Integration of Membrane Bioreactor and Reverse Osmosis for Textile Wastewater Treatment and Reclamation: A Pilot-Scale Study

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Received 13 April 2023; received in revised form 27 June 2023; accepted 28 June 2023

DOI: https://doi.org/10.46604/peti.2023.5273

Abstract

Membrane bioreactor (MBR) technology, a combination of traditional activated sludge and membrane filtration, has been widely used for industrial wastewater treatment and reclamation. This paper highlights a pilot-scale MBR system treating textile wastewater from a textile factory in Taiwan. Over 7 months of continuous operation, the average MBR influent chemical oxygen demand (COD) is 332 mg/L, and the average effluent COD is 38 mg/L, which results in approximately 88% COD removal. A reverse osmosis (RO) module is installed after 2 months of MBR operation and uses the MBR permeate as its influent. The RO produces pure water with average COD, conductivity, and color of 7 mg/L, 16 μS/cm, and 7 Pt-Co, respectively. The RO permeate is suitable for reuse in manufacturing processes, and the RO membrane shows stable performance with TMP, which is less than or equal to 0.5 kg/cm^2 during the test. The study demonstrates the great feasibility of MBR combined with RO for treating and reclaiming textile wastewater.

Keywords: membrane bioreactor, textile wastewater, reverse osmosis, transmembrane pressure

1. Introduction

The textile processing industry is considered a water-intensive sector as it uses large quantities of water during production processes including scouring, bleaching, dyeing, printing, and finishing. It is reported that more than 100,000 commercial textile dyes are available in the market and approximately 700,000-1,000,000 tons of dyes are produced while 280,000 tons are discharged annually from the textile industry to the global environment [1]. The composition of textile wastewater is highly complex and depends on various factors, including the type of fabric, dyeing method, and chemicals used in the process [2]. Textile wastewater is often rich in color and of extreme pH with various toxic and recalcitrant organic compounds [2]. Thus, several countries have introduced more stringent discharge limits for textile wastewater. Stricter regulations are compelling treatment plants to upgrade the existing wastewater treatment systems or adopt new treatment technologies. Furthermore, the reclamation of purified effluent will become increasingly relevant due to water scarcity, raising water costs, and the preservation of natural water resources [3].

A membrane bioreactor (MBR) is a hybrid process combining activated sludge units and membrane filtration. The degradation of pollutants occurs inside the bioreactor, while the separation of the treated wastewater from the activated sludge is completed in a membrane module. The small pore size of the membrane can retain a high concentration of microorganisms in the bioreactor, and produce very high-quality recyclable treated water [4-5].

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English language proofreader: Yen-Chun Hsieh

The advantages of MBR include high solid-liquid separation efficiency, small footprint, high volume loading, high-efficiency organic removal, low sludge production, and higher removal of nutrients, organic and persistent organic pollutants (POP) over conventional activated sludge processes [6-8]. However, membrane fouling, defined as the deposit of materials on the membrane surface with the possible existence and growth of microorganisms on it, is the main challenge of the MBR process. It can lead to a decline in permeate flux or an increase in transmembrane pressure (TMP) over time, which results in higher operational costs for membrane cleaning and eventually reduces the lifespan of the membranes [9-10].

Over the last two decades, MBRs have attracted great attention due to their ability to produce high-quality effluent. It is currently considered one of the most promising technologies to treat domestic and industrial wastewater and is suitable for direct recycling or further additional purification steps [10-11]. It was reported that 22.4% of the compound annual growth rate (CAGR) was expected for the MBR market [12]. A recent Business Communication Company (BCC) report revealed that the market size of MBR was 3.0 billion USD in 2019, and is expected to reach 4.2 billion USD by 2024, with a CAGR of 7% [13].

Several studies have demonstrated the effectiveness of MBR in treating textile wastewater [11, 14-17]. Furthermore, the combination of MBR with other membrane technologies, such as nanofiltration (NF) and reverse osmosis (RO), is applied for the treatment and reclamation of textile wastewater. In the research conducted by Li et al. [18], high water recovery could be achieved through the recirculation of nanofiltration concentrate to the MBR in the MBR-NF hybrid process for textile wastewater treatment. In another study, a laboratory-scale MBR-RO unit was employed to treat textile wastewater. The results indicate that the MBR system can achieve 99%, 90.3%, and 82.5% reduction of total suspended solids (TSS), chemical oxygen demand (COD), and color, respectively. It is highly effective for pre-RO treatment [18]. However, more practical experience through field trials in textile factories is still needed.

In this study, a pilot-scale submerged hollow fiber MBR with a capacity of up to 400 L/d is applied to treat the textile wastewater from a textile factory for 7 months. In addition, an RO module using the MBR permeate as its influent was installed to produce pure water. This is one of the few successful pilot MBR-RO tests conducted in Taiwan for textile wastewater treatment and reclamation. This study examines water quality parameters such as COD, color, oil, and conductivity, as well as operating parameters including TMP, permeate flux, and recovery rate. It provides a new concept for recycling wastewater in textile mills.

2. Materials and Methods

This section introduces the materials and methods used to investigate the efficiency of the integration of MBR and RO in treating and reclaiming textile wastewater. The wastewater treatment processes implemented by the textile factory, including physical-chemical and biological processes, are described. The wastewater source and characteristics, the pilot-scale MBR and RO plant, as well as operational conditions, are also explained. The section provides a comprehensive overview of the experimental setup and procedures used to evaluate the performance of MBR and RO in treating textile wastewater.

2.1. Description of the wastewater treatment processes of the textile factory

Fig. 1 illustrates the schematic diagram of the wastewater treatment processes implemented by the textile factory. Wastewater produced from various manufacturing processes is collected, mixed in the equalization tank, and passed through a cooling tower to reduce the water temperature. The treatment processes involve physical-chemical processes such as rapid mix, slow mix, and dissolved air flotation (DAF) system. Aluminum sulfate (alum) was added as a coagulant in the rapid mix tank, while polymer was added as a flocculant in the slow mix tank to bridge small flocs to larger flocs. If necessary, sodium hydroxide (NaOH) is used to maintain neutral pH. The DAF system can generate micron-sized bubbles that attach to the suspended particles, causing them to float to the surface where they can be skimmed off. The DAF can effectively remove suspended solids, as well as minor biological oxygen demand (BOD) and COD. Subsequently, several activated sludge systems are employed as biological treatments to remove major BOD and COD. Finally, the effluent from the clarifier undergoes rapid mixing, slow mixing, and DAF processes again before being discharged.

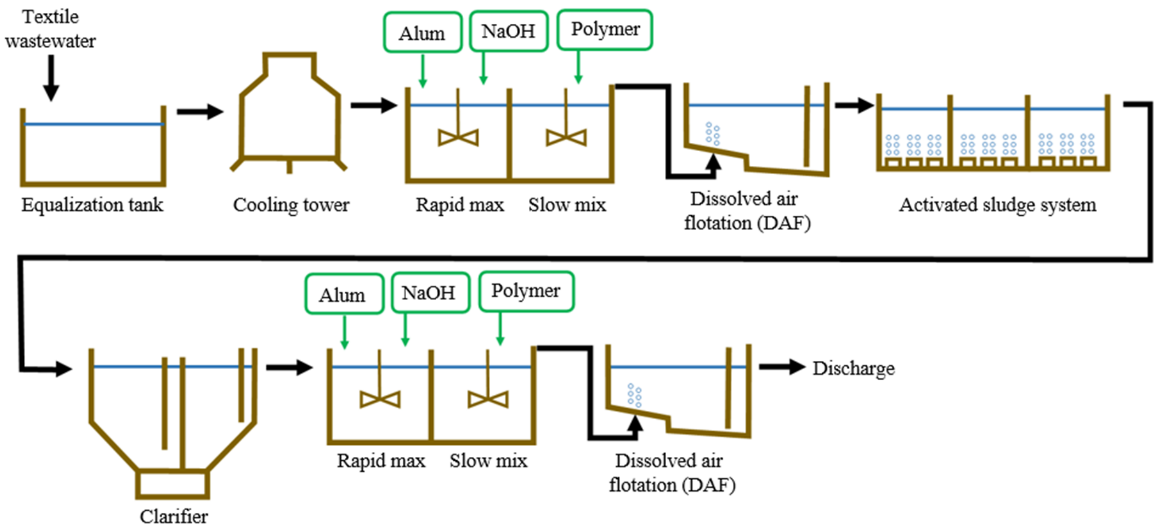


Fig. 1 The schematic diagram of the wastewater treatment processes of the textile factory

2.2. *Wastewater source and characteristics*

The daily wastewater quantity ranges approximately between 2500 and 3200 m^3/day (CMD). The COD and pH of the raw wastewater range from 600 to 800 mg/L and 8.58.7, respectively. In this study, the treated wastewater from the first DAF system was used as the influent of the pilot-scale MBR plant. The COD of the MBR influent ranged from 200 to 500 mg/L; the color ranged from 300 to 400 Pt-Co. During the test, the MBR influent was switched to the mixed liquor of the activated sludge system to increase biomass concentrations and evaluate membrane fouling under high biomass conditions. The COD of this stream ranged from 100 to 200 mg/L.

2.3. *Pilot-scale MBR and RO plant*

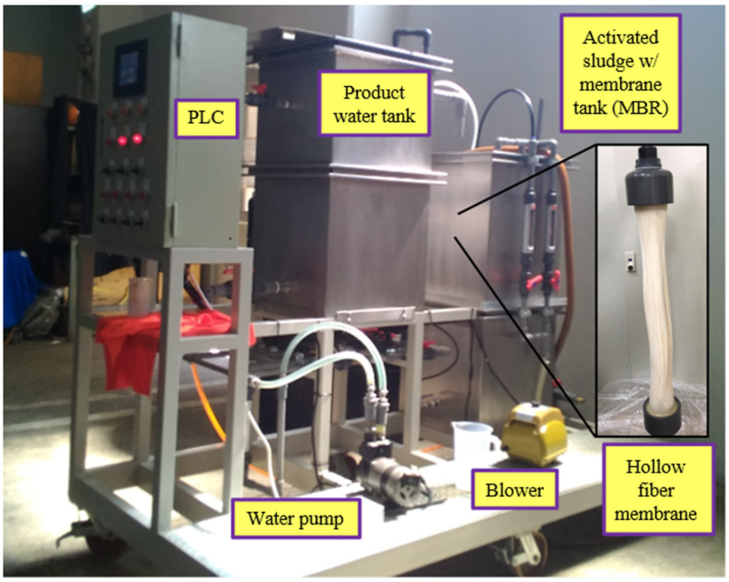


Fig. 2 The pilot-scale MBR module

The picture of the pilot-scale MBR module is shown in Fig. 2. The entire module has dimensions of 1 m wide, 2 m long, and 1.8 m high, with a capacity of up to 400 L/d. The system consisted of an activated sludge tank with polyvinylidene fluoride (PVDF) hollow fiber membranes (SUEZ, ZeeWeed® 500D), with a membrane length of 60 cm and a pore size of 0.04 μm.

The system also included a product water tank, a programmable logic controller (PLC) system, a water pump, and a blower. The effluent from the first DAF system flowed into the activated sludge tank with hollow fiber membranes, and the resulting filtrate was collected in the product water tank.

The picture of the pilot-scale RO module is shown in Fig. 3. The system consisted of an influent tank, which stored the MBR product water, a 90 cm RO membrane, a water pump, a PLC system, and a 5 μm filter installed before the RO membrane. The RO membrane utilized in the system was a spiral-wound element with a polyamide thin-film composite supplied by SUEZ. The purpose of the filter was to protect the RO membrane from large particles that could potentially clog the membrane.

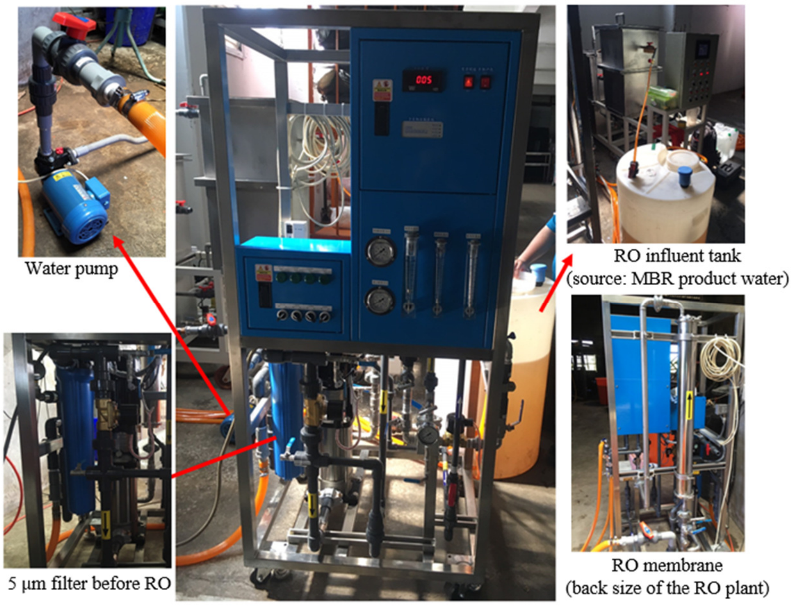


Fig. 3 The picture of the pilot-scale RO module

2.4. Operational conditions

At the beginning of the test period, the MBR was inoculated with 10 liters of activated sludge obtained from the activated sludge system in the textile factory. The schedule of the important working items is listed in Table 1. The initial MBR permeate flux was 15 LMH and increased to 20 LMH on the 36th day. The initial backwash flux was 34 LMH and was conducted for 60 sec with a 9 min interval of producing water. As the system achieved stability, the producing water interval was increased, while the backwash time was decreased, as shown in Table 1. During the first 20 days of RO operation, the permeate flow rate ranged from 2.3 to 2.8 mL/min with a recovery rate of 13 to 17%. Subsequently, the RO brine with a flow rate ranging from 33 to 35 mL/min was recycled to increase the recovery rate from 44 to 48%.

Table 1 The schedule of the important working items during the test period

Time (day)	Working items
1	1. Inoculated with 10 L of activated sludge obtained from the activated sludge system in the textile factory. 2. Started running the pilot MBR module.
16	Inoculated with 10 L of activated sludge obtained from another activated sludge system.
25	Increased filtration time (9 to 12 min) and decreased backwash time (60 to 30 sec).
36	Increased permeate flux from 15 to 20 LMH.
40	1. Increased MBR filtration time from 12 to 15 min. 2. Started running the pilot RO module.
56	Recycled the RO brine to increase the recovery rate.
83	Switched the MBR influent from the DAF to the mixed liquor of the activated sludge system.
97	Switched MBR influent back to the DAF

3. Results and Discussion

In this section, the experimental tests of the pilot-scale MBR using different sources of wastewater were conducted for 7 months. The temporal variations in COD and MLSS were observed during the operation. Membrane fouling in the MBR system was monitored and evaluated. In addition, the operation and performance of the RO module were also extensively monitored and analyzed. These results provide valuable insights into the potential applications of MBR and RO in textile wastewater treatment and reclamation.

3.1. Pilot-scale MBR

The pilot-scale MBR has been operated for approximately 7 months (198 days). Fig. 4Fig. 4 illustrates the temporal variations of COD in the MBR influent and effluent. The COD of the DAF effluent ranged from 169 to 523 mg/L (average: 332±84 mg/L) and the MBR effluent ranged from 5 to 88 mg/L (average: 38±24 mg/L), resulting in an average removal efficiency of 88%. The fluctuations in the influent COD levels can be attributed to the variation of the manufacturing processes, in which different chemicals and additives are applied. In addition, the variability in production quantities and batch sizes in the textile factory can also contribute to COD fluctuations. On the other hand, the COD of the activated sludge mixed liquor ranged from 107 to 200 mg/L (average: 165±39 mg/L), and the MBR effluent ranged from 50 to 143 mg/L (average: 94±35 mg/L). The average removal efficiency was only 43%, significantly lower than the removal efficiency using the DAF effluent as the MBR source wastewater.

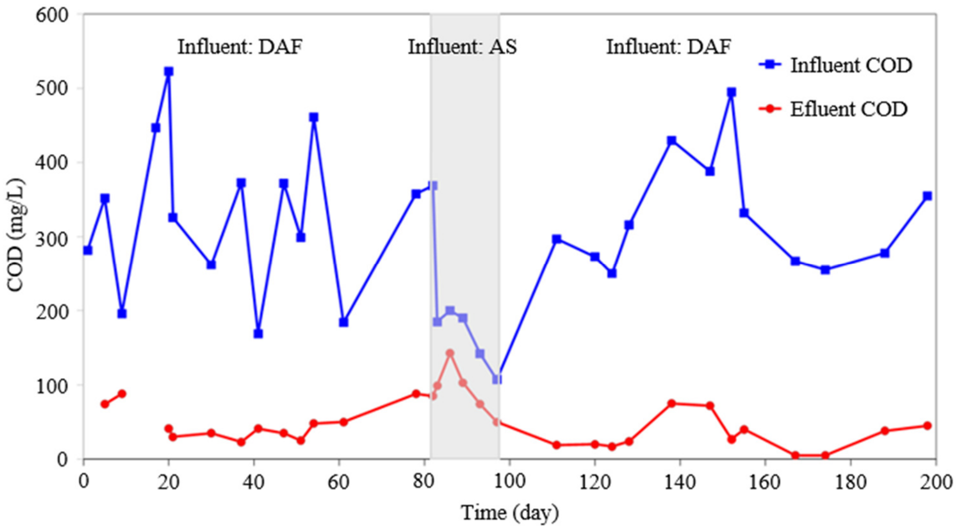


Fig. 4 MBR influent and effluent COD as a function of time. (AS: activated sludge)

The mixed liquor-suspended solids (MLSS) of the MBR as a function of time is presented in Fig. 5. During the first 80 days of operation, the MLSS in the MBR system gradually increased due to the growth of the biomass in the system. During the 83rd to 97th day, there was an MLSS spike when the activated sludge mixed liquor was used as the MBR influent. Theoretically, such high MLSS should result in better COD removal efficiency. However, the COD removal decreased from 83% to 43%. Two phenomena were observed: (1) the pressure during membrane backwash was significantly increased from 10 Kpa to 50 Kpa (data not shown); (2) the oil and grease were observed in the MBR system. Therefore, two samples were collected from the activated sludge system on two different dates, and the oil concentrations were measured. The results were 310 and 503 mg/L, respectively (Fig. 5), which was significantly higher than the normal oil concentration that MBR can treat.

Abass et al. [19] found that increasing oil and grease concentration in the MBR influent from 83 mg/L to 260 mg/L accelerated membrane fouling, despite the repeated physical cleaning operation performed [20]. It was found that the oil could be from the kitchen or manufacturing processes and accumulate in the activated sludge. The high oil concentration can cover the microorganism biomass in the MBR and significantly affect the ability to degrade the organics in the wastewater [20]. The oil could also cause membrane fouling for long-term operation, reducing the filtration efficiency, requiring more frequent chemical cleaning, and eventually increasing operating costs. Therefore, the MBR influent was switched back to DAF effluent to prevent oil contamination. Meanwhile, part of the MLSS in the MBR was discharged to remove oily biomass, which made the MLSS low during the 111th to 147th day.

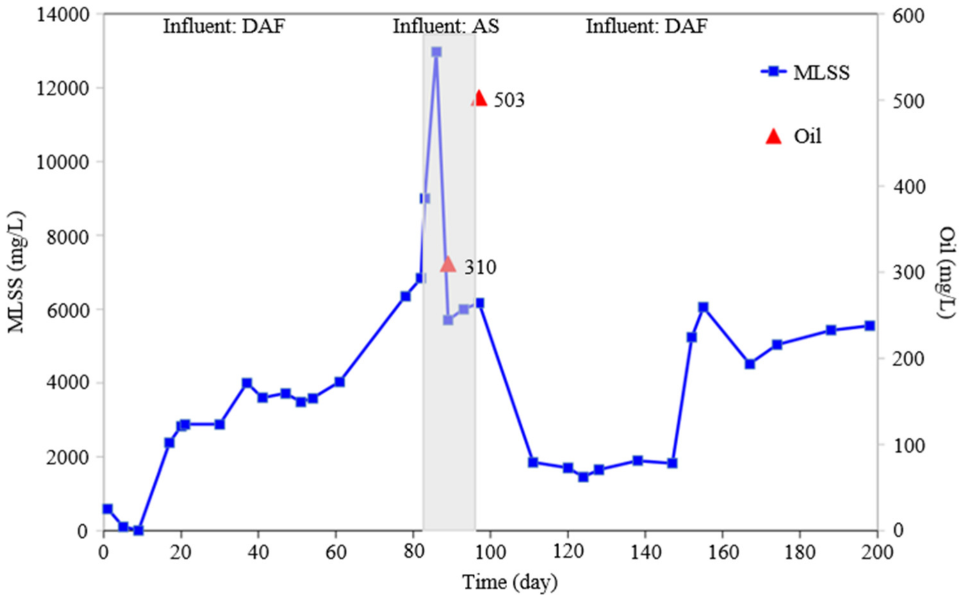


Fig. 5 MLSS and Oil concentration in MBR over time

Membrane fouling is a major drawback of the MBR process, leading to a decline in permeate flux or an increase in the TMP over time. This subsequently results in higher operating costs, reduced treatment capacity, and ultimately shortens the life span of membranes [21-22]. To evaluate whether the wastewater from the textile factory severely fouled the hollow fiber membrane, the TMP was monitored throughout the test period. Fig. 6 shows the MBR TMP of the produced water as a function of operation time.

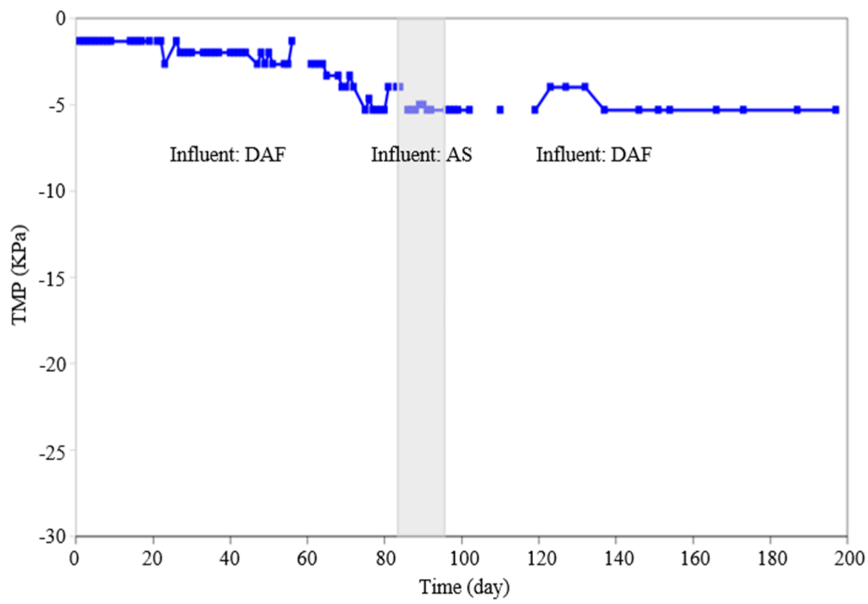


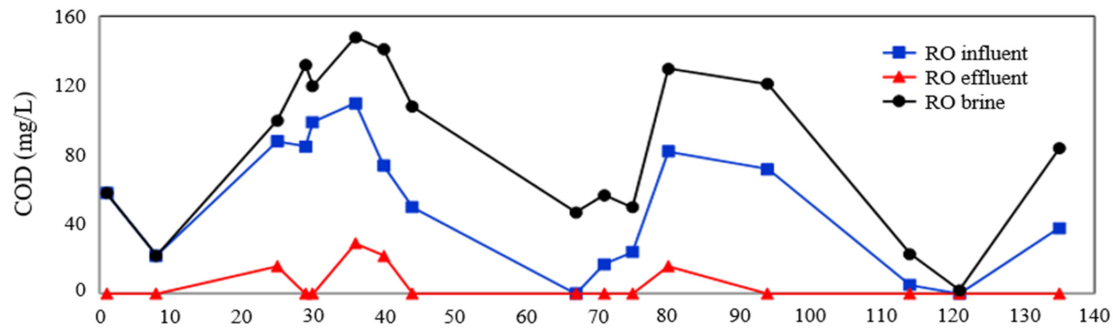
Fig. 6 MBR TMP of producing water as a function of operation time

The TMP started from -1.3 Kpa, gradually decreased to -5.3 Kpa on the 75th day, and remained stable until the end of the test. The final TMP was still significantly lower than the TMP requiring chemical cleaning (usually -50 KPa, but it varies by different manufacturers). The membrane permeability (the ratio of flux to TMP) during the test period ranged from 3.9 to 11.2

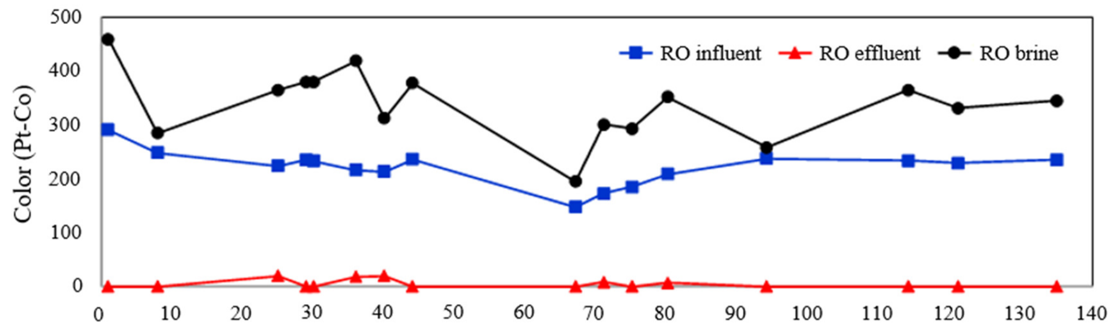
LMH/KPa, similar to the permeability reported in other MBR systems for industrial wastewater reuse (i.e., 3 to 1000 LMH/KPa) [23]. These results indicate that the hollow fiber membrane used in this study performed extremely well and was suitable for treating the wastewater produced by this factory. However, the MBR effluent did not meet the reused standards directly (COD < 30 mg/L, and conductivity < 1800 μS/cm) [24-25]. Therefore, from a water reuse perspective, the implementation of other advanced treatment technologies should be considered to achieve reuse standards.

3.2. Pilot-scale RO

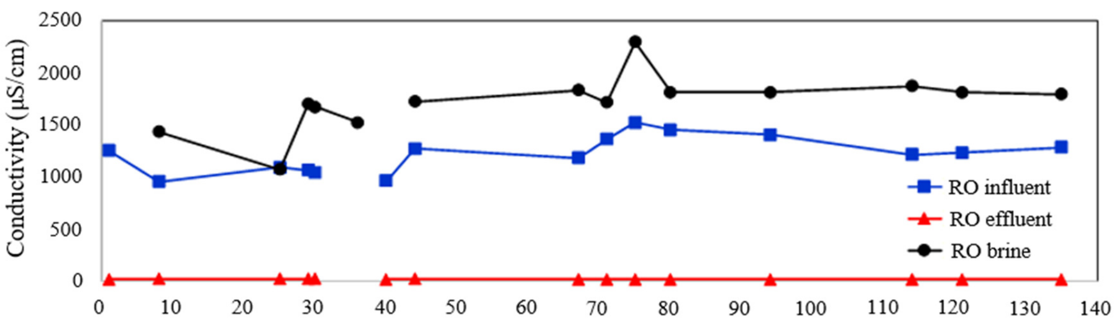
The pilot-scale RO module has been operated for more than 4 months (135 days). During the test period, COD, color, and conductivity of the RO influent, effluent, and brine were monitored as shown in Fig. 7. It is noted that RO brine was not recycled for the first 7 days of operation, which resulted in a recovery rate of 13~17%. Afterward, RO brine was recycled once till the end of the test, and the average recovery rate was 50%. The average COD, color, and conductivity of the RO permeate was 7 mg/L, 7 Pt-Co, and 16 μS/cm, respectively, and the removal efficiency of COD, color, and conductivity were 92%, 98%, and 99%, respectively. The RO permeate is qualified for reuse in the manufacturing processes within this textile factory, enabling a significant reduction in the quantity of freshwater used in the production process.



(a) COD of the RO influent, effluent, and brine



(b) Color of the RO influent, effluent, and brine



(c) Conductivity of the RO influent, effluent, and brine

Fig. 7 COD, color, and conductivity of the RO influent, effluent, and brine as a function of time

Similar to MBR systems, fouling is a primary issue in RO applications. Generally, RO membrane fouling is classified into inorganic fouling, organic fouling, biofouling, and colloidal fouling [26]. Among them, biofouling is a significant concern for RO membranes because microorganisms are widespread in most waters. Bacteria can secrete extracellular polymeric substances (EPS) that facilitate their attachment to membrane surfaces. This can lead to the formation of biofilms. Biofilms provide an environment for bacterial colonization and continuous release of EPS and organic compounds such as polysaccharides and proteins. These substances accumulate within the membrane [26]. Ismail et al. [27] indicate that biofouling accounts for over 45% of all membrane fouling.

In this study, the TMP of the RO membrane remained below 0.5 kg/cm^2 during the entire test (ranged from 0.1 to 0.4 kg/cm^2, data not shown), which was still below the critical pressure required for chemical cleaning (i.e.,1 kg/cm^2). The results obtained not only indicated that fouling or scaling of the RO membrane was not an issue when applying the MBR effluent as its inlet water but also demonstrated the feasibility of combining MBR and RO for the treatment and reclamation of textile wastewater. Furthermore, the average COD, color, and conductivity of the RO brine were 85 mg/L, 340 Pt-Co, and 1730 µS/cm, respectively. These values were below the wastewater discharge standards [28], indicating that the RO brine is likely suitable for direct discharge without additional treatment.

3.3. Summary and suggestions

The study demonstrated that MBR resembles a highly effective system for treating DAF effluent. Combining with the RO module can produce high-quality permeate suitable for textile processes in the factory, indicating the feasibility of the MBR-RO system for wastewater treatment and reclamation in full-scale treatment processes. The water characteristics of each treatment stage and corresponding pictures of water samples are shown in Fig. 8.

Based on the test results, it is recommended to replace the current sludge in the activated sludge system with new sludge when constructing a full-scale treatment process. Since the current sludge contains high-concentration oil due to long-term accumulation from the wastewater (i.e., kitchen wastewater or manufacturing processes). Wastewater streams containing oil need to be pretreated to decrease the impact on the sludge and membranes. High oil concentration could cover the biomass and significantly affect its ability to degrade the organics in the MBR, resulting in low COD removal. The oil accumulating in the system can foul the membrane and cause severe membrane clogging. Furthermore, part of the oil can penetrate the membrane and reach the RO module, and eventually foul the RO membrane.

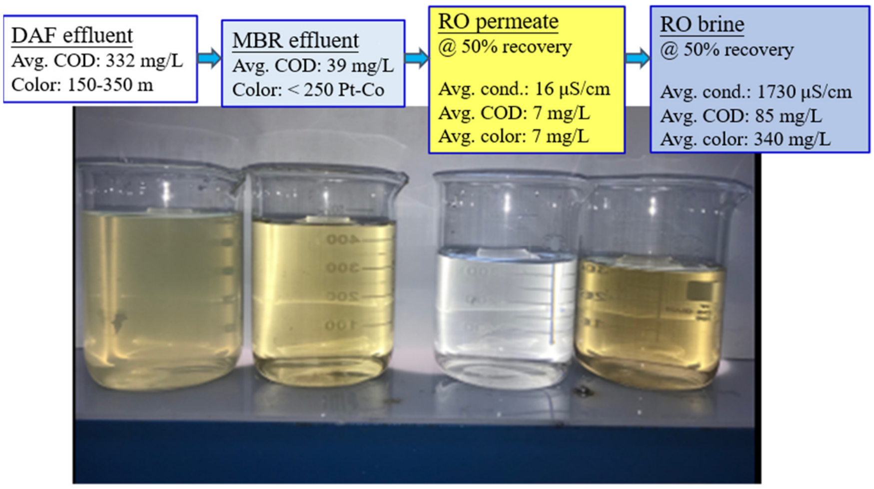


Fig. 8 Water characteristics of each treatment stage and corresponding pictures of water samples

4. Conclusions

The pilot MBR system was continuously operated for 7 months, and the pilot RO module was operated for more than 4 months with a recovery rate of 50%. The experimental results lead to the following conclusions:

(1) The average COD of MBR effluent is 38±24 mg/L when applying the DAF effluent as its inlet water, which results in an average removal efficiency of 88%.

(2) The TMP of the MBR ranged from -3 to -5 Kpa with a permeate flux of approximately 20 LMH during the test. The results demonstrate that the hollow fiber membrane used performed extremely well, hence it can apply to the wastewater produced from the factory.

(3) The average COD, color, and conductivity of the RO permeate are 7 mg/L, 7 Pt-Co, and 16 μS/cm, respectively. The removal efficiency of COD, color, and conductivity are 92%, 98%, and 99%, respectively.

(4) The result indicates that the RO permeate is suitable for reuse in the manufacturing processes. Additionally, the TMP of the RO membrane was ≤ 0.5 kg/cm^2 during the entire test.

(5) The results of this study demonstrate the great feasibility of using MBR combined with RO to treat and reclaim textile wastewater.

Acknowledgment

The authors gratefully acknowledge EClean-Tech Enterprise Co., Ltd for providing the pilot equipment and financial support. The authors would also like to express their appreciation to Ms. Chiou-Mei Chen for her helpful discussion.

Conflicts of Interest

The authors declare no conflict of interest.

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