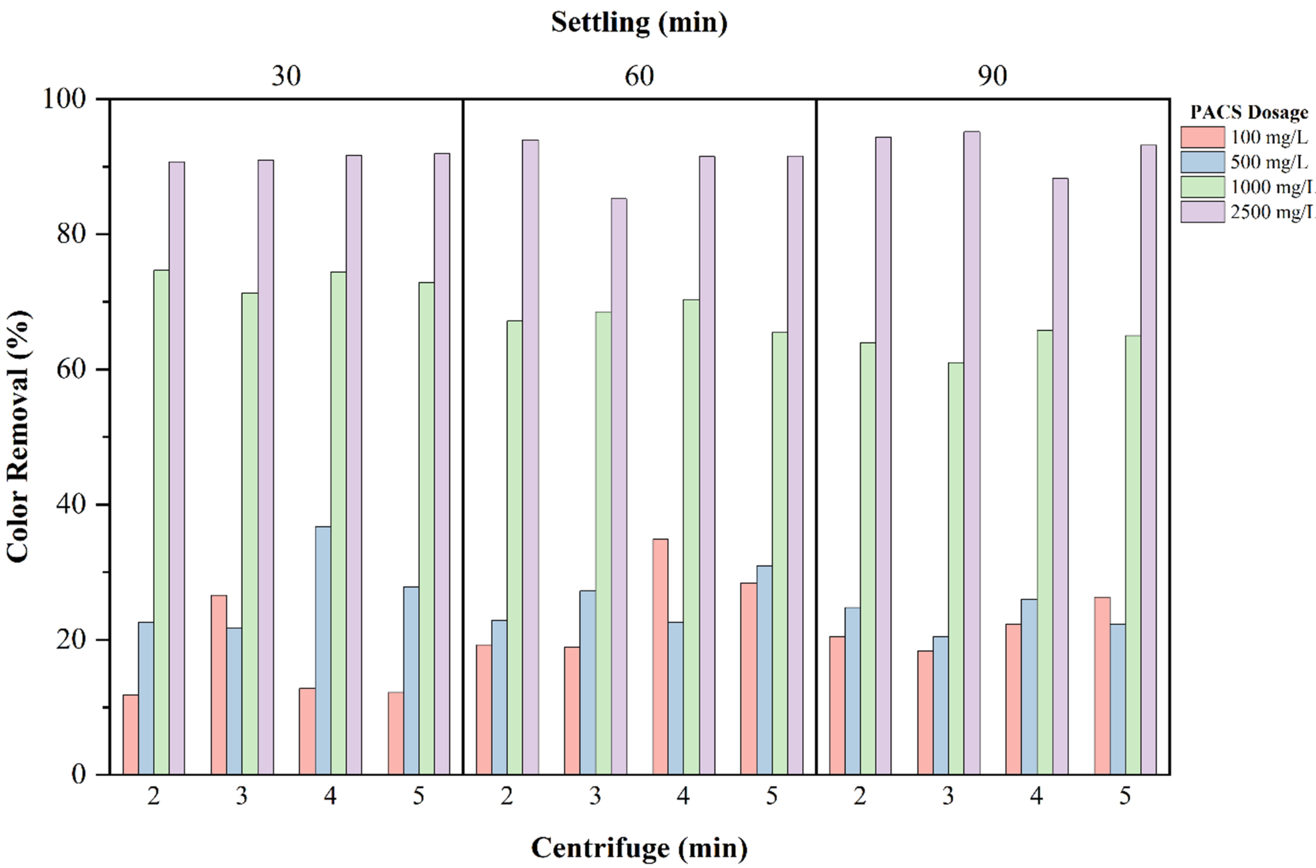

Fig. 4 Effect of PACS dosage, centrifugation time, and settling time on color removal efficiency during the coagulation pretreatment of MDF wastewater

times may be attributed to partial floc breakage caused by prolonged exposure to high centrifugal forces.

Based on the experimental results, all measured parameters were examined, and the optimum dosages and contact times were determined accordingly. Considering the chemical usage, energy consumption, and treatment results for pre-treatment, the optimal operating conditions were determined to be a 90-minute settling time, 1,000 mg/L PACS concentration, and 3-minute centrifugation time. Under these conditions, COD removal reached approximately 81%, while turbidity, color, and suspended solids were removed at significantly higher efficiencies. Although higher PACS dosages slightly improved the removal of particulate pollutants, the improvement in COD removal remained limited, making 1,000 mg/L the most efficient dosage in terms of treatment performance and chemical consumption. The selection of the optimal PACS dosage is further supported by the comparative removal efficiencies of the main water quality parameters shown in Fig. 7, where increasing the PACS dosage beyond 1,000 mg/L did not lead to a significant improvement in COD removal, while turbidity, color, and TSS removal efficiencies were already sufficiently high at this dosage level.

During coagulation pretreatment, pollutant removal was primarily governed by charge neutralization and sweep flocculation mechanisms, leading to the aggregation and settling of suspended solids, colloidal particles, and high-molecular-weight organic compounds. This pretreatment step effectively reduced fouling precursors in MDF wastewater, thereby improving the feed quality prior to the MD process. In contrast, pollutant removal during MD was driven by phase change and vapor transport through the hydrophobic membrane, allowing effective rejection of non-volatile organic and inorganic species.

Nevertheless, despite effective pretreatment, residual dissolved organics and inorganic ions accumulated at the membrane surface during MD due to concentration polarization effects, thereby contributing to fouling and partial membrane wetting.

Performance of MD

In Figs. 8, 9, 10, 11, 12, 13, and 14 the analytical results of the filtrate are presented. . Regarding COD parameter, a significant reduction in COD was observed at all temperatures, with the lowest COD value (1,501 mg/L) observed

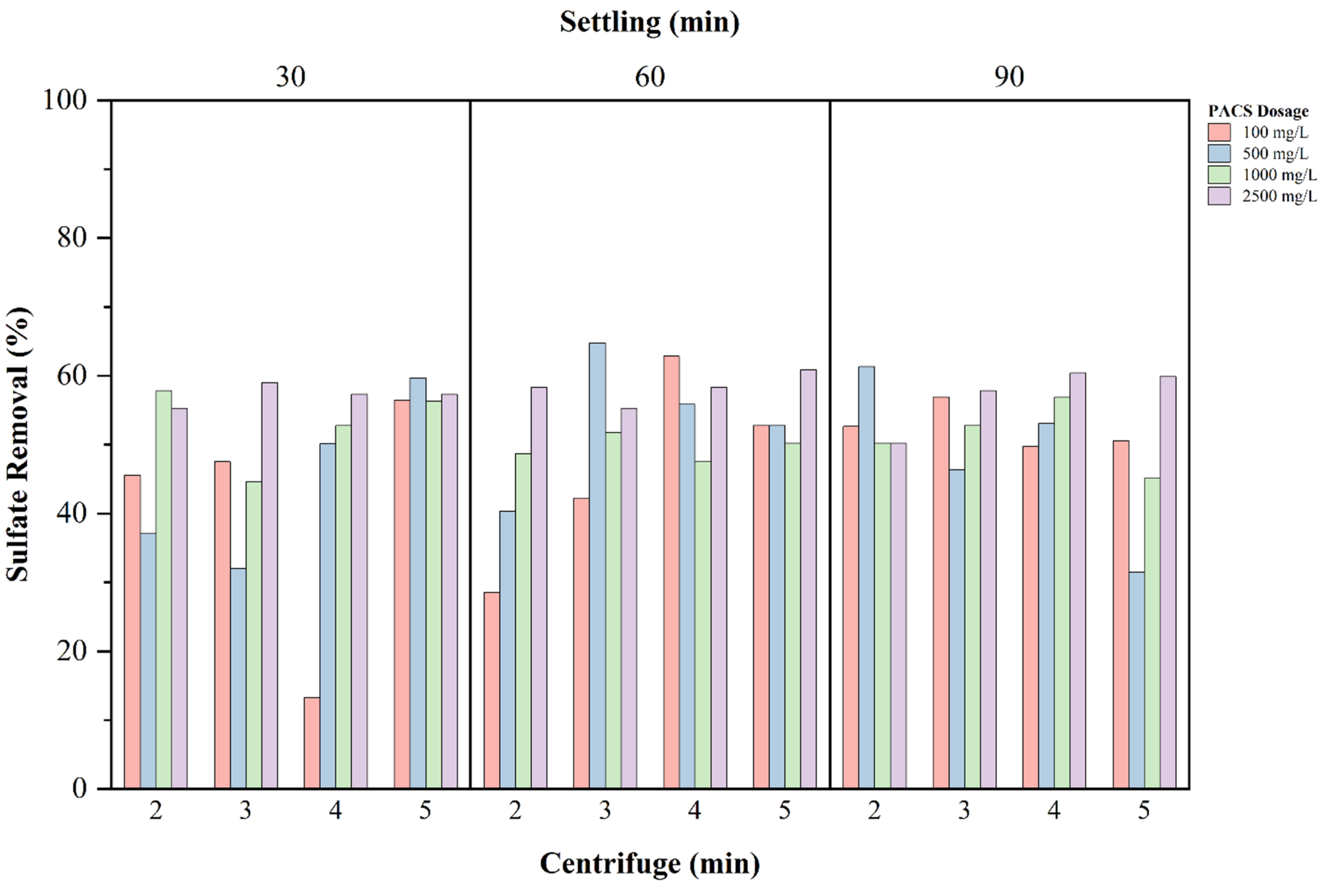

Fig. 5 Effect of PACS dosage, centrifugation time, and settling time on sulfate removal efficiency during the coagulation pretreatment of MDF wastewater

at a feed temperature of 50 °C. Similar to COD, the lowest conductivity value (50 µS/cm) was also obtained at a feed temperature of 50 °C, but the conductivity increased with rising temperature. The MD process is particularly effective in rejecting dissolved ions and non-volatile organic compounds, resulting in significant reductions in conductivity and COD in the permeate, especially at lower feed temperatures (Alkhudhiri et al. 2012b; Alklaibi and Lior 2005).

Deterioration in filtrate quality with increasing feed temperature can be attributed to membrane wetting, temperature polarization, and thermal degradation. At elevated feed temperatures, the membrane surface becomes more susceptible to fouling and wetting due to the accumulation of dissolved salts and organic compounds (Gryta 2008).

Temperature polarization can also negatively affect the membrane flux and filtrate quality by preventing the formation of an effective temperature gradient along the membrane, reducing the vapor pressure (Alklaibi and Lior 2005). The thermal degradation of the membrane material at high temperatures can also adversely affect MD performance and the structural integrity of the membrane (Fig. 15, 16, and 17).

Membrane Characteristics

The clean PTFE membrane, known for its hydrophobic character, has a contact angle of 140°. The high contact angle indicates strong hydrophobicity and high water repellency. Changes in the membrane surface contact angle after MD treatment of MDF wastewater are shown in Fig. 15. Although pretreatment effectively removed many suspended solids and colloidal matter, residual dissolved organic compounds and inorganic ions were not completely removed. During MD operation, these species accumulated at the membrane surface due to concentration polarization, resulting in organic fouling and inorganic scaling layers, as observed in Fig. 18.

One of the major disadvantages of MD, namely membrane wetting, was observed in certain areas of the membrane. In non-wetted areas, a slight decrease in contact

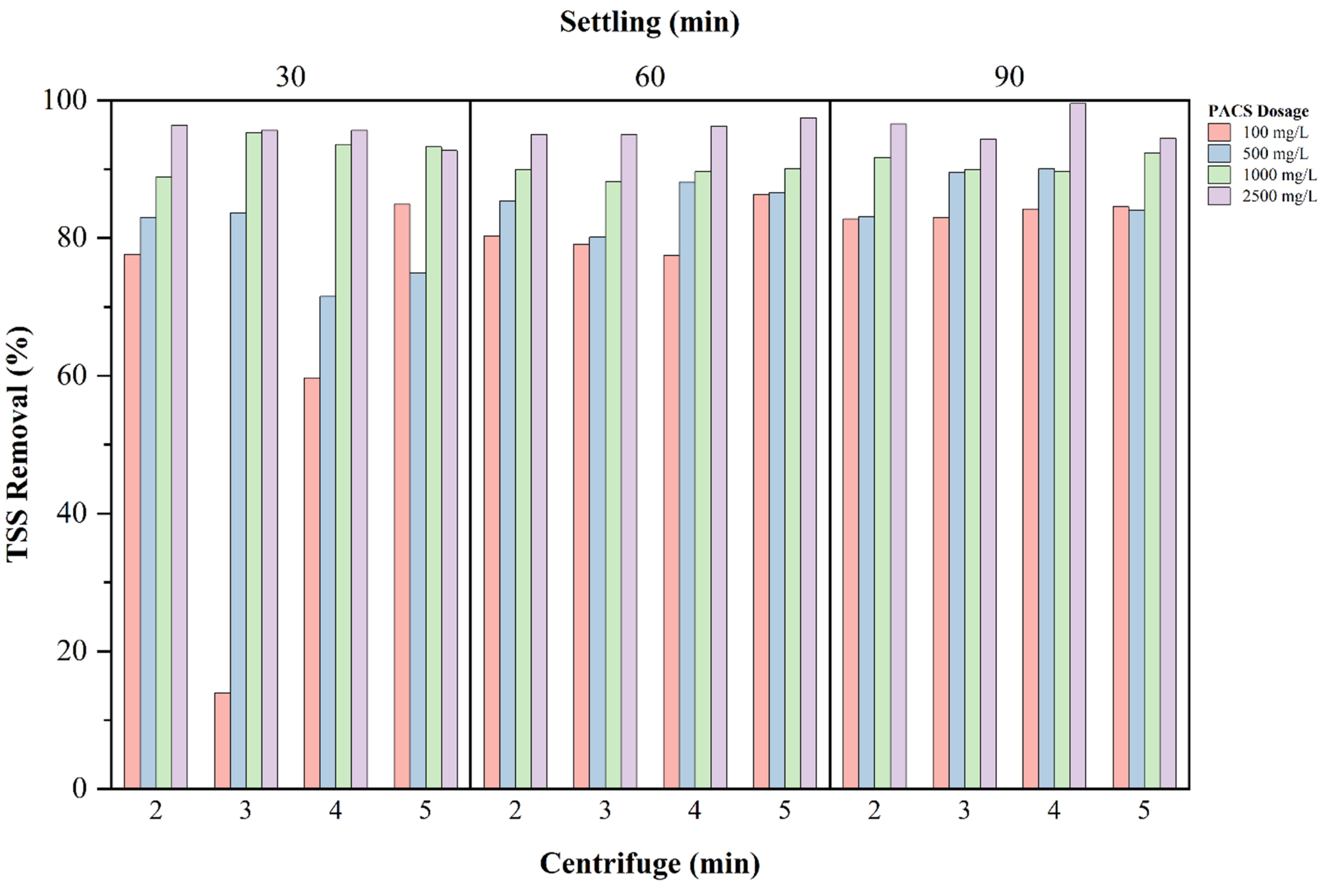

Fig. 6 Effect of PACS dosage, centrifugation time, and settling time on TSS removal efficiency during the coagulation pretreatment of MDF wastewater

angle was observed compared to the clean membrane, whereas the contact angle in wetted areas significantly decreased. The decrease in contact angle is due to the loss of hydrophobicity in these regions after MD operation, leading to the adsorption of pollutants and alterations in surface properties (McGaughey et al. 2017; Rehman et al. 2019). The difference in contact angles between wetted and non-wetted areas indicates the varying degrees of interaction between the wastewater and the membrane surface. Conductivity is an important parameter that indicates the filtration performance in membrane processes. An increase in conductivity at elevated feed temperature indicates that the hydrophobic PTFE membrane is wetted and that the feed water has penetrated into the permeate side. The increase in color and COD in the permeate also confirm this. Additionally, post-experimental membrane analysis revealed significant accumulation on the membrane surface.

The ATR-FTIR spectrum of the clean and fouled PTFE membrane used for treating MDF wastewater with MD are shown in Fig. 16. The strong peaks observed at 1200 and 1140 cm^{-1} are C-F stretching vibrations caused by -CF_2 and -CF_3 groups, which are characteristic peaks of the PTFE membrane (Zoungrana et al. 2017; Wang et al. 2014, 2015). The absence of significant peaks at other wavelengths in the clean membrane indicates the purity and homogeneity of the PTFE material. In comparison to the clean membrane, the appearance of new peaks in the range of 3400–3200 cm^{-1}, 2900–2800 cm^{-1}, and 1700–1200 cm^{-1} in the fouled membrane indicates that functional groups originating from the wastewater were adsorbed onto the membrane surface.

The broad peak observed between 3500–3000 cm^{-1} corresponds to O–H stretching vibrations, indicating the presence of water molecules or hydroxyl groups. The peak at 2900 cm^{-1} corresponds to C–H stretching vibrations,

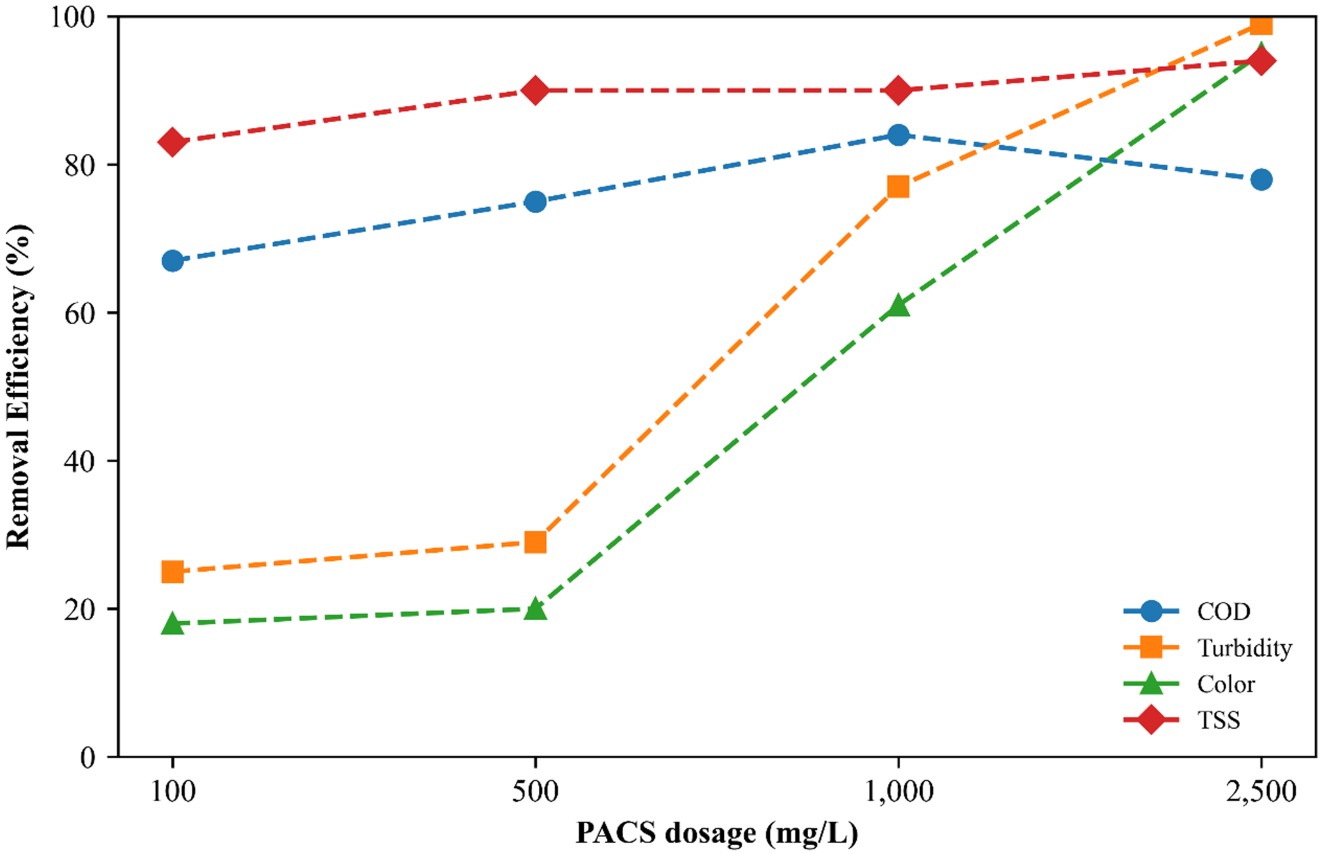

Fig. 7 Effect of PACS dosage on the removal efficiencies of COD, turbidity, color, and TSS during coagulation pretreatment of MDF wastewater

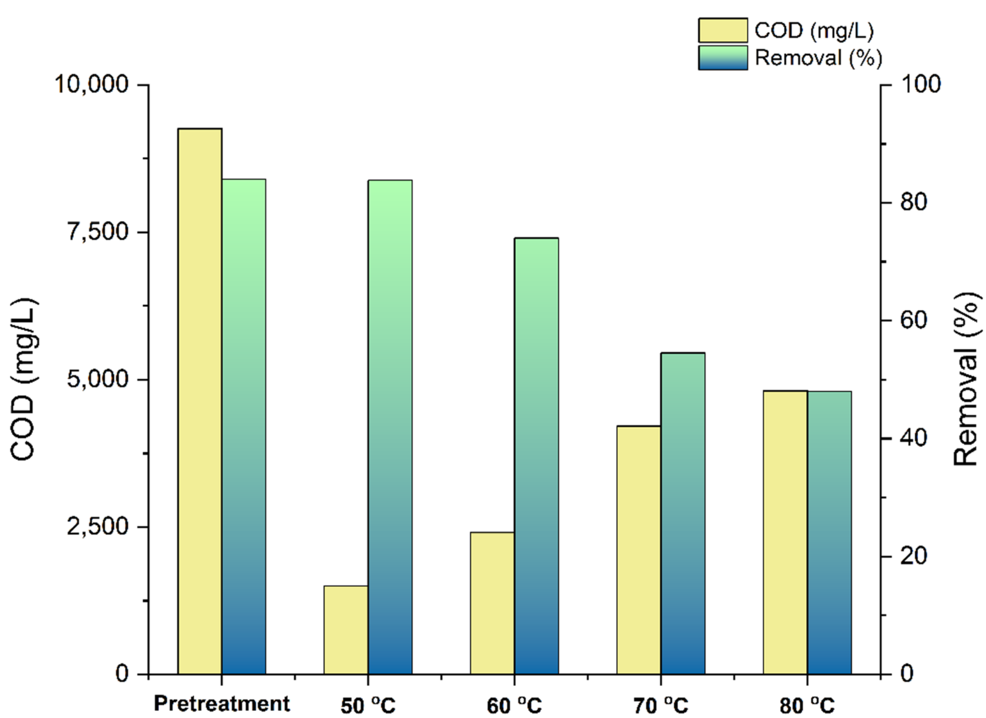

Fig. 8 Variation of COD levels and removal efficiency at different feed temperatures during MD after pretreatment

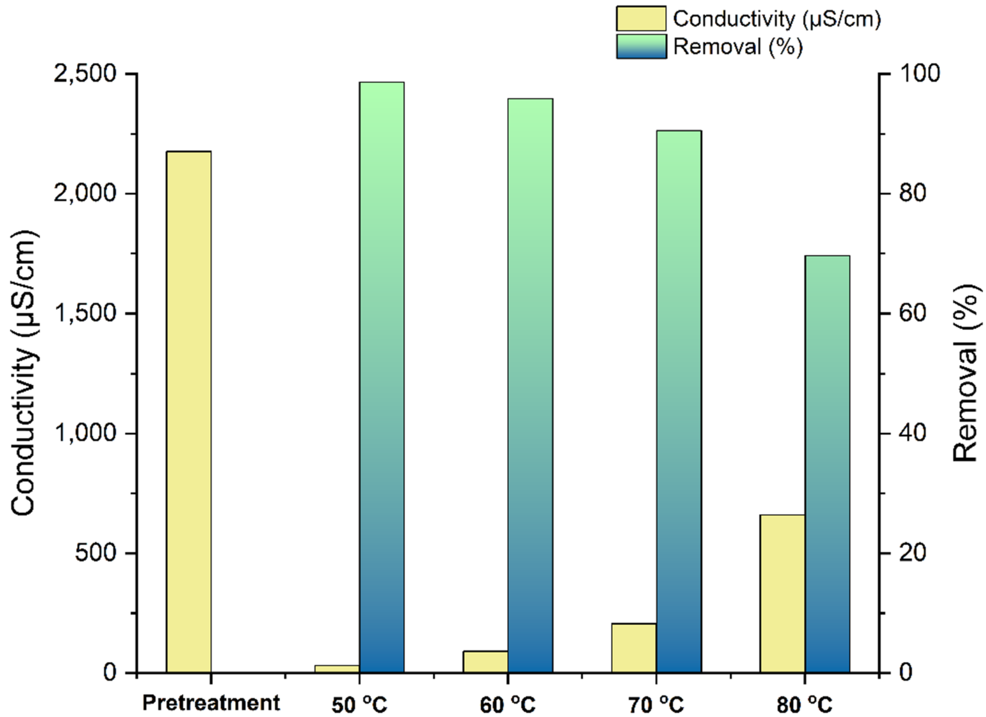

Fig. 9 Variation of conductivity levels and removal efficiency at different feed temperatures during membrane distillation after pretreatment

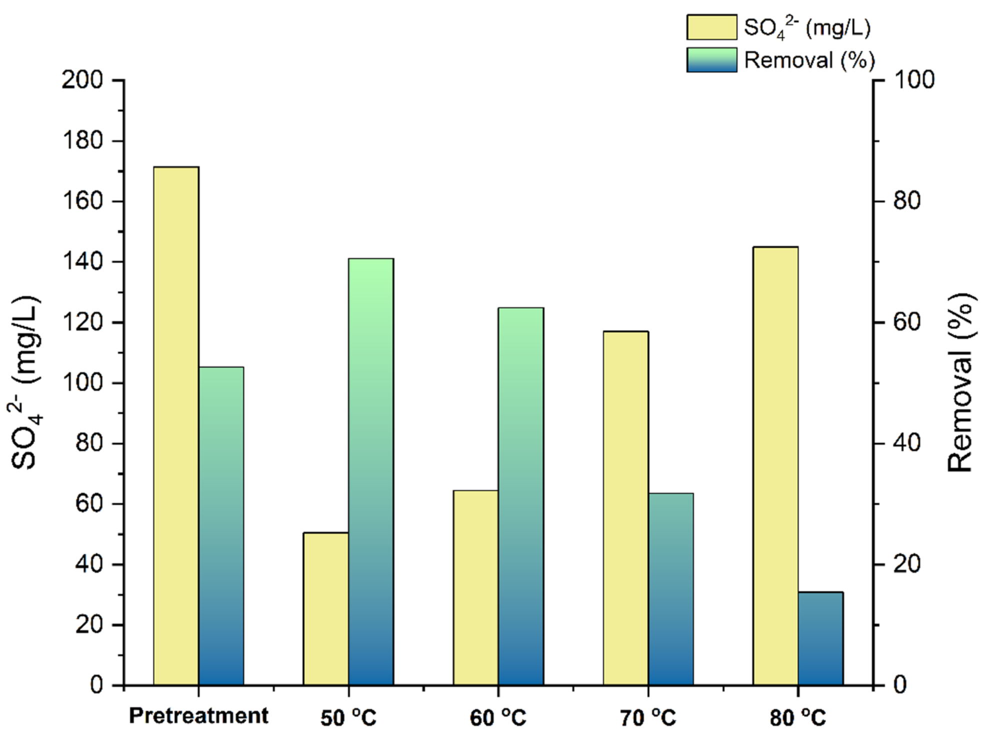

Fig. 10 Variation of sulfate levels and removal efficiency at different feed temperatures during MD after pretreatment

indicating the presence of organic compounds adsorbed onto the membrane (Hu et al. 2016).

The strong peak observed at around 1700 cm^{-1} is characteristic of carbonyl groups (C=O), indicating the presence of organic acids, esters, or aldehydes on the membrane surface.

Figure 17 shows the time-dependent flux variation of the PTFE membrane during the distillation of pretreated MDF wastewater at different feed temperatures (50, 60, 70, and 80 °C). The membrane flux decreased over time during the 120 min operation at all feed temperatures. At a feed temperature of 50 °C, the average flux was 9.45 L/m^2.h, which was more stable than at higher temperatures. Increasing the

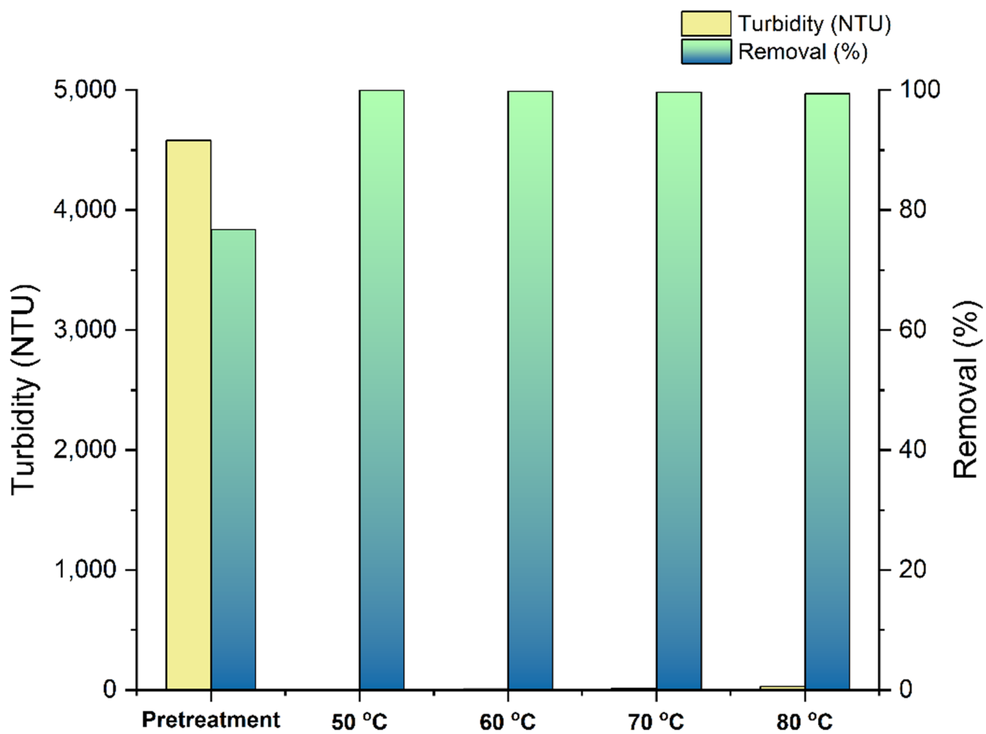

Fig. 11 Variation of turbidity levels and removal efficiency at different feed temperatures during MD after pretreatment

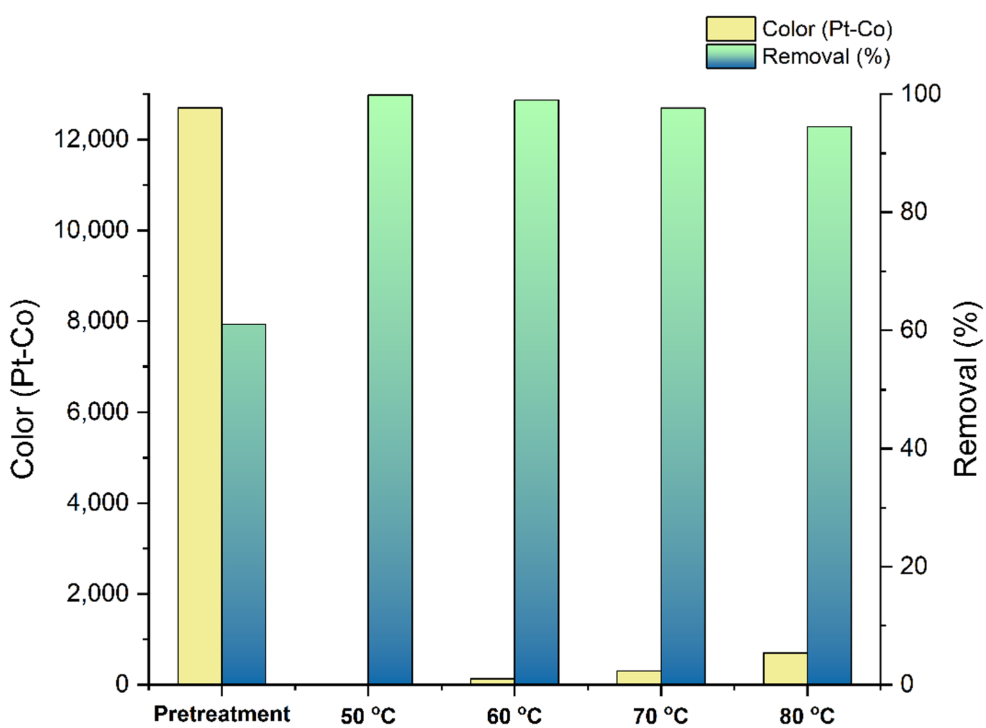

Fig. 12 Variation of color levels and removal efficiency at different feed temperatures during MD after pretreatment

feed temperature increased the temperature difference and vapor pressure across the membrane, resulting in higher membrane flux.

However, the increased mass transfer due to the higher driving force also led to increased temperature polarization, causing a more significant drop in flux (Yu et al. 2024). Although the average flux increased to 19.4 L/m^2.h at 80 °C, the rise in temperature polarization contributed to a greater decline in flux. Additionally, the deterioration of permeate quality observed at higher feed temperatures can be attributed to increased membrane wetting. This observation indicates a clear trade-off between flux enhancement and permeate quality at elevated feed temperatures. Although higher temperatures increase the vapor pressure difference

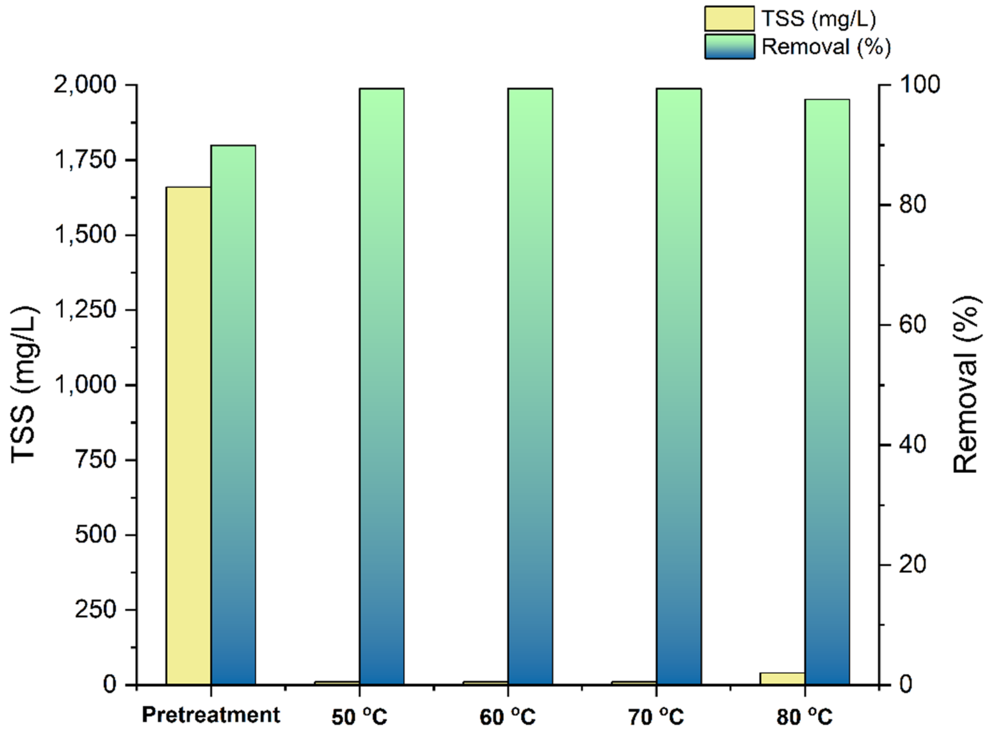

Fig. 13 Variation of TSS levels and removal efficiency at different feed temperatures during MD after pretreatment

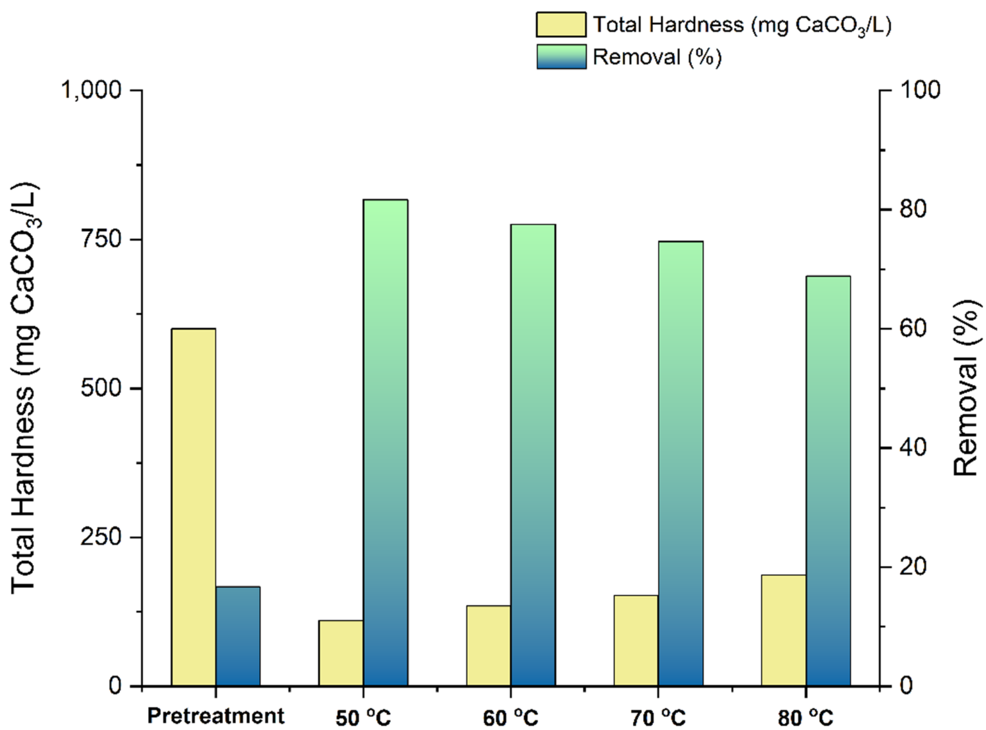

Fig. 14 Variation of total hardness levels and removal efficiency at different feed temperatures during MD after pretreatment

and consequently the membrane flux, they also accelerate membrane wetting and fouling, leading to deterioration of permeate quality.

Figure 18 shows the SEM-EDS images of the clean and used PTFE membrane after MD operation. The surface of the clean PTFE membrane appears uniform and fibrous. Elemental analysis indicates that the surface is composed of C and F atoms, which are typical components of a PTFE membrane. In contrast, the used PTFE membrane, various deposits are observed on the membrane surface. The presence of new elements such as oxygen, aluminum, and calcium, which were absent in the clean membrane, indicates

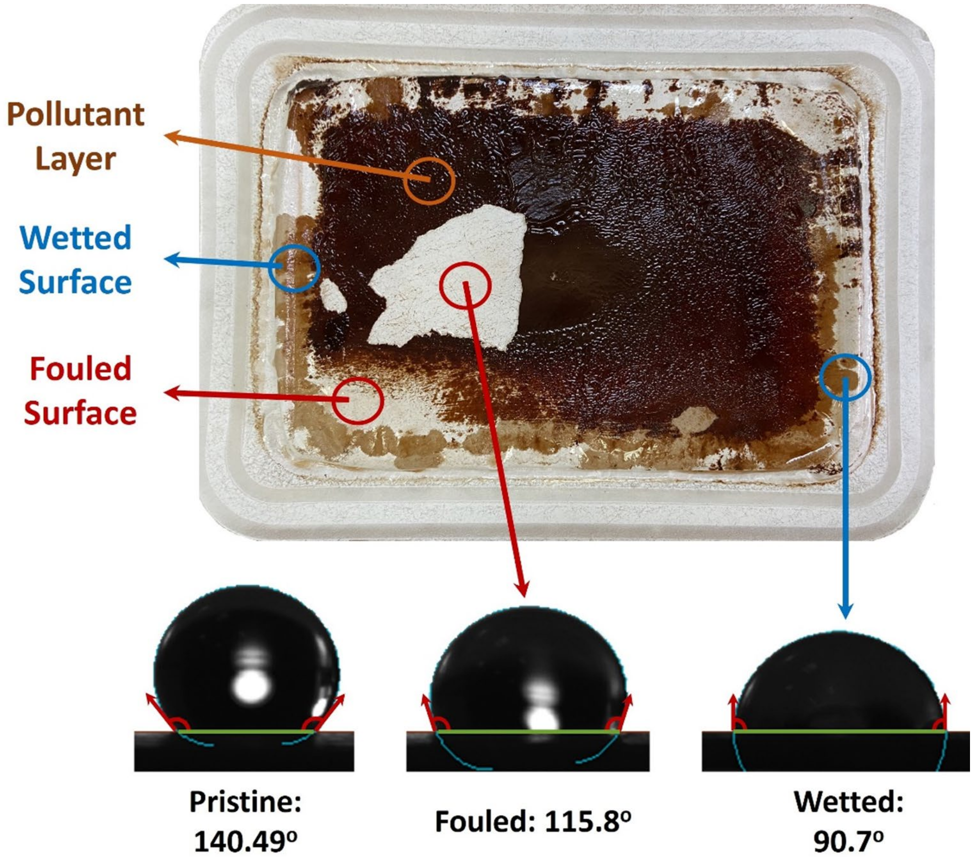

Fig. 15 Changes in contact angle of PTFE membrane after MD

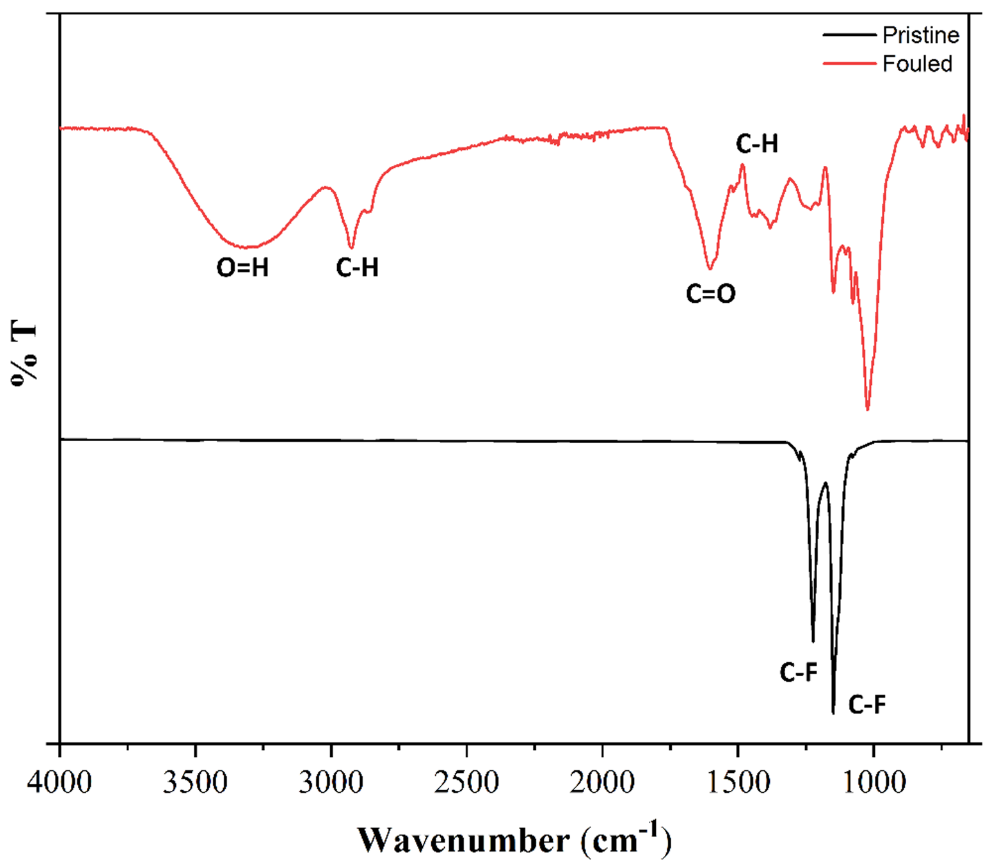

Fig. 16 ATR-FTIR spectra of PTFE membrane before and after treatment

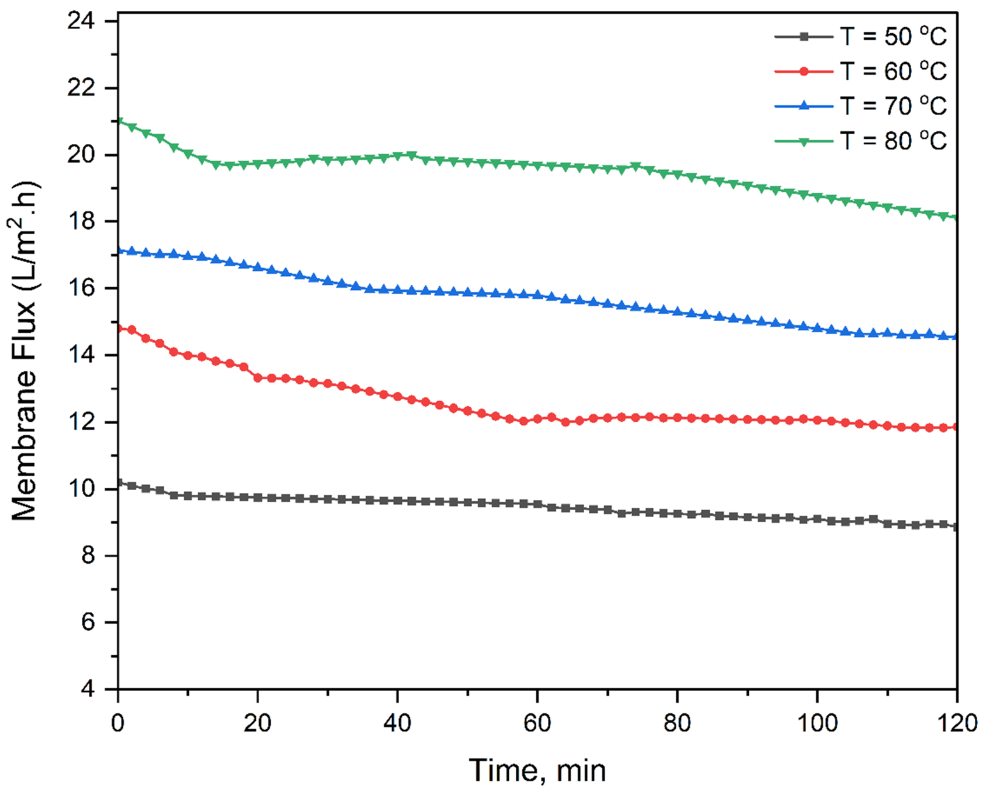

Fig. 17 Time-dependent flux changes of PTFE membrane at different feed temperatures

the accumulation of foulants on the membrane surface. The weight percentage of carbon increased from 17.62% to 24.17% in the used membrane, suggesting the presence of organic fouling. Consistent with this finding,Yang et al. (2023), reported that the detection of oxygen on the surface of the PTFE membrane after treating landfill leachate via MD was a result of the accumulation of natural organic matter on the membrane surface. Additionally, the decrease in the weight percentage of fluorine compared to the clean membrane further indicated the presence of fouling on the membrane surface (Yang et al. 2023).

The scaling potential of MDF wastewater was evaluated by analyzing sulfate (SO_4^{2-}) and total hardness (as $CaCO_3$) in the permeate. Sulfate concentrations in the permeate increased to 145 mg/L, while total hardness rose to 187 mg $CaCO_3$/L as feed temperatures (e.g., 80 °C) increased. These findings suggest that elevated temperatures promoted the precipitation of inorganic salts, particularly calcium sulfate ($CaSO_4$), onto the membrane surface. This is supported by EDS analysis of the fouled membrane, which confirmed the presence of Ca (2.1 wt%) and S (0.8 wt%), indicating scaling associated with sulfate and hardness ions. The presence of aluminum is attributed to residual aluminum species originating from the PACS coagulant used during the coagulation pretreatment, which were not completely removed prior to MD.

The PTFE membrane exhibited partial wetting and fouling after treatment, as evidenced by reduced contact angles and organic/inorganic deposits observed in SEM-EDS analysis. Although the membrane maintained stable flux at 50 °C (9.45 L/m^2·h), repeated exposure to high temperatures (80 °C) accelerated pore wetting and scaling, potentially shortening membrane lifespan. However, the mechanical integrity of the PTFE membrane remained intact, indicating its potential for reuse following appropriate cleaning.

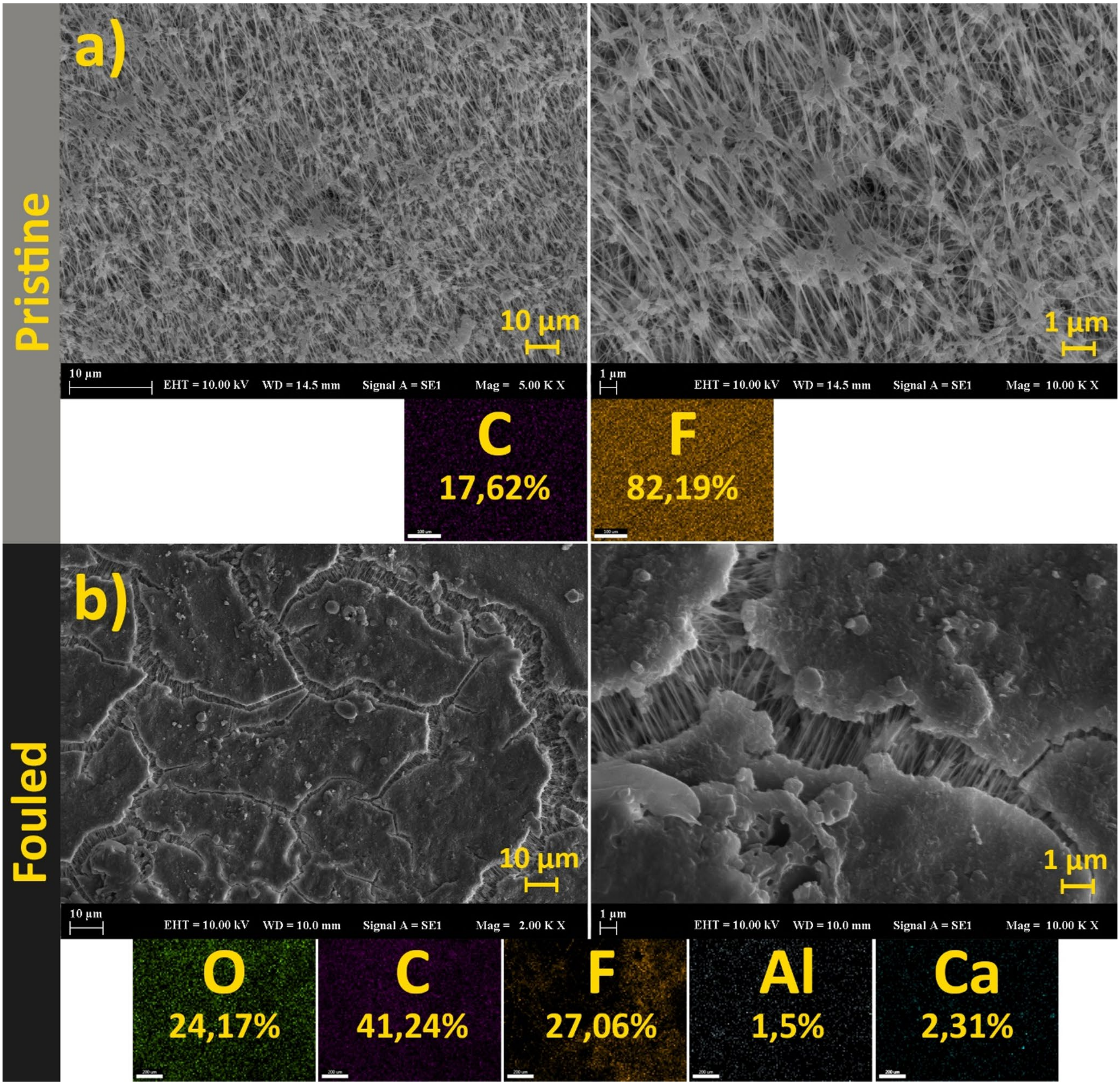

Fig. 18 SEM and EDS images of PTFE membrane: **a** pristine **b** fouled membrane

Conclusion

This study demonstrates the strong potential of the hybrid coagulation-MD process for the treatment of MDF wastewater as it achieved 95.02% COD removal and over 95% reduction in conductivity, turbidity, TSS, and color at a feed temperature of 50 °C. However, further research is required to facilitate practical implementation of the process.

The coagulation pretreatment step played an important role in improving the performance of the MD process by removing suspended solids, colloidal particles, and a significant fraction of organic matter, thereby reducing the fouling potential of the feed solution. The elevated temperature of freshly discharged MDF wastewater (≈50 °C) presents a significant opportunity for direct utilization of waste heat, which may significantly reduce the external energy demand of the MD process and improve overall process sustainability.

Future research should therefore focus on continuous-flow hybrid system design, long-term membrane performance under real operating conditions, and energy integration strategies that maximize the use of inherent thermal energy. Furthermore, comprehensive investigations into fouling mechanisms and the effects of temperature and concentration polarization are essential to further enhance flux stability and extend membrane lifespan.

Supplementary Information The online version contains supplementary material available at https://doi.org/10.1007/s11696-026-04847-w.

Acknowledgements We thank the Scientific Research Projects Coordination Unit of Yildiz Technical University (YTU BAP) for supporting this work through a research seed grant (Project Number: FBA-2023-5561).

Funding This work was not supported by any external funding other than the funding provided by YTU BAP.

Declarations

Conflict of interest The authors declare that they have "no conflict of interest" with respect to the research work carried out in this study.

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