Received: 5 January 2021 Revised: 24 February 2021 Accepted article published: 1 March 2021 Published online in Wiley Online Library: 15 March 2021

(wileyonlinelibrary.com) DOI 10.1002/jctb.6716

Investigation of the treatability of pre-coagulated slaughterhouse wastewater using dead-end filtration

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Abstract

BACKGROUND: In the present study, the performance of the membrane process, one of the advanced treatment methods that can enable the reuse of slaughterhouse wastewater, was evaluated. The wastewater was treated using ultrafiltration (UF) (10, 50 kDa), nanofiltration (NF) (150–300 DA) and reverse osmosis (RO) (500 kDa) membranes alone, and UF + NF, UF + RO membrane combinations at different pressures. In addition to rejection and permeate flux considerations, it was attempted to select the most effective membrane by performing scanning electron microscopy, Fourier transform infrared, contact angle, and atomic force microscopy analyses of the membranes used.

RESULTS: As a result of the experiments, the highest flux was observed at 5 bar for the 50 kDa UF membrane. When the performances of the sequential application of 10 and 50 kDa UF membranes followed by NF and RO membranes were evaluated, the highest flux was obtained for the sequential application of the 50 kDa UF membrane with the NF membrane as 19.68 and 9.05 L m^{-2} h, respectively.

CONCLUSION: The highest chemical oxygen demand (COD) removal was obtained for the RO membrane at 20 bar as 88.67%, and for the 50 kDa UF + RO sequential application, the COD removal was increased from 70% to 88.67%.

Keywords: slaughterhouse wastewater; membrane treatment; nanofiltration; ultrafiltration; reverse osmosis; dead-end filtration

INTRODUCTION

With the rapid population growth, the increasing demand and need for food products accelerate the development of the food industry. At the same time, adverse effects of the amount of wastewater originating from this industry on the environment have also increased. The amount of water used during animal slaughter to obtain products is also quite high. In particular, the damage caused by wastewater to the receiving environment varies depending on its volume and concentration.[1] When slaughterhouse wastewater is discharged to the receiving environment without any treatment, it causes the dissolved oxygen of the receiving environment to be depleted and the aquatic environment to deteriorate. The depletion of dissolved oxygen influences the aerobic life in water, especially the life of living beings. When oxygen in the environment is completely depleted, anaerobic decomposition occurs, and undesirable decomposition products, such as methane and hydrogen sulfide, are formed. Blood is the most important pollution parameter in facilities where slaughter is performed. The biochemical oxygen demand (BOD) of the blood is approximately 100 000 mg L^{-1}. This wastewater should be treated since it contains high amounts of pollution, and various physical,[2,3] chemical,[4–7] and biological[8–11] treatment techniques are used to treat this water. However, these treatment techniques also bring some operational problems due to the high amount of pollution in the wastewater. This necessitates investigating alternative treatment technologies. Since slaughterhouse wastewater is highly biodegradable and has a high organic matter content, it is usually treated by biological treatment methods. In anaerobic and aerobic processes used as a biological treatment method, parameters such as temperature, high organic load, the length of residence time, and suspended solids concentration influence the process efficiency. Therefore, these processes must be kept under constant control. Furthermore, the volume of wastewater and excess organic load are among the main problems encountered in applying these processes.[12]

In conventional treatment facilities, advanced treatment techniques are used to make persistent substances, which cannot be removed or degraded, harmless. In recent years, advanced treatment techniques have been employed in the treatment of this type of wastewater to narrow the discharge standards and reuse the water. In pre- and post-treatment, BOD values are significantly reduced, and harmful microorganisms are destroyed. Nevertheless, such water may contain suspended solids and large amounts

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of water-soluble organic and inorganic substances. Membrane processes, which are among advanced treatment techniques,[13,14] are used in studies to remove these substances, although at a low rate. In this study, the performance of membrane processes in this wastewater treatment was investigated because of the low number of membrane separation systems, an advanced treatment technique used in the management of waste. Membrane processes are preferred because they require fewer chemicals, have high effluent water quality, are easy to operate and take up less space. Furthermore, by using membrane processes after pre-treatment, the output water values specified in the regulations were obtained, and high-quality water was produced. To this end, the pre-treatment of slaughterhouse wastewater was carried out by the coagulation–flocculation process using alum coagulant. Afterwards, the pre-treated wastewater was treated using ultrafiltration (UF), nanofiltration (NF), reverse osmosis (RO) membranes and the individual and sequential combinations of these membranes at different pressures and with different molecular weight cut-offs (MWCOs) applied. As a result of the experiments, flux losses in the membranes, the contaminant removal performance of the membranes, scanning electron microscopy (SEM), Fourier transform infrared (FTIR), contact angle and atomic force microscopy (AFM) analyses were investigated, and we attempted to select the most effective membrane.

MATERIALS AND METHODS

Characterization of slaughterhouse wastewater

Samples of slaughterhouse wastewater were obtained from Nigde Municipality Slaughterhouse in Turkey. The characterization of slaughterhouse wastewater is given in Table 1.

Membrane filtration experiments

Before membrane filtration tests, slaughterhouse wastewater was pre-treated by the coagulation–flocculation process using alum coagulant (pH 6.5, alum concentration of 1000 mg L^{-1}, rapid mixing rate of 150 rpm, and settling time of 10 min).[15] The chemical oxygen demand (COD) value of the wastewater after pre-treatment was determined to be 940 mg L^{-1}. Membrane experiments were carried out by collecting the supernatant part of the wastewater after pre-treatment.

RO and NF membranes were used with and without the UF process after pre-treatment. Consequently, five different alternatives were tested in membrane processes. The first used a UF-only process (3–5 bar), the second used an NF-only process (8–10 bar), the third used an RO-only process (15–20 bar), the fourth used the NF (10 bar) process after UF (5 bar), and the fifth used the RO (20 bar) process after UF (5 bar). In the experiments, low and high pressures were selected by considering the properties of the membrane used to more clearly determine the effect of pressure change on flux and removal in the membranes with different pore sizes. Membrane tests of coagulated slaughterhouse wastewater were conducted in a stirred filtration unit (Sterlitech HP4750, Kent, WA, USA) with a 300 mL capacity given in Fig. 1. The tests were carried out at room temperature (25 ± 2 °C). After 250 mL wastewater was placed in the filtration unit, pressure setting (3–5–8–10–15–20 bar) was performed. The membrane system was stirred continuously to prevent concentration polarization on the surface of the membrane. The desired membrane pressure in the system was provided by nitrogen gas fed directly to the module. The pure water fluxes were examined before and after the wastewater passed through the membrane.

Table 1. Characterization of slaughterhouse wastewater

Parameter	Result
pH	7.11
Turbidity (NTU)	92.4
Chemical oxygen demand (COD) (mg COD L^{-1})	3800
Total organic carbon (TOC) (mg L^{-1})	1595.5
Conductivity (mS cm^{-1})	4.32
Suspended solid (SS) (mg L^{-1})	188
Total phosphorus (TP) (mg L^{-1})	11.7

Analytical methods

All characterization analyses were conducted according to the standard methods (SM).[16] The WTW Inolab pH7110 (Germany) for pH, HACH 2100 N (USA) as the turbidimeter, WTW CR3200 (Germany) as the COD digester, and WTW Inolab multi 9320 device for conductivity were used in all analyses. COD was realized according to the closed reflux titrimetric method (SM 5220 C). Suspended solids (SS) and conductivity analyses were performed according to the SM 2540 D and SM 2510 B methods, respectively. Removal efficiency (R) was determined using the following equation:

$$R(\%)=\left[1-\frac{Y}{Y_0}\right]\times 100 \quad (1)$$

where Y_0 indicates the initial values for turbidity, SS and COD, and Y denotes the values found in the experiment.

The general properties of the membranes used in the experiments are presented in Table 2.

SEM

The morphological properties of the virgin and fouled membranes tested for wastewater treatment were examined by SEM. The membrane samples were cut approximately 3 mm long and 0.5 mm wide and then mounted on an SEM grid. Prior to the examination, each sample was coated with platinum using a JFC 1600 Auto Fine Coater (JEOL, Akishima, Japan). In the analysis of the samples, a scanning electron microscope (LEO 440, Leica Zeiss, Oberkochen, Germany) was used at 10 kV. The average fiber diameter of each membrane was examined by SoftPadia in different positions using Digimizer, and appropriate and clear images were taken.

Fourier transform infrared

FTIR spectra of the virgin and fouled membranes were measured by collecting in the wavelength range of 500–4000 cm^{-1} in the transmission mode using a Thermo Nicolet Avatar 370 spectrometer (Thermo Nicolet, USA). Before FTIR determination, measurements were made after drying the samples in a drying oven at 120 °C for 15 min.

Atomic force microscopy

AFM measurements were made for the analysis of fouling on the membrane surface. Measurements were performed using a MultiMode 8-HR, RTESP-300 model AFM device. R_a, R_{rms}, and R_z parameters were obtained by the AFM measurements, allowing us to comment on membrane roughness:

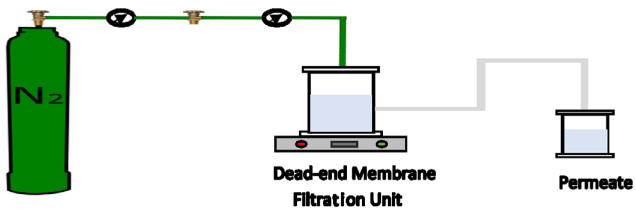

Figure 1. Dead-end membrane filtration setup used in the experiments.

Table 2. Membranes used during the experiments and their properties

Membrane type	MWCO	Properties
UF	10 kDa	GE PW, polyethersulfone (PES), UF, 47 mm
UF	50 kDa	GE MW, polyacrylonitrile (PAN), UF, 47 mm
NF	150–300 Da	GE DL nanofiltration (NF), 47 mm
RO	500 kDa	GE AG (RO), polyvinylidene fluoride (PVDF), 47 mm

$$R_a = \frac{1}{p}\sum_{i=0}^{p}|Z_{cu} - Z_{av}| \quad (2)$$

where R_a is the average roughness value on the membrane surface (nm); p is the number of measured points in the membrane surface area; Z_{cu} is the height at a certain point on the membrane surface (nm); Z_{av} is the average height at a certain point on the membrane surface (nm);

$$R_{rms} = \sqrt{\frac{\sum (Z_{cu} - Z_{av})^2}{p}} \quad (3)$$

where R_{rms} is the standard deviation of the average roughness on the membrane surface (nm); and R_z is the average of the five highest and five lowest points on the membrane surface (nm).

Contact angle analysis

Contact angle measurements were made to determine the change in the hydrophobic/hydrophilic properties of the virgin and fouled membrane surfaces. They were performed using the Attension-Theta-Lite Model Goniometer device by the 'sessile drop' method. Approximately pure water was dropped onto the dirty and stripped membrane surface using a microsyringe, and the resulting image was instantly imaged by a camera connected to the device. The right and left angles formed by the water drop and the membrane were automatically measured on the computer with the software support on the device. The average of these two angles was recorded as the contact angle of the membrane.

Fouling performance measurement

To study the fouling performance of the membranes, flux losses and flux recovery ratio (FRR) were determined by separately calculating the total flux loss, flux loss due to fouling, and flux loss due to concentration polarization. To calculate flux losses, it is necessary to know the pure water flux (J_0) of the clean membrane, the wastewater flux (J) formed after the wastewater is passed, and the pure water flux (J_f) of the contaminated membrane. The equations employed to compute flux losses and flux recovery ratio (FRR) are as follows:

$$\text{Total flux loss} = \frac{J_0 - J}{J_0} \times 100 \quad (4)$$

$$\text{Flux loss due to fouling} = \frac{J_0 - J_f}{J_0} \times 100 \quad (5)$$

$$\text{Flux loss due to concentration polarization} = \frac{J_f - J}{J_0} \times 100 \quad (6)$$

$$\text{FRR}(\%) = \frac{J_f}{J_0} \times 100 \quad (7)$$

RESULTS AND DISCUSSION

Membrane experiments

The flux values of the different 10 kDa UF, 50 kDa UF, 150–300 Da NF, and 500 kDa RO membranes measured individually and UF + NF, UF + RO combinations are given in Fig. 2. Experiments were

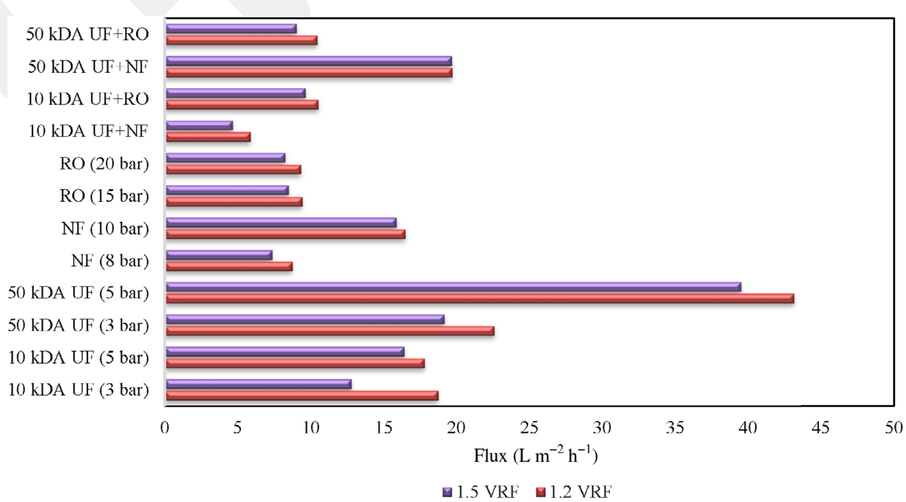

Figure 2. Flux values at different pressures.

Table 3. Flux losses of the membranes used as a result of passing wastewater

Membrane type	Flux loss (%) Total flux loss	Flux loss due to fouling	Flux loss due to concentration polarization	FRR (%)
10 kDa UF (3 bar)	80.61	58.91	21.7	41.08
10 kDa UF (5 bar)	67.60	0.68	66.92	32.98
50 kDa UF (3 bar)	84.10	44.99	39.11	55.01
50 kDa UF (5 bar)	80.69	57.53	23.16	42.47
150–300 Da NF (8 bar)	57.89	5.94	51.94	94.05
150–300 Da NF (10 bar)	27.27	3.89	23.38	96.71
RO (500 kDa) 15 bar	71.30	60.62	10.68	39.38
RO (500 kDa) 20 bar	59.21	32.76	26.45	67.24
10 kDa UF + NF	79.89	1.99	77.90	98.01
10 kDa UF + RO	43.11	20.02	23.09	79.97
50 kDa UF + NF	42.67	22.8	19.87	77.19
50 kDa UF+RO	38.77	22.12	16.65	77.87

Table 4. COD, turbidity, and conductivity removal performance of the membranes used for slaughterhouse wastewater treatment

Membrane/pressure	COD removal (%)	Turbidity removal (%)	Conductivity removal (%)
10 kDa UF (3 bar)	48.57	70	32
10 kDa UF (5 bar)	71.43	95.45	27.33
50 kDa UF (3 bar)	45.71	88.33	8.33
50 kDa UF (5 bar)	70	69.17	11.33
NF (8 bar)	71.43	93.67	55.33
NF (10 bar)	68.57	75.67	81.4
RO (15 bar)	82.86	63	93.07
RO (20 bar)	88.57	95.17	88.67
10 kDa UF + NF	78.57	90.87	57
10 kDa UF + RO	68.57	69.5	94.92
50 kDa UF + NF	62.86	97.07	79.43
50 kDa UF + RO	88.57	96.05	90.5

carried out with two different volume reduction factors (VRF) (1.2 and 1.5).

Flux values increased as the pressure increased in the 50 kDa UF membrane and NF membrane. When the experiments with two different UF membranes and two different pressures were compared, the flux values obtained in the 50 kDa UF membrane and at a pressure of 5 bar were higher. The reason for the higher flux difference compared to the 10 kDa UF membrane was the fact that the polyethersulfone (PES) membrane was hydrophobic and more resistant to chemical corrosion.[17] Based on this, flux values increased as the pore diameter decreased and the applied pressure increased. Likewise, since MWCO of the 150–300 DA NF membrane was smaller compared to the UF membrane and when the pressure was increased from 8 to 10 bar, the obtained flux values increased. Similarly, in the study conducted by Kaleli,[18] the flux value increased as the pressure value increased. Aydiner[19] also stated in his study that when the flux results of membranes with different pore sizes were compared, the flux of the membrane with a large pore size was higher. When the experiments conducted with the 500 DA RO membrane are examined, it is observed that the pressure increase did not affect flux. Considering the flux losses obtained at all pressure values, although the flux loss occurring at 15 bar was higher, the flux loss due to concentration polarization occurred faster with the increase of the pressure at 20 bar, and the resulting flux loss was approximately 60% more than the loss at 15 bar. Due to this high concentration polarization, the increase in the osmotic pressure between the filtrate and the feed solution did not affect the flux. In their study on the treatment of poultry processing wastewater with 10–300 kDa PES and regenerated cellulose membrane, Malmali *et al.*[14] obtained 50–350 L m^{-2} h flux values, COD above 94%, and 100% TSS removal. Lo *et al.*[20] performed a study on the treatment of poultry processing wastewater with a 30 kDa polysulfone membrane, and they obtained >200 L m^{-2} h flux values, 58.86% COD, and 35.79% TSS removal.

When the experiments performed with 10 and 50 kDa UF membranes together with NF and RO membranes are compared, it is observed that the highest flux was obtained with the combination of the 50 kDa UF membrane and NF membrane. This is thought to be due to the chemical structure of the PAN membrane.

Flux losses were determined by separately calculating the total flux loss, flux loss due to fouling, and flux loss due to concentration polarization. The flux loss and FRR values calculated as a result of the experiments are presented in Table 3.

When the flux losses of the 10 kDa UF membrane at different pressures are examined, it is observed that the total flux losses

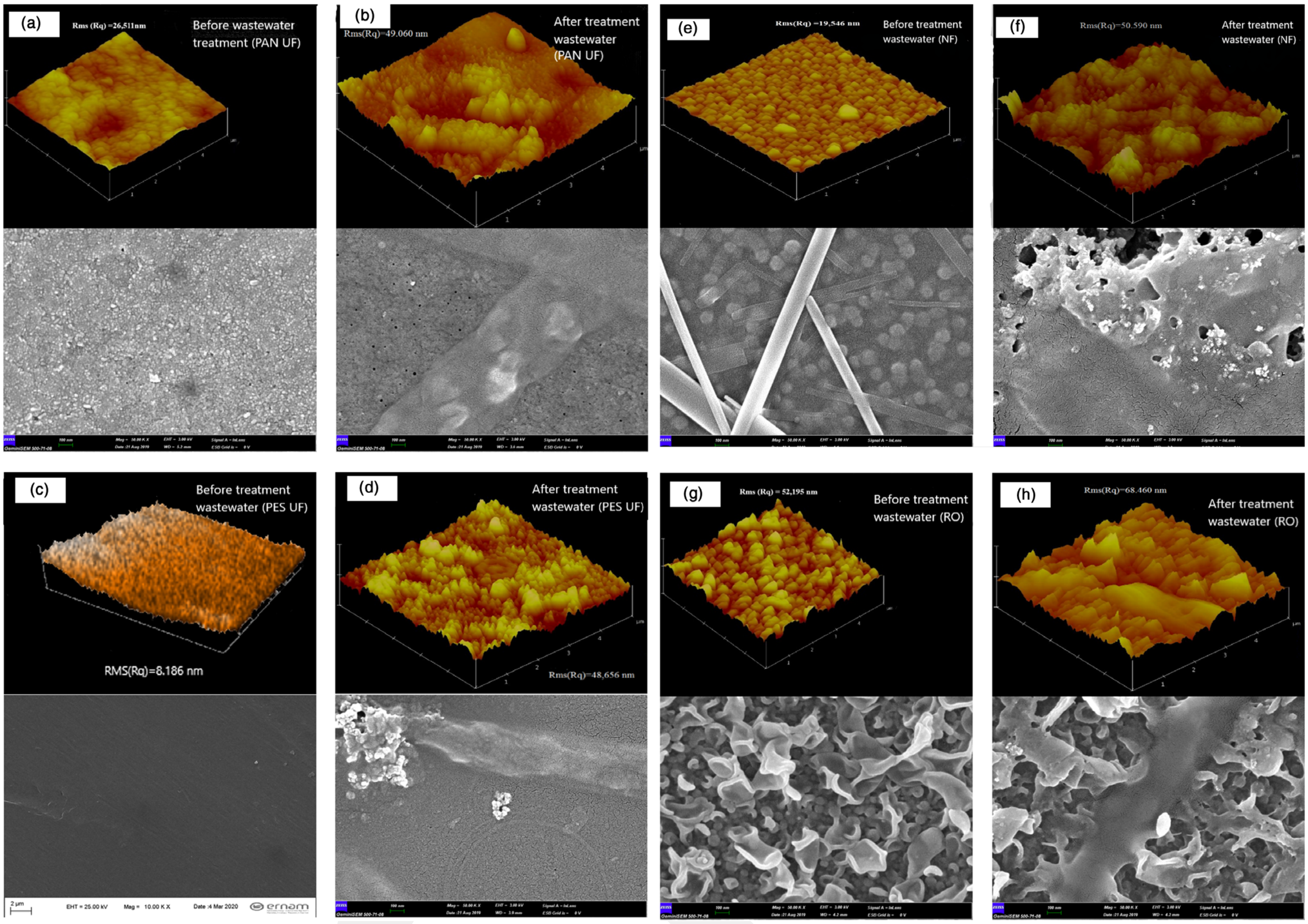

Figure 3. AFM and SEM images of the wastewater before and after treatment.

are close to each other. However, when the flux loss in the experiments conducted at 3 bar is examined, the flux loss due to fouling is higher than the flux loss due to concentration polarization. It was determined that the total flux losses obtained from the experiments performed with UF membranes were higher than the total flux losses obtained using the NF membrane. Flux loss is less in membranes with small pore sizes compared to membranes with large pore sizes. Therefore, in the small pore size membrane, due to the decrease in the particle diameter and porosity of the cake layer, the amount of contaminants in the mass retained in the membrane is less than in the large pore size membranes. This leads to an increase in the amount of mass and fouling values retained in membranes with small pores, but the flux value does not decrease in proportion to contamination due to less cake formation. As a result, it can be said that more flux loss occurs due to increased membrane fouling. Furthermore, it was revealed that the flux loss due to concentration polarization was higher in the experiments carried out at both 8 and 10 bar in NF membranes. The total flux losses obtained in the experiments with NF and RO membranes were the lowest after the 50 kDa UF membrane. While the flux loss due to fouling causes the pollutants in wastewater to accumulate on the surface or in the membrane pores, the fouling caused by concentration polarization depends largely on the feed concentration. The interaction between the membrane and the foulant on the surface of the NF membrane used alone and the combinations of UF + NF and UF + RO membranes is weak and reversible. This means that the membrane can be recovered after use by simple cleaning methods such as washing or backwashing.[21]

Upon examining the removal performance of the membranes given in Table 4, the best result in terms of COD removal was obtained in the RO (20 bar) (88.67%) and 50 kDa UF + RO (88.67%) membranes. It is observed that COD removal increased as the pore size of the membranes decreased. Membranes with small pore sizes can perform filtration for a longer time at higher flux without fouling than membranes with larger pore sizes. Small-sized particles cannot enter pores and form a cake layer on the membrane surface. Therefore, irreversible fouling that may occur on and/or within pores does not occur, or the formation of occlusion takes longer[22–24] Likewise, Coskun *et al.*[25] treated poultry slaughterhouse wastewater using RO, NF and UF membranes, and obtained the highest COD removal as 90% for NF and as 97.4% for RO. They reported that the conductivity parameter decreased by 51.7% for NF and by 96.6% for RO. Yordanov[26] obtained 94% COD removal and 98% suspended solids removal for the treatment of poultry slaughterhouse wastewater with a 25 kDa UF membrane. Aydiner[19] revealed that the COD removal of the NF membrane was much higher compared to the UF membrane. Likewise, Elcik *et al.* [27] examined the treatment of domestic wastewater using UF and NF membranes in their study. They indicated that the COD removal efficiency of the NF membrane was higher than that of the UF membrane.

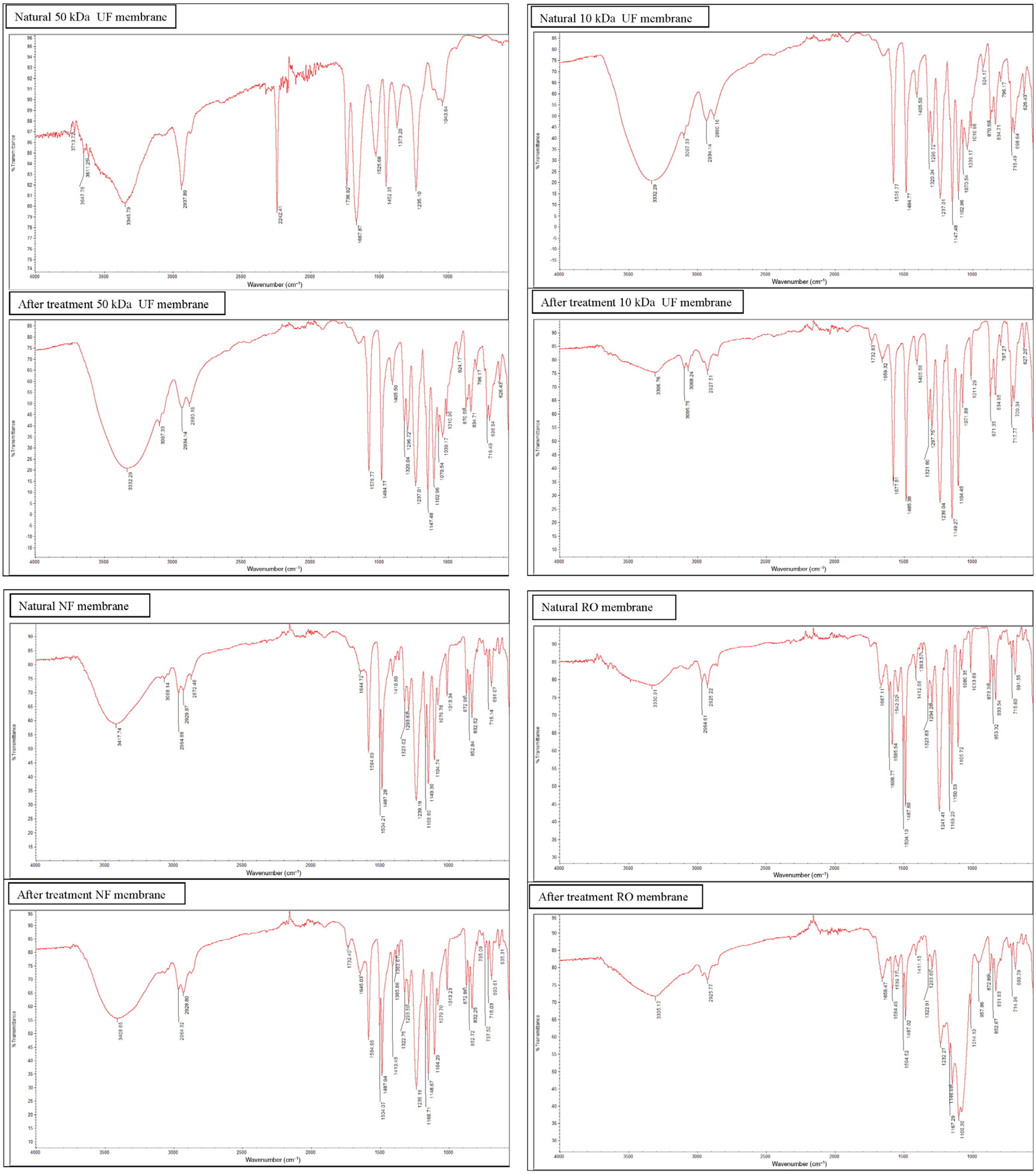

Figure 4. FTIR images of the wastewater before and after treatment.

Shih and Kozink[28] obtained 85% total solids and 95% COD removal efficiency in the treatment of poultry wastewater using the UF membrane. As pressure increased, COD removal increased in all membranes, except for the NF membrane. According to Darcy's law, the filtrate flow increases under the influence of increasing pressure. Moreover, in some cases, the pressure increase can have an adverse effect. A cake layer may occur on the membrane surface, which may cause a large flux reduction and a decrease in COD removal efficiency.[29] Göksel[30] examined the treatment of wood industry wastewater by membrane processes. To this end, they evaluated the COD removal performance of membranes with different pore sizes (50, 100, 200 nm) under different pressures. The researcher stated that the pressure increase in different pore sizes affected the COD removal efficiency differently.

Table 5. Average contact angle values

Membrane	Contact angle (°) Before slaughterhouse wastewater treatment	After slaughterhouse wastewater treatment
50 kDa, UF	32	53.8
10 kDa, UF	77.9	77.5
NF	57	79
RO	75	47.9

They stated that while increasing pressure in smaller pore sizes decreased COD removal, an increase in pressure increased COD removal efficiency in large pore size membranes. In their study, Akdemir and Özer[31] treated olive oil wastewater at different pressures using two different UF membranes. They concluded that COD removal was better at lower pressures. Rinquest *et al.*[8] evaluated the performance of a laboratory-scale poultry slaughterhouse wastewater treatment system consisting of a single-stage nitrification–denitrification (SND) bioreactor and a static granular bed reactor combined with ultrafiltration membrane systems. The dead-end filtration mode was used as an ultrafiltration system. As a result of the combined use of biological and physical treatment processes for this wastewater, COD, orthophosphate, TSS, and total dissolved solids (TDS) removal efficiencies were found to be 91%, 51%, 97%, and 52%, respectively. Almandoz *et al.*[32] examined the effectiveness of UF for the treatment of slaughterhouse wastewater. The present study recorded the high removal efficiencies of COD and TN as 90.63% and 45.22%, respectively. Sardari *et al.*[33] demonstrated the performance of EC-UF in comparison with individual UF for removal efficiency. Almost complete removal of TSS is obtained in EC-UF. A significant increase in the removal of COD and BOD is found when pre-treating PPW via EC prior to UF. COD and BOD were removed by up to 92% and 98%, respectively.

The AFM and SEM images of the clean and fouled membranes are presented in Fig. 3. When a comparison is made according to RMS values in AFM images, the RMS value of dirty membranes is higher in all membranes than clean membranes. The reason for this can be stated as the formation of a cake layer with an increase in the membrane capacity due to the clogging of pores.[34] When the SEM images are examined, it is observed that there are more pores in clean membranes, the pores are filled, and roughness occurs as a result of the fouling of membranes.

The FTIR spectra of the clean and after-slaughterhouse wastewater treatment membranes used in the experiments are presented in Fig. 4. When the FTIR analysis results of the clean and dirty membranes are examined, it is observed that there are many peaks at different wavelengths of the spectrum. Each wavelength refers to organic bonds and groups in the membrane. When the FTIR spectra of the membranes are examined, the peaks at wavelengths between 3713 and 3345 cm^{-1} correspond to the —O—H stretch,[35] the peaks at wavelengths between 3417 and 2872 cm^{-1} correspond to the C—H alkane group stretch,[36] the 2323 and 2242 cm^{-1} bands correspond to the C≡C stretch,[37] the peaks at wavelengths between 1736 and 1452 cm^{-1} correspond to the C═O stretch,[38] the peaks at wavelengths between 1373 and 1010 cm^{-1} correspond to the C—O stretch,[38] and the peaks at wavelengths between 957 and 552 cm^{-1} correspond to the C—H stretch.[36]

In Table 5, when the clean membranes were compared with the membranes through which wastewater was passed, an increase occurred in the contact angles after the wastewater was passed in all membranes, except for the RO membrane, and the hydrophobicity of the membranes increased. The PAN clean membrane changed from hydrophilic to hydrophobic. In the RO membrane, the hydrophobicity of the membrane, through which wastewater was passed, decreased, although slightly, compared to the clean membrane. There was no change between the clean and dirty membrane in the 10 kDa membrane.

As a result of all the analyses performed after the membrane tests, it is observed that the use of the RO membrane alone and 50 kDa UF + RO membrane has significant effects on the treatment of the slaughterhouse wastewater. Whereas the 50 kDa UF membrane alone does not have a significant effect on COD removal, its sequential use together with the RO membrane increased the treatment efficiency. While increasing the roughness of the membrane surface does not have an adverse effect on the membrane performance, it effectively improves the permeate flux and antifouling properties of the membrane.[39] Concerning the flux decrease, the lowest flux decrease was observed in the NF membrane (5.94%, 3.29%) and 10 kDa UF + NF (2%) membrane.

There are few studies in the literature on the treatment of slaughterhouse wastewater with membrane systems. Similarly to this study, Coskun *et al.*[25] investigated removal using RO, NF, and UF membranes after the centrifugation of wastewater and obtained a high COD removal efficiency of 97.4% with different RO membranes. When evaluated in terms of the membrane flux, the researchers reported that it was very important to use UF membranes as a pre-treatment stage. Similarly to the present study, 94% COD and 98% SS removal were obtained in the treatment of poultry slaughter wastewater using a 25 kDa UF membrane in another study.[26] Likewise, 85.8% removal efficiency was acquired for COD in a study in which slaughterhouse wastewater was treated with RO membranes as a secondary waste.[40]

CONCLUSION

The slaughterhouse wastewater removal performance of the membranes used in this study, membrane fluxes and flux losses were evaluated, and SEM, FTIR, contact size, and AFM analyses were performed. In general, the following results were obtained from the study:

(1) Within the tested 10 kDa UF, 50 kDa UF, 150–300 DA NF, 500 kDa RO and 10 and 50 kDa UF membranes combined with NF and RO membranes, the highest flux was obtained with the 50 kDa membrane at 5 bar. The lowest flux was obtained with the 10 kDa UF + NF membrane. In the study, the flux increased as the pressure increased in all membrane tests, except for the RO membrane.

(2) When the comparison is made in terms of flux losses, it is observed that the total flux losses at different pressures of the 10 kDa UF membrane were close to each other, but in the flux losses obtained in the experiments conducted at 3 bar the flux loss due to fouling was higher than the flux loss due to concentration polarization. It was revealed that the total flux losses obtained with UF membranes were higher than the total flux losses obtained with the NF membrane. Furthermore, it was determined that the flux loss due to concentration polarization was higher in the experiments carried

out both at 8 bar and 10 bar in NF membranes. The lowest total flux losses were obtained with the NF and RO membranes applied after the 50 kDa UF membrane.

(3) When the removal efficiencies of the membranes were compared, the best result in terms of COD removal was obtained for the RO membrane at 20 bar as 88.67%, and for the 50 kDa UF + RO sequential application COD removal was increased from 70% to 88.67%.

(4) SEM, FTIR, contact angle, and AFM analyses of the slaughterhouse wastewater before and after treatment by the membrane processes were performed to select the most effective membrane. Clean membranes were compared with the membranes through which slaughterhouse wastewater was passed, and an increase occurred in the contact angles after the wastewater was passed in all membranes, except for the RO membrane, and the hydrophobicity of the membranes increased. At the AFM analysis, the surface roughness coefficient increased as the pore sizes decreased. In AFM images, the RMS value after slaughterhouse wastewater treatment was higher than before slaughterhouse wastewater treatment. When the SEM images were examined, it was observed that the pores were filled and roughness occurred as a result of the contamination of membranes used in slaughterhouse wastewater treatment.

ACKNOWLEDGEMENTS

The authors would like to express their gratitude to Nigde Omer Halisdemir University for its financial support for the current research with project No. FEB 2017/23 BAGEP. The language of the paper was edited by language experts.

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