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Communication

Fouling Behavior of Direct Microfiltration for Wastewater Up-Concentration

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Abstract: In the context of rapid urbanization and increasing demand for decentralized wastewater treatment, membrane-based technologies offer high effluent quality with a reduced footprint. Direct microfiltration (DMF) is a promising approach for simplified wastewater treatment. In this study, a lab-scale DMF system was operated for 65 h at an initial flux of 20 LMH to evaluate membrane fouling behavior with actual sewage. The results showed that the trans-membrane pressure (TMP) followed a typical three-stage fouling pattern, with a TMP jump between hours 10 and 15 at a fouling rate of 16 kPa/hour, sharply reducing permeate flux. Analysis of fouling resistance revealed that cake resistance (Rc) accounted for 94% of the total resistance, while membrane (Rm) and irreversible fouling (Rf) contributed only 2% and 4%, respectively, highlighting the dominant role of cake formation. These findings suggest that DMF systems are feasible for municipal sewage treatment at fluxes around 20 LMH. Finally, mitigation strategies such as backflushing, pretreatment and chemical cleaning to control early-stage fouling should be further investigated.

Keywords: direct microfiltration; sewage; membrane fouling; flux

1. Introduction

Wastewater treatment plays a vital role in the energy-water nexus, where energy is essential for water management, and water systems have significantly impact energy consumption. Conventional wastewater treatment plants typically rely on energy-intensive aerobic biological processes, followed by anaerobic digestion of sludge for stabilization of residual solids. They consume about 3% of national electricity, predominantly due to aeration and sludge processing [1]. Additionally, untreated effluent poses environmental and public health risks.

With rising energy costs, increasing freshwater scarcity, and the growing pressure for carbon neutrality, there is an urgent need for wastewater treatment strategies that are not only energy-efficient but also capable of resource recovery. In this context, DMF, which concentrates organic matter before anaerobic processes, has emerged as a promising approach for achieving energy-positive wastewater treatment [2].

In this context, DMF stands out among the available technologies due to its operational simplicity, relatively low energy demand, and ability to selectively retain particulate and colloidal organics. When integrated with anaerobic digestion or co-digestion processes, DMF has shown potential to enhance methane production and improve overall treatment efficiency. In recent years, DMF has been increasingly investigated as a pretreatment method to concentrate low-strength municipal wastewater before anaerobic digestion. Several studies have demonstrated the effectiveness of DMF for concentrating sewage or graywater. For instance, DMF was capable of achieving 59–71% of concentrated COD concentration and enhancing methane production when applying DMF to domestic wastewater treatment [3]. Effective organic recovery was also observed using ceramic membranes with 90% of COD in the concentrate stream and stable flux of 41.7 LMH [4]. The potential carbon and energy benefits of membrane-based concentration systems highlight the essential role of DMF in energy-neutral wastewater treatment. These researches primarily focused on parameters such as COD concentration, permeate flux, energy consumption, and long-term performance of the system. Despite these advancements, the widespread application of DMF is challenged by membrane fouling, which remains a significant operational challenge. Fouling not only reduces membrane permeability but also increases energy consumption due to high TMP, requiring frequent cleaning, compromising the long-term viability of the system [5].

Although previous studies have examined the feasibility of using membranes for the up concentration of municipal wastewater, limited attention has been paid to the short-term fouling dynamics of DMF. This is especially true when treating low-strength, real sewage under non-pretreated conditions in DMF, especially under real wastewater conditions with low organic strength and high variability. Most studies focus on long-term performance without detailed analysis of early fouling behavior. Additionally, many studies either utilize synthetic wastewater under controlled laboratory conditions or do not conduct comprehensive membrane resistance analysis during the initial operation phase. Therefore, investigating the fouling dynamics of DMF under actual low-strength sewage conditions is crucial to address these gaps. In the filtration process, membrane material plays a critical role in fouling behavior, as hydrophilic membranes (e.g., polyether sulfone) typically exhibit lower fouling than hydrophobic membranes such as polypropylene, while Polyvinylidene fluoride is considered intermediate [6,7]. Furthermore, membrane fouling remains the primary constraint for scaling DMF, making it essential to gain a better understanding of initial fouling behavior. This understanding will help inform cleaning protocols and improve operational stability, particularly for low-strength wastewater.

Therefore, this study investigates the short-term fouling characteristics of a lab-scale DMF treating low-strength sewage collected from a university canteen in Ho Chi Minh City without any pretreatment. The primary objective is to evaluate the intrinsic characteristics and fouling behavior of membranes when operating with actual wastewater. From there, the threshold of fouling would be determined to consider whether appropriate pretreatment is needed. The lab-scale DMF system was operated for 15 h with an average initial permeate flux of approximately 20 LMH. Key performance parameters, including transmembrane pressure (TMP) evolution, fouling rate, and fouling resistance components, were evaluated to characterize the fouling progression over time. Special attention was given to identifying the dominant fouling mechanisms during early-stage operation. The findings from this study are expected to provide practical insights for improving the operability of DMF systems.

2. Materials and Methods

2.1. Lab-Scale Direct Membrane Filtration Unit

This study mainly focuses on evaluating the fouling behavior of DMF. Therefore, a lab-scale DMF system was conducted for 65 h of operation (Figure 1).

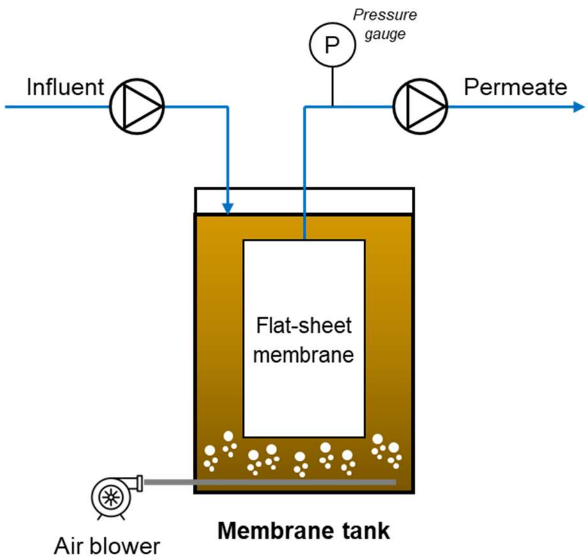

Figure 1. Process diagram of direct microfiltration unit.

Normally, permeate flux for aerobic microfiltration ranges very widely, from only a few LMH up to several tens of LMH, depending on the membrane type and wastewater quality. Among them, a flux of around 20 LMH is considered typical and suitable for microfiltration of municipal wastewater, which was conducted by [8] and summarized by [9]. Therefore, an initial flux of 20 LHM was chosen for this study. The system consisted of a single membrane tank with a working volume of 3.5 L. Raw wastewater was continuously pumped into the tank for direct filtration. A flat-sheet polypropylene membrane with an effective filtration area of 0.1 m^2 was submerged in the bioreactor. An air diffuser was installed at the bottom of the membrane tank to create well-mixed condition and mitigate membrane fouling. To enhance membrane performance and extend operational stability, the filtration was conducted in intermittent mode, with a cycle of 8 min on and 2 min of relaxation. The membrane fouling behavior was evaluated by monitoring the variation in TMP by a pressure gauge.

2.2. Characteristics of Feed Wastewater

Actual wastewater was collected directly from a canteen located on the campus of Ho Chi Minh University of Technology, Vietnam National University—Ho Chi Minh City, Viet Nam. It included both kitchen wastewater and effluent from a septic tank. According to the on-site actual surveys, the average concentrations of chemical oxygen demand, total Kjeldahl nitrogen and total phosphorus were 268 ± 130 mg/L, 26 ± 6 mg/L and 4.0 ± 1.9 mg/L, respectively.

2.3. Assessment of the Distribution of Fouling Resistance

At the end of the experiment, the components of membrane fouling resistance were evaluated using a procedure modified from our previous protocol to ensure compatibility with the specifications of the membrane used [10]. Specifically, the chemical cleaning sequence employed to distinguish different resistance components involved the sequential use of 0.1% (*w*/*w*) sodium hypochlorite (NaOCl) followed by 0.1% (*w*/*w*) nitric acid (HNO_3).

3. Results and Discussion

3.1. Fouling Characteristics

The fouling behavior of the DMF system was monitored through trans-membrane pressure (TMP) variations during operation (Figure 2).

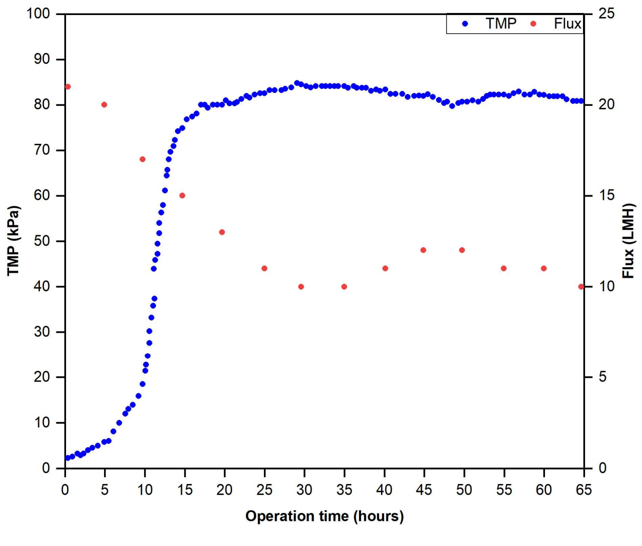

Figure 2. Trans-membrane pressure (TMP) profile of the direct microfiltration (DMF) system showing the fouling stages.

It can be seen that the TMP profile clearly exhibited a three-stage fouling pattern [11]. In the first 5 h, the TMP remained relatively stable, ranging from 2 to 5 kPa, indicating minimal fouling and a clean membrane surface. During the second stage, TMP gradually increased and reached 16 kPa by hour 10, with a fouling rate of approximately 2 kPa/hour. A significant TMP jump was then recorded between hours 10 and 15, where the pressure rapidly increased to 78 kPa, corresponding to a sharp fouling rate of 16 kPa/hour. After this rapid increase, the TMP stabilized at approximately 80 kPa to the end of operation. This behavior indicates that the early phase of operation is a critical period for fouling development, especially when using a pristine membrane. At the beginning, the membrane allows maximum flux, which facilitates the transport of organic, colloidal, and particulate colloidal matter from raw wastewater to the membrane surface. These foulants gradually accumulate overtime, forming a cake layer and blocking membrane pores, which in turn increases the TMP of the DMF system. The significant increase in TMP between 10 and 15 h of operation was due to the intensive accumulation of foulants on the membrane surface, which markedly reduced the permeate flux [12]. Furthermore, it can be noted that the fouling rate at the first stage of this study was 3-fold higher than that reported by Subtil et al. (2025) when operating with raw wastewater and 10-fold higher when operating with coagulated wastewater [13]. This significant difference suggests that, despite operating the same filtration process at the same flux (~20 LMH), variations in pretreatment and fouling control strategies strongly influenced the fouling behavior of DMF. In particular, the pretreatment of raw wastewater led to a more gradual increase in TMP and extended the filtration duration compared to the case without any pretreatment in this study. Similarly, using coagulants suppresses the increase in TMP, allowing for long-term operation. In addition, a short relaxation period (2 min) might be insufficient to relieve membrane compaction or promote foulant detachment, even with the continuous aeration. Another critical aspect of the DMF system is that it does not require biological treatment, which would otherwise reduce the impact of raw wastewater characteristics on the membrane through biodegradation. As a result, pollutants gradually accumulate and partially decompose under aerobic conditions, leading to increased filtration resistance and a higher TMP requirement to maintain stable permeate flow.

As this experiment did not include recovery ratio measurement, flux profiles were used to assess fouling behavior. It was recognized that the increase in TMP profile resulted in the decline in permeate flux, which gradually dropped by half (to approximately 10 LHM), and became nearly stable after hour 30. The permeate flux reduced rapidly at the dramatic fouling rate, then followed by a moderate decline until a pseudo-steady state. This balanced relationship is explained by Darcy's law. Organic matters in sewage were unexpectedly accumulated within/on the membrane pores; therefore, fouling resistance increased. As long as the permeate flux was maintained, the TMP increased. However, the TMP increase was finally not enough to compensate for the increase in fouling resistance. The pseudo-steady-state flux and TMP were observed concurrently implying that the fouling layer was formed fully after 15 h of filtration. As a result, methods employed to mitigate membrane fouling such as backflushing, coagulation, etc. and experiments on different kinds of wastewater could be considered in future work with corresponding configuration.

3.2. Distribution of Fouling Resistances

To have comprehensive assessment for membrane fouling process and mitigation method, the distribution of fouling resistance was measured, as shown in Figure 3.

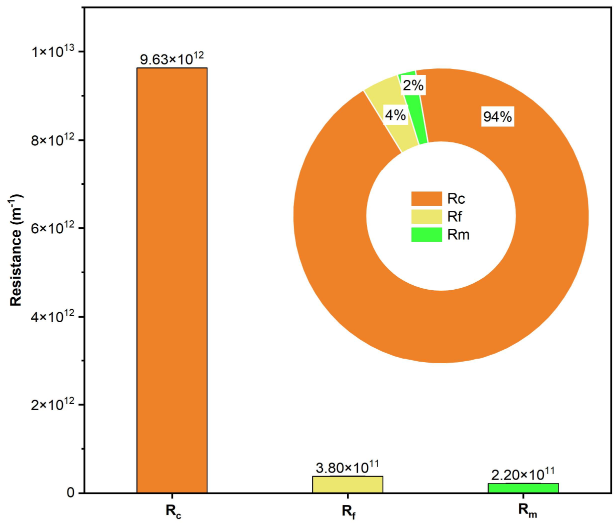

Figure 3. Distribution of fouling resistance components showing the dominance of cake resistance.

It can be seen that the major contributor to the total filtration resistance was the cake layer formed on the membrane surface, with a cake resistance (R_c) of 9.63×10^{12} m^{-1}, accounting for approximately 94% of the total resistance. In contrast, irreversible fouling resistance (R_f) and intrinsic membrane resistance (R_m) were negligible, measured at 3.80×10^{11} m^{-1} and 2.20×10^{11} m^{-1}, corresponding to only 4% and 2%, respectively. The dominance of cake resistance in this study aligns with the observed TMP profile, particularly the early-stage rapid increase and subsequent stabilization. However, adsorption and pore-blocking processes occurring during the early stage may have contributed to the initial TMP increase and could have been partly masked by the larger cake resistance. In this study, filtration occurred by the sieve mechanism. The predominant fouling mechanism in this DMF system was identified as surface cake formation through a sieving effect, whereby suspended solids and colloidal particles in the raw wastewater were directly deposited onto the membrane surface. These accumulated materials gradually narrowed the pore openings, increasing the overall filtration resistance and contributing to the steep TMP rise. This type of fouling is typically reversible and can often be mitigated by physical cleaning methods, such as air scouring or backflushing. However, the system used in this study employed a single submerged flat-sheet membrane, and although aeration was applied, the frictional force generated was insufficient to effectively dislodge accumulated foulants. Furthermore, the absence of a backflushing mechanism allowed continuous deposition of foulants under suction pressure, resulting in a sustained upward TMP trend. Once the membrane surface became saturated with contaminants, a steady-state fouling condition was observed, reflected by a plateau in TMP values.

Regarding irreversible fouling, its contribution was minimal. This was likely due to colloidal particles being adsorbed into membrane pores over time under high suction pressure (operating TMP approximate 80 kPa). Unlike conventional MBRs, where biological activity at low C/N ratios tends to enhance extracellular polymeric substances and soluble microbial products, the DMF system in this study avoided such effects by excluding activated sludge, thereby reducing biofouling potential. In addition, the hydraulic resistance of the membrane was almost recovered to the initial value after off-line chemical cleaning 2.20×10^{11} m^{-1} (Figure 3), indicating that irreversible fouling was minor and effectively mitigated. This implied that off-line chemical cleaning was effective to mitigate irreversible fouling in direct microfiltration of sewage. However, to accurately determine irreversible changes, it is essential to measure and compare pure water permeability between original and used membrane. Overall, the fouling distribution confirms that reversible fouling, particularly cake layer formation, was the dominant fouling mechanism in this direct microfiltration of sewage. Controlling reversible fouling is more practical, and several strategies have been successfully applied in MBRs to manage it, such as relaxation cycles, backflushing, intermittent aeration, use of moving bed biofilm carriers (MBBR), and vortex-enhanced membranes. These strategies are applicable to DMF systems and should be considered to delay the onset of TMP jump and improve long-term membrane performance. In addition, system design parameters such as filtration-to-relaxation ratio, aeration intensity, membrane surface area, and hydraulic configuration should be further optimized in future studies to minimize early-stage fouling and enhance membrane longevity.

4. Conclusions

This study confirmed that direct microfiltration (DMF) has strong potential as a practical technology for the up concentration of municipal wastewater. The membrane fouling behavior followed a typical three-stage fouling mechanism, with severe fouling occurring between 10 and 15 h of filtration at a fouling rate of approximately 16 kPa/h, indicating a critical point for operational adjustment. Without pretreatment, the fouling rate in the initial phase is 3 to 10 times faster than reported in previous studies operating with coagulated or screened wastewater. In addition, the filtration cycle (8 min of filtration: 2 min of relaxation) was insufficient to control fouling, as the short relaxation period did not provide enough time for effective removal of the deposited cake layer, resulting in a rapid TMP increase. Resistance analysis revealed that the cake layer contributed approximately 94% of the total fouling resistance and could be effectively removed by physical cleaning such as air scouring and backflushing. For long-term and stable operation, chemical cleaning and pretreatment steps (e.g., coagulation, sedimentation, or fine screening) should be incorporated to minimize irreversible fouling and maintain performance. In addition to its filtration capability, DMF offers benefits in organic recovery for anaerobic digestion, contributing to more sustainable wastewater management systems. Overall, the findings suggest that DMF is a viable option for decentralized treatment or as a pre-treatment step for energy and resource recovery applications. Future research should investigate the influence of operational cycle, aeration intensity, and pretreatment steps on fouling dynamics to develop more robust operational strategies for full-scale applications.

Author Contributions

P.-T.N.: conceptualization, methodology, software, data curation, writing—original draft preparation; N.-N.P.: visualization, investigation; H.-V.N: visualization, investigation; T.-K.-C.P.: writing—original draft preparation; P.-D.N.: writing—reviewing and editing, supervision; X.-T.B.: writing—reviewing and editing, supervision. All authors have read and agreed to the published version of the manuscript.

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Not applicable.

Data Availability Statement

No data was used for the research described in the article.

Conflicts of Interest

The authors declare no conflict of interest. The funders had no role in the design of the study; in the collection, analyses, or interpretation of data; in the writing of the manuscript; or in the decision to publish the results.

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