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Tangential Flow Treatment of Poultry Processing Wastewater Using Stainless Steel Ultrafiltration Membrane

Saubana Olorunsola Dada
University of Arkansas, Fayetteville

Tangential Flow Treatment of Poultry Processing Wastewater Using Stainless Steel Ultrafiltration Membrane

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by

Saubana Olorunsola Dada
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University of Arkansas

This thesis is approved for recommendation to the Graduate Council.

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Ranil Wickramasinghe, Ph.D.
Thesis Director

____
Will Richardson, Ph.D.
Committee Member

____
Wen Zhang, Ph.D.
Committee Member

ABSTRACT

The current treatment of poultry processing wastewater (PPW) requires a large expanse of land, takes time, and requires chemical usage. The wastewater is typically treated prior to discharge. Apart from aiming to reuse the treated water for non-potable activities, this project aimed to reduce the footprint and time required for PPW treatment. To intensify the PPW treatment units, we studied the possibility of replacing dissolved air floatation (DAF) with a stainless steel ultrafiltration membrane (SSUF). Combined PPW from all processing units taken before the first DAF and the second DAF were used for this study with no pretreatment. The SSUF used for this study has a pore size of 0.02 μm, and the performance of the SSUF membrane was studied by measuring the flux at 40 psi, 70 psi, and 110 psi transmembrane pressure. The flux was normalized to 25^0C. To understand the properties of the PPW, we characterized the PPW by first measuring the particle size analysis to determine the distribution of particles in the PPW. Also, COD, BOD, TSS, TKN, PH, oil, and grease were measured before and after each experiment. A cleaning procedure that entails using alkali and acid was developed for the SSUF. The result shows that the flux became steady at 30 L/m^2h after 2 hours of experiment, irrespective of the TMP. We also determine the critical flux and the critical pressure of the SSUF. The critical flux was found to be around 48 L/m^2hr, and the critical pressure is 5 psi at 1.90 m/s cross-flow velocity. The SSUF membrane removed TSS 99.9%, oil and grease 99.9%, COD 90%, BOD 90%, nitrogen 76%, and soluble BOD 60%. The removal efficiency was higher at 110 psi. On comparing the result obtained with the data from the industry, it shows that the SSUF performance was comparable. The membrane removed E. coli and coliform up to 99.9%, which validated the pathogen removal ability of the SSUF. In conclusion, the results show that SSUF achieved comparable performance to that of the current treatment used for the PPW treatment.

ACKNOWLEDGMENT

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Thank you.

Saubana Olorunsola Dada

DEDICATION

This thesis is dedicated to my family members in Nigeria, my girlfriend Yolanda, and my roommates Joseph and Samuel.

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CHAPTER 1

INTRODUCTION

1.1 Poultry Processing and Wastewater

Meat consumption in the United States is continuously growing, higher than in other developed countries (including the European Union). The quantity of meat (both red meat and poultry) consumed in the United States is about three times the global average. While there was a decrease in red meat consumption between 1905 and 2007, there was a steady increase in the number of poultry products consumed globally. The quantity of poultry products consumed is fast approaching the number of other meats consumed [1,2]. In 2020, 2021, and 2022, over 9 billion birds were slaughtered annually in the United States. The birds include broilers, turkeys, geese, and other chickens [3,4]**.** A live bird transported to the processing plant undergoes the following processes: slaughtering, scalding, picking, eviscerating, washing, chilling, weighing, packaging, and transporting [5]. The processing of live birds into the finished product requires water at every processing stage [6], but most water is used for scalding, washing, chilling, and cleaning the birds [7]. The processing of a bird requires an average of 26 L of water. Considering the number of birds processed within the last three years from 2020, over 250 billion liters of water was used annually for poultry processing (excluding other industrial operations and household use). The quantity of water used for poultry processing necessitates treating and reusing the PPW for other activities. Recycling and reusing wastewater can improve water quality and alleviate pressure on water resources [8,9,10].

1.2 PPW Properties

The PPW is highly contaminated with blood and rejected particles from the poultry called offals. According to **Kiepper et al.** [8], offals are the inedible part of the poultry, including the feather, the head, the intestine, and other rejected parts. The presence of these particles in the PPW varies daily from plant to plant and contributes to the concentration of different parameters in the PPW [11].

Parameters like chemical oxygen demand (COD), biochemical oxygen demand (BOD), total suspended solids (TSS), total Kjeldahl nitrogen (TKN), ammonia (NH_3), phosphates, total dissolved solids (TDS), oil & grease (OG) were measured to determine PPW's contamination level [5,12]. Different factors contributed to the level of each measured parameter. For instance, the blood in PPW is the major contributor to PPW's BOD and COD. A typical poultry plant has a blood-draining time of about 2 minutes. It was reported that increasing the blood draining time will significantly reduce the COD level in the PPW. Although limited studies have been carried out on the economic impact of increasing the bleeding time, their study reported that increasing the bleeding time will reduce cost. But it is evident that increasing the time will increase total production time, and the effect must be measured on the entire operation [7]. Characterization of PPW from different sections of the processing plant has been studied in previous works. **Sardari et al.** [12] reported as high as 1050 mg/L for COD, 500 mg/L for BOD, 190 mg/L for FOG, 280 mg/L for TSS, and pH 7.5 for PPW taken from the chilling section of the poultry processing plant. A corresponding result was reported by another study of the chilling section PPW, but a higher concentration of pollutants was recorded from the PPW taken from the washing section [5]. Another report recorded the highest BOD, COD, TSS, and turbidity from the cooling section when they compared the PPWs obtained from the de-feathering, the eviscerating, and the cooling sections [13]**.** The combined PPW from all processing units has a higher concentration compared to the results from individual sections [2].

The knowledge of particle distribution is necessary to determine the appropriate membrane size for treating PPW. The average particle size within the PPW was reported to be about 0.14 µm, but studies on the processing plant subunits show that the average particle size of the chilling section is 0.084 µm, whereas the washer section has a larger average particle size of 0.375 µm [2,5,12].

1.3 PPW Treatment

Like other processing industries, poultry processors must treat their wastewater before discharging it. Dissolved air floatation (DAF) is the most common method for treating slaughterhouse wastewater (including PPW) in the USA. Fig 1 below shows the schematic flow diagram of the current PPW treatment method used in the process plant and the method anticipated by this study. The current treatment method entails using two dissolved air flotations (DAFs) and an activated sludge process.

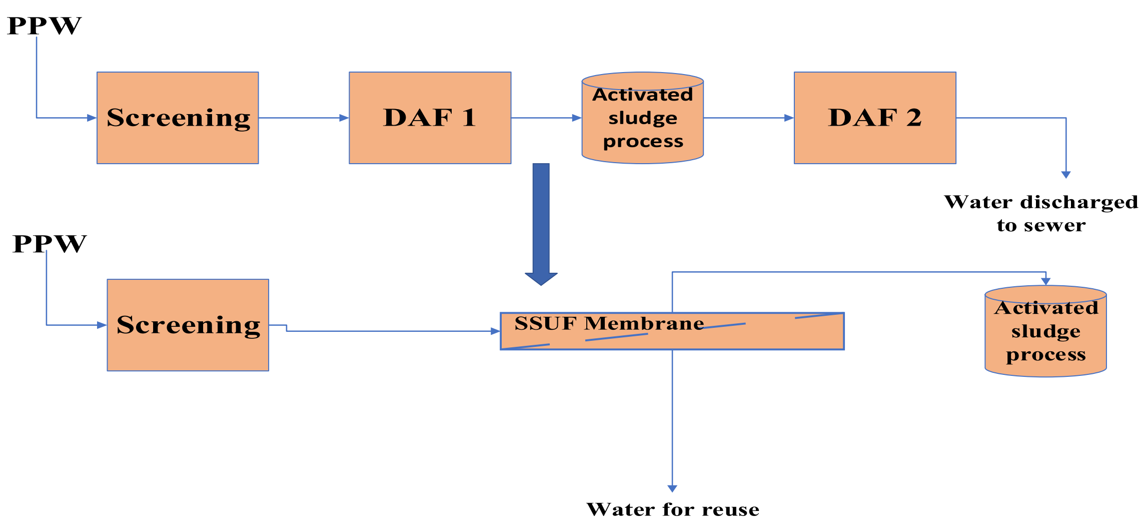


Figure 2: Schematic diagram of the current PPW treatment method and the anticipated method

DAF is effective in treating PPW, but it involves the use of chemicals (flocculants) and requiring large footprints. The content of the PPW is also destabilized by DAF, making it hard for product recovery [10]. Several studies have been conducted on the use of other techniques to treat PPW.

Terán Hilares et al. [2] used H_2SO_4 precipitation followed by algae cultivation to treat PPW. They evaluated the effect of pH on the treatment of the PPW by measuring the COD removal using this procedure. They found out that the optimum pH is 4. The acid precipitation removed about 80% of COD, and further treatment by the microalgae yielded an efficiency of over 98% removal of COD.

Another technique that has been explored for PPW treatment is the use of ultrafiltration (UF) membranes. UF is a low-pressure driven technique with a pore size ranging from 0.001 to 0.1 µm, and it can be in different configurations. It could be a flat sheet, submerged, or hollow fiber. UF operation requires less energy, no coagulant, and a lesser footprint. It was suggested that UF could help remove microbes from the PPW [5,10]. Research has been done on using UF or UF integrated with other techniques for PPW treatment. Fouling is the main challenge with UF (peculiar to membrane separation). At the initial stage, concentration polarization (deposition of particles on the surface of the membrane) due to the boundary layer occurs, while at the later stage, the membrane pores are blocked by smaller particles. UF membrane regeneration is needed after fouling before the membrane's further usage [5,12]. In one of the applications of UF for PPW treatment, a 30 kDa polysulfone UF membrane was used to treat PPW after the primary treatment for protein recovery, and the system removed almost all protein in the PPW with COD less than 200 mg/L in the effluent [14]**.** Another study was conducted on the treatment of PPW from the chiller and the washer units with UF using membranes made of different materials and with different pore sizes. Expectedly, the flux declined sharply initially, but later the decline became steady. The larger particles (TSS and OG) were almost removed completely by the membrane, but the lesser particle removal was a function of the pore size [5]. In a similar study**, Sardari et al.** [12] treated PPW from the chilling section with a 30 kDa regenerated cellulose (RC) membrane.

They compare the performance of the RC membrane for treating PPW with pretreatment (electrocoagulation using an aluminum electrode) and without pretreatment. The result shows that combining electrocoagulation with UF reduced the fouling of the membrane. Over 90% efficiency was recorded for most parameters measured when a combination of electrocoagulation, ultrafiltration, and the photochemical system was used to treat PPW from de-feathering, eviscerating, and cooling processes [13].

1.4 Critical Flux

Fouling is the main drawback of a membrane operation, and it could be a result of molecular adsorption, pore plugging, or cake formation [15]**.** One way to avoid fouling is to operate the UF below the critical flux, and this can be achieved by operating at low TMP (i.e., below the critical TMP). Critical flux was defined as the flux below which there is no irreversible membrane fouling and depends on the hydrodynamics [16]**.** Several methods have been deployed in the measurement of critical flux. **Le Clech et al.** [15] determine the critical flux of submerged membrane using the flux-step method. Although the study could not determine the critical flux, valuable results that explain the fouling of the membrane at different TMP were obtained. In their work, the permeate flux was made constant, and the corresponding flux was recorded. Increasing fouling led to an increase in TMP. The method used is similar to what was used in an earlier study by **Field et al.** [16]. In their study, the flux and TMP were made constant. They reported that the TMP did not increase as much as the flux below the critical flux. However, increasing the TMP above critical flux will lead to fouling, and subsequent reversal to the initial TMP will result in a lower flux value than initially. In another study, the process was started at a low TMP, and the corresponding flux was recorded. A gradual increase in TMP led to a linear increase in flux. At some point, a further increase in TMP led to no increase in flux. The point at which the plot of flux-TMP deviates from linearity is the critical flux [17]**.**

Youravong et al. [18] determined the UF critical flux using skimmed milk by investigating the TMP response to stepwise increase and decrease of flux. At lower flux, TMP responded to changes in flux as expected, but at higher flux (above critical flux), the TMP-flux relation became unstable and opposite. A similar method was used by **Maruf et al.** [19]. In a study by **Espinasse et al.** [20], they proposed a new technique alternative to positive and negative pressure. They continuously set a new pressure and studied the flux's steady-state response to determining the membrane's reversibility. Although none of these works were done using a stainless steel UF membrane, it is evident from all the studies conducted that running a UF membrane below the critical flux is essential.

1.5 Current Work

Although studies on the use of UF membranes for treating wastewater (including PPW) have been done, the use of stainless steel ultrafiltration (SSUF) membranes for PPW and other wastewater has not been explored. Polysulfone is widely used in making membranes for wastewater treatment but is highly susceptible to fouling, and SSUF may be an excellent alternative to solving the issue of membrane fouling [10]**.** Currently, the DAF system occupies almost 90 m^2 and the water production limits the operation of the poultry industry studied in this project. The implementation of SSUF will intensify the wastewater plant by almost 20%, and it could proffer solution to the issue of fouling for wastewater with organic foulants. Also, it is important to recycle and reuse water to lessen the pressure on water resources. In other to achieve this, an effective treatment method must be used. In this work, we treated the wastewater leaving the poultry plant to the wastewater treatment plant with a 0.02 µm SSUF membrane. For the first set of studies, we treated the wastewater before the second DAF with the SSUF, and the performance was recorded. For the subsequent study, wastewater taken after the screening (before the first DAF) was treated with SSUF without pretreatment. The position of the first and second DAF is shown in Fig 1. Before the treatment, we analyzed the particle size within the wastewater to determine if the particles would pass through the membrane pore. The research aims to treat wastewater for utilization for non-potable activities within the industry.

1.6 Objectives

The objective of this work is to:

1. Study the time-based performance of the SSUF in treating poultry processing wastewater.
2. Develop a cleaning procedure for regenerating the SSUF after treating the PPW.
3. Investigate the efficiency of the SSUF in removing particles and pathogens (coliform counts and E. coli counts) from the PPW.
4. Determine the critical flux of the SSUF.

CHAPTER 2

MATERIALS AND METHODS

2.1 Materials

The poultry processing wastewater (PPW) used for this project was obtained from Tyson Foods Inc. (Springdale, AR). It is a combination of wastewater from all the poultry processing units. PPW for this study was taken from two points (a) before the first DAF and (b) before the second DAF. Initially, the PPW was stored for a few days, but due to the changes observed, the subsequent PPW was used the same day it was taken from the facility. The study was carried out using a 2.5-gallon NSF-certified feed tank made by Ace Roto-Mold (Hospers, IA). An analytical scale from Mettler Toledo (Columbus, OH) was used to measure the permeate mass received. The pumping system contains a marathon motor made by Regal Rexnord (Beloit, WI), a head made by Wagner Engineering (Minneapolis, MN), and a control system made by TECO Westinghouse (Round Rock, TX).

2.2 Membrane specification

The stainless-steel ultrafiltration (SSUF) membrane was obtained from Scepter®, a registered trademark owned and operated by Graver Technologies (Glasgow, DE). The membrane specifications are listed in the table below:

Table 1: Membrane specifications

Parameters	Surface area	Length	Pore size	Diameter	Material	Type	Flow type
Values	0.0625 sq ft	12 inches	0.02 µm	6 mm	Stainless steel	tubular	Tangential

2.3 Water Characterization

Before each experiment, the particle distribution in the PPW was measured using a Laser Diffraction Particle Size Analyzer (Beckman Coulter, LS 13 320, Brea, CA). The PPW and the permeate were characterized for total soluble solids (TSS), chemical oxygen demand (COD), biochemical oxygen demand (BOD), pH, oil & grease, soluble BOD, and total Kjeldahl nitrogen (TKN) at the Tyson Food Rivers Valley Regional Laboratory (Scranton, AR). The result was used to determine the removal efficiency of the SSUF. Also, the E-coli count and the total coliform count in the PPW and the permeate were carried out at the Arkansas Water Resources Center (Fayetteville, AR). Pathogen removal was validated using IDEXX Colilert 24-97 Well Tray (APHA 9223, B standard). The removal efficiency was calculated using the formula below:

$$Efficiency = \frac{Cppw - Ctreated}{Cppw} X\ 100$$

2.4 Filtration Experiment

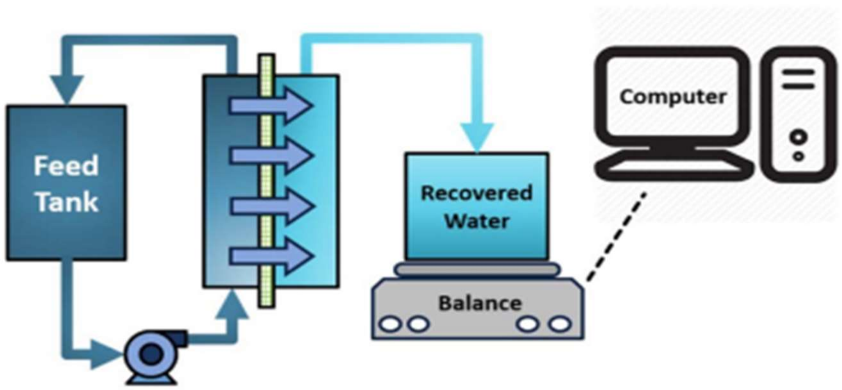


Figure 2: Schematic diagram of the experimental set-up [5]

An experimental method was used for this study. Fig. 2 above shows the schematic diagram of the experimental set-up used for this study. The set-up includes a pumping system, feed tank, stainless-steel membrane, weighing scale, temperature sensor, and a desktop computer. The membrane was rinsed by pumping DI water through the system. After the DI water rinsing, 1.5 gallons of thoroughly mixed PPW was fed into the NSF-certified feed tank. Initially, there was a fluctuation in the pressure gauge reading, and the experiment was left running for a short time with the permeate side being closed. Once the reading in the pressure gauge stabilized, the pump was adjusted till the desired feed flow rate was achieved. The permeate side was opened, and the control valve at the membrane outlet was adjusted to achieve a specific transmembrane pressure (TMP). The TMP was calculated using the equation below;

$$TMP = \frac{(Pout + Pin)}{2} - Ppermeate$$

For this filtration experiment, the permeate pressure was zero, and the equation above became;

$$TMP = \frac{(Pout + Pin)}{2}$$

The filtration experiment was operated at 0.85 GPM (0.000063 m^3/s) for all the experiments, and the TMP was constant for each experiment. The permeate mass was measured using a weighing scale attached to the computer every fifteen minutes. The temperature reading from a sensor attached to the feed tank was recorded alongside the mass. The flux was normalized to 25ºC using the viscosity at the measured temperature. Experiments were carried out at a TMP of 40 psi, 70 psi, and 110 psi for 3 hours, 6 hours, and 10 hours.

2.5 Membrane Regeneration

The membrane was regenerated after each experiment. Due to the novelty of using SSUF membranes for treating poultry processing wastewater, some existing regeneration methods were studied—two regeneration methods performed adequately for the SSUF membrane for PPW application. Firstly, the membrane was soaked with a solution containing Protease A (0.03mg/ml) and SDS that was heated to 38ºC for 24 hours [21]**.** Next, the membrane was rinsed with DI water. 1M NaOH mixed with 3g of SDS solution heated to a temperature of 60ºC was circulated in the membrane for an hour with the permeate side fully closed. This was followed by rinsing the membrane with DI water for 5 minutes. The next step was circulating HNO_3 (1% v/v) heated to a temperature between 70 and 80ºC in the membrane for an hour. Finally, the membrane was rinsed with DI water for another 5 minutes [22]. After the cleaning process, DI flux was measured to ascertain SSUF cleanliness.

Two factors necessitated the second cleaning method; (i) after using the membrane for over eight (8) months, the DI flux was gradually declining after cleaning using the cleaning method above (ii) the time taken to regenerate the membrane using the first method was too much for the industrial application. The second cleaning method entails using NaOH, SDS, and HCl, as described above. The difference is that the flow direction was reversed, and soaking the membrane with Protease A (mixed with SDS) for 24 hours was also eliminated.

2.6 Critical Flux Experiments

The same experimental set-up above was used to determine the membrane's critical flux. A pressure gauge was installed on the permeate side of the membrane to measure the permeate side pressure. The permeate side valve was fully closed before one gallon PPW was fed into the feed tank. The pump was started, and the flow was adjusted to the desired flow rate. The system was allowed to stabilize for a few minutes, and the permeate valve was open slightly. The three pressure readings (inlet, outlet, and permeate) were noticed, and they were adjusted till the desired TMP was obtained. The flux was recorded for 30 mins. The permeate pressure gauge was adjusted to increase the TMP, and the flux was recorded for 30 mins. The experiment was repeated by alternating the TMP. Also, the experiment time was increased from 30 mins to 2 hours. In the last investigation, the TMP was continuously increased gradually, and the flux was recorded at an interval.

CHAPTER 3

RESULTS

3.1 PPW Characterization

PPW was taken from Tyson Food Inc. on several occasions between June and December 2021. It was observed that the properties of the PPW vary daily. Due to this variation, the wastewater sample was characterized to determine the contamination level. The particle size in the PPW is within the same range. The result shows that the ammonia level ranges from 11.5 mg/L to 31.9 mg/L, and the pH was from 5.31 to 6.91. The soluble BOD was from 650 mg/L to 1335 mg/L. Fig. 3 below shows the different days' BOD, COD, O&G, TKN, and TSS levels in the PPW. Although PPW from different poultry processing units to overall treatment units has been studied, several reports [5,23,24] presented values ranging from one-fifth to half of the values observed in this study. However, **Basitere et al.** [23] reported COD as high as 9600 mg/L from the effluent of a PPW treatment plant, which is almost twice the average COD recorded in this study. The variation in the PPW is shown in Fig. 3. From the figure, it is evident that the level of contamination is independent of the day of the week. Table 2 below shows the statistical value of the PPW used for this project.

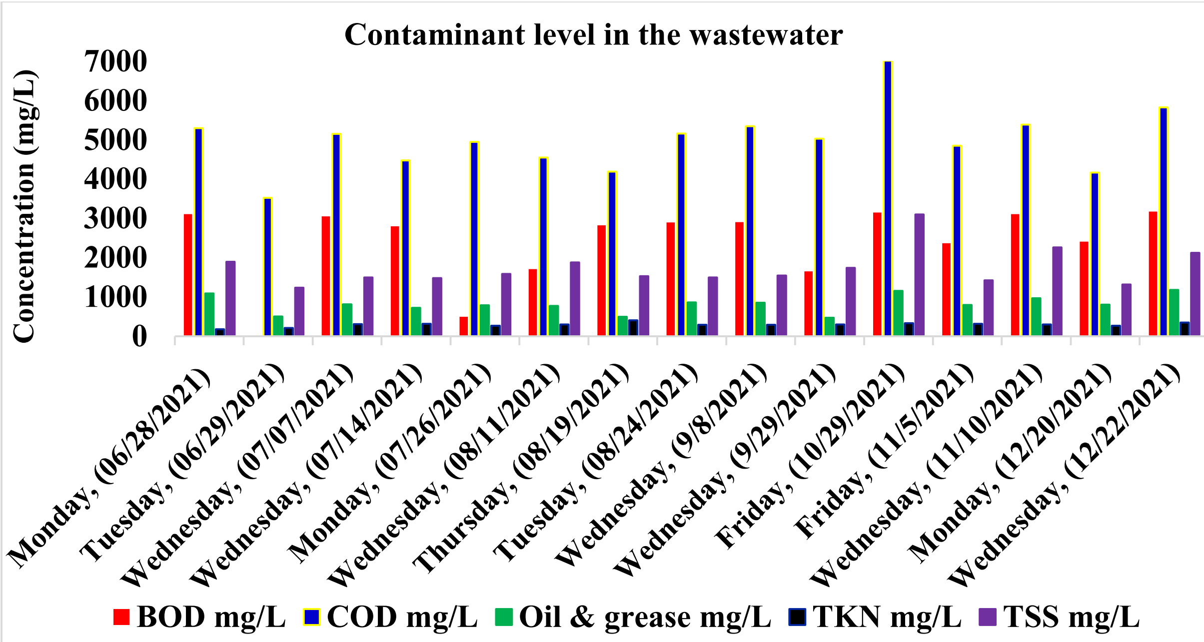


Figure 3: PPW characterization for different days.

Table 2: statistical analysis of the wastewater for different days

Feed water quality parameters	**BOD mg/L**	**COD mg/L**	**Oil & grease mg/L**	**TKN mg/L**	**TSS mg/L**
Average	2691.473	4996	818.9333	296.1387	1742
Range	2684	3500	702	228.25	1860
St Dev	742.2224	811.3463	219.5513	53.68617	472.3679

3.1.1 Particle Size Analysis

The PPW sample was analyzed to know the size distribution of particles within it. The analyses show that the particle distribution in the samples used for this study falls within the same range. Fig. 4 below shows the result of the particle size analysis. From the result, the particle size in the PPW ranges from 0.05 μm to 1000 μm. The number-average distribution of particles in PPW is 0.28 μm, while the volume-average distribution of particles in the PPW is 39.78 μm. The figure shows that the volume of the large particles (around 39.78 μm) in the PPW is higher, whereas the number-based average shows that the number of smaller particles (about 0.28 µm) is higher in the PPW. **Sardari et al.** [12] reported a similar analysis in their study that used the same PPW from Tyson Food Inc.

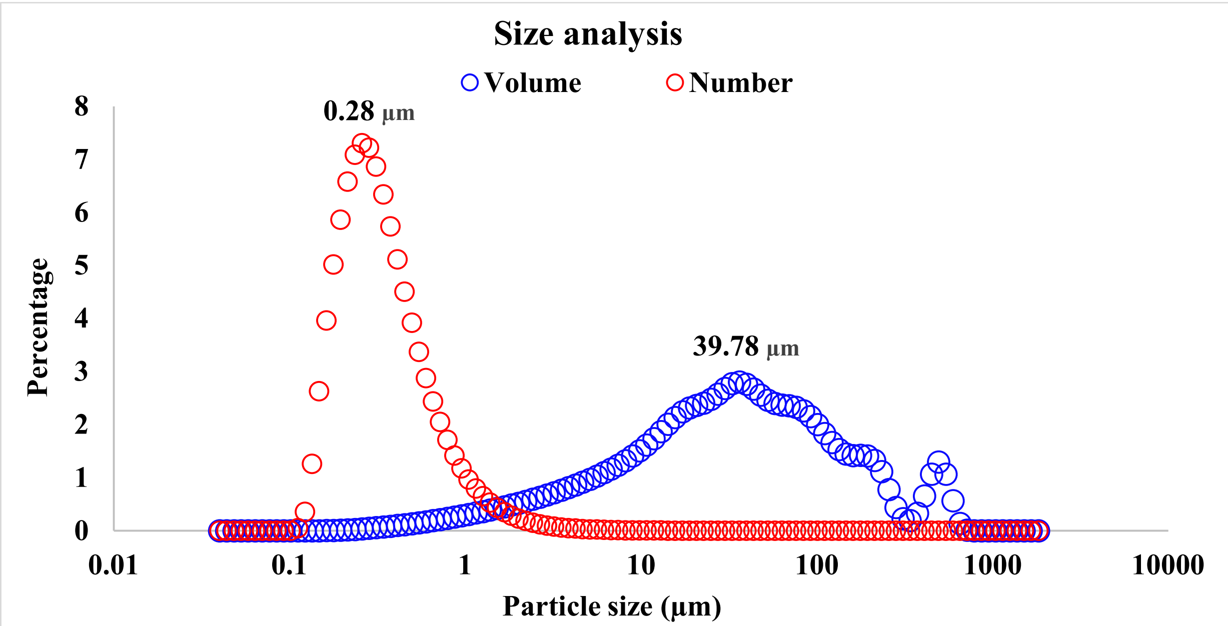


Figure 4: Distribution of particles in PPW.

3.2 Membrane Performance

3.2.1 DI Water Flux

Before the experiments, the SSUF performance was measured using DI water at three TMPs (40, 70, and 110 psi) and a cross-flow velocity (CFV) of 2.01 m/s. Figure 5 shows the performance of the SSUF using DI water. The result shows the performance of SSUF with DI water for seven minutes. The first data is for the 40 psi TMP, and the DI flux is almost 700 L m^{-2} h^{-1}. On increasing the TMP to 70 psi, the DI water flux increased to 1100 L m^{-2} h^{-1} and 1600 L m^{-2} h^{-1} when the TMP was increased to 110 psi. Comparing the results show that the DI flux increases linearly with an increase in the TMP. **Ren et al.** [25] also reported that increasing the TMP leads to an increase in flux for pure water.

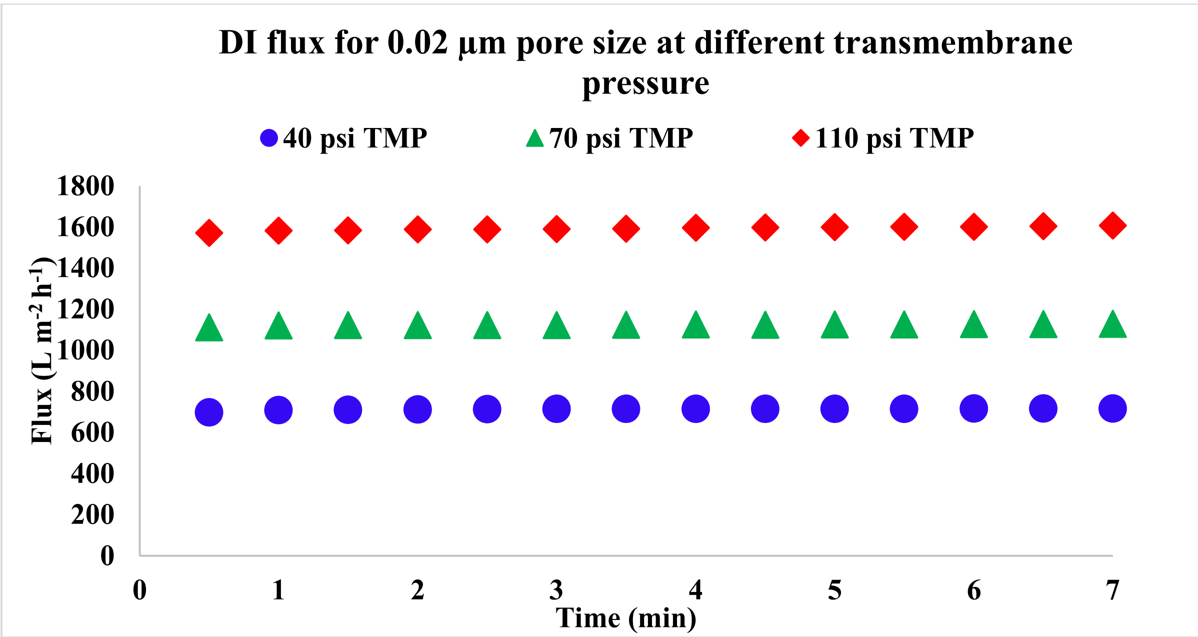


Figure 5: Initial DI water flux at different TMP

3.2.2 PPW (MBR) Filtration

The use of stainless-steel ultrafiltration (SSUF) membrane is currently uncommon in water treatment operations, especially for treating wastewater with organic pollutants like poultry processing wastewater (PPW). Understanding the performance of SSUF at a laboratory scale is a necessary precursor to using the membrane for industrial applications. Fig. 6 shows the results of treating PPW before the second DAF (MBR) with 0.02 µm at three TMPs (40 psi, 70 psi, and 110 psi) and a cross-flow velocity of 1.90 m s^{-1} without any pretreatment. The flux obtained was normalized to 25°C using the viscosity at the measured temperature. From Fig. 6, the flux declined sharply at the three TMP, but the flux at 110 psi TMP declined more sharply than at the other TMP at the initial stage. While flux at other TMPs was approaching a steady state, the flux at 110 psi

TMP continued to drop for the duration of the experiment. From Fig. 6a, the permeate recovered at 70 psi TMP was higher than the others, and the least recovery was achieved at 110 psi TMP. This can be attributed to the concentration polarization and increased fouling due to higher pressure and boundary layer [26]**.** Although flux decline was also noticed when the TMP was 40 psi and 70 psi, the decline was gradual and minimal. A repeated experiment was conducted at the same TMPs; the result is shown in Fig. 6b. The behavior observed during the repeated experiment at both 40 psi and 70 psi TMPs was similar to the result in Fig. 6a. Although the flux declined at 110 psi TMP, the decline was not as sharp as in Fig. 6a, and the volume recovered was higher (similar to at 70 psi).

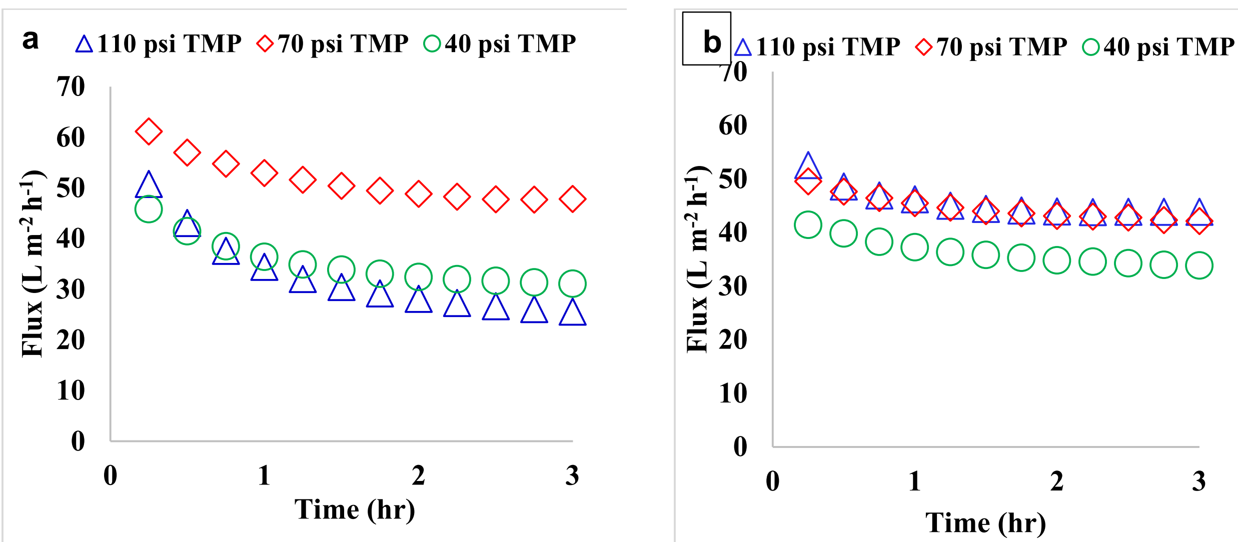


Figure 6: (a) Normalized flux for Hybrid MBR wastewater (b) repeated experiment under the same conditions.

3.2.3 Treatment of PPW Before First DAF

The PPW used for the first set of studies had undergone treatment from the first DAF. Replacing the entire DAF unit with the SSUF membrane will make the wastewater treatment process more environmentally friendly and reduce the footprint by about 20%. Due to the potential benefits, more emphasis was laid on the PPW before the first DAF for subsequent studies. Fig. 7 presents the variation of the normalized permeate flux with time using the 0.02 μm SSUF at CFV of 1.90 m s^{-1}. The SSUF performance was analyzed for 6 hours (excluding 70 psi) and 10 hours to match the duration of a shift at the facility. Both studies show a sharp decline in flux initially, which became gradual after 2 hours. In Fig. 7a, permeate recovery at 40 psi was higher, and the lowest flux was recorded at 110 psi. The trends converged after 2 hours, and the behavior from the 40 and the 110 psi TMP were similar throughout the remainder of the study. For the repeated study (fig. 7b), the flux decline was similar at all TMP, and the flux recovered at the 40 psi and 70 psi TMP were similar. Two studies were conducted at 110 psi, and they both showed similar behavior throughout the experiment.

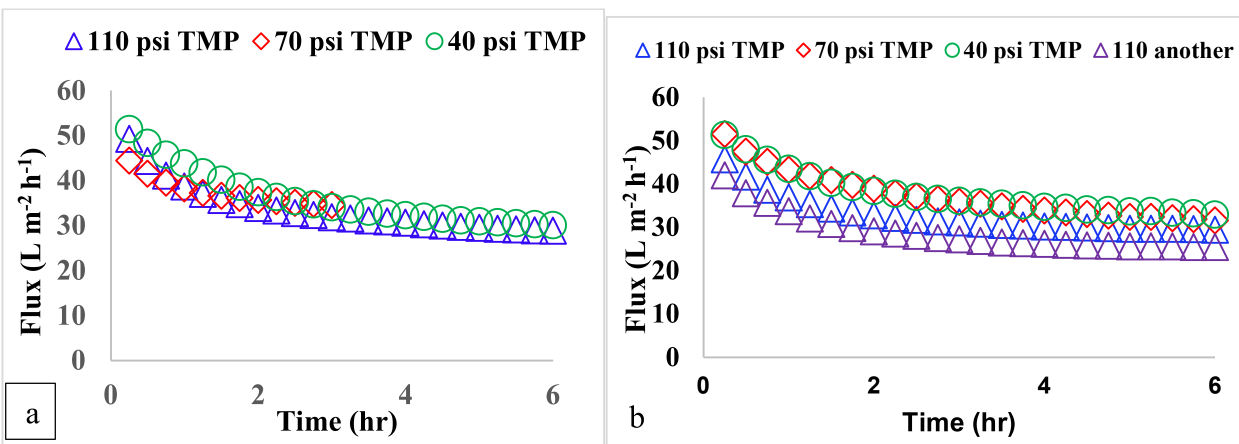
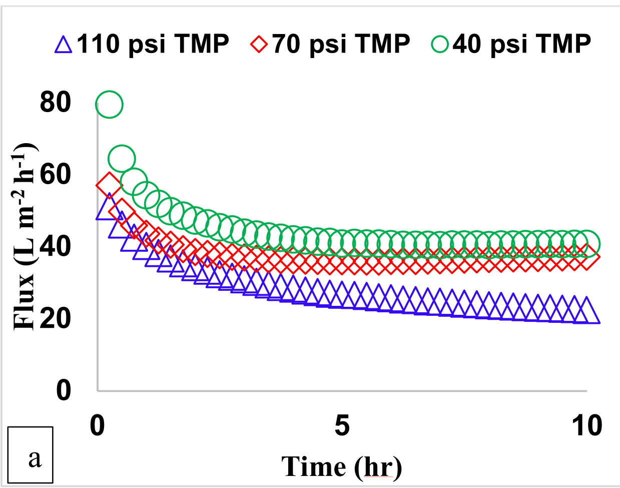


Figure 7: (a) Normalized flux for primary treatment wastewater using 0.02 μm SSUF membrane (b) repeated experiment under the same condition

As part of the effort to understand the long-time behavior of the SSUF for treating PPW, 10 hours of studies of the flux behavior at different TMPs were conducted using the 0.02 μm SSUF. The normalized flux versus time is presented in Fig. 8a. Similar to the previous study, a sharp flux decline occurs at the initial stage for 2 hours at all the TMPs. After 2 hours of operation, the flux became steady at 40 psi and 70 psi, but for the 110 psi experiment, the flux decline was continuous for the entire duration of this study. Also, the result shows that the highest flux was recorded at 40 psi, in accordance with the results stated earlier. According to **Marchesi et al.** [26], this is due to concentration polarization and fouling at higher pressure. The earlier results show that a higher permeate volume was recovered at 40 psi, and the removal efficiency at 40 psi was comparable to other TMPs. We further experimented with 40 psi repeatedly to ascertain the behavior of the SSUF. The variation of the normalized flux with time is presented in Fig 8b. From the first two studies, there was a decline for the first 2 hours of the study, and the flux remained steady for the remaining 8 hours. The third study shows a continuous decline in flux for the duration of the experiment.



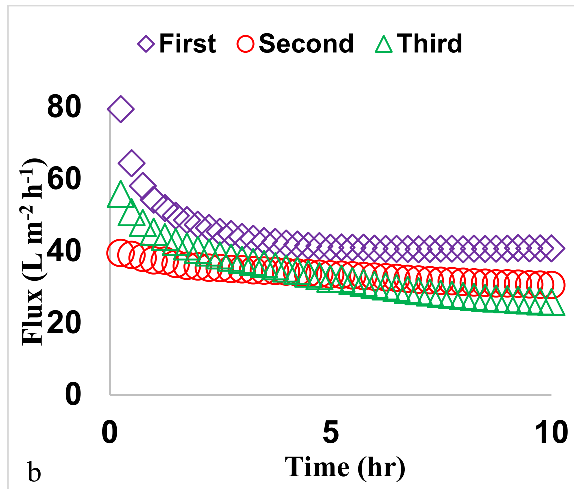


Figure 8: (a) Normalized flux for primary treatment wastewater at different TMP (b) normalized flux for repeated experiments at 40 psi TMP.

3.3 Removal Efficiency

The membrane removal efficiency was measured by calculating the percentage of pathogens and particles removed. The removal efficiency was calculated using

$$Efficiency = \frac{Cppw - Ctreated}{Cppw} X\ 100$$

Where C_{ppw} is the concentration of the PPW and $C_{treated}$ is the concentration of the treated water. The SSUF performed impressively in removing pathogens and pollutants from the PPW. Over 99% removal rate was recorded for pathogens and some contaminants.

3.3.1 Pathogen Removal Validation

Table 3 below shows the result of the pathogen removal of the SSUF. The E. coli count and the total coliform count were analyzed for both the wastewater and the permeate. For the wastewater, the dilution rate for both the coliform count and E. coli count was 10000 times. While for the permeate, the dilution rate used for the coliform count was 100 times, no dilution was used for the E. coli count. The total coliform count and E. coli observed in the wastewater was more than 24196000 MPN/100ml. The SSUF successfully removed 99.99% of the E. coli at all the operating TMP, although the highest removal was observed at the highest TMP. The highest removal was observed at 110 psi, where over 99.9% of coliform was removed, and 100% of E. coli was removed. Over 99% efficiency was achieved at other TMP for both the E. coli and the coliform.

Table 3: Pathogen removal validation Using IDEXX Colilert 24-97 Well Tray

Sample Name	E. coli A	Total Coliform A	E. coli B	Total Coliform B	E. coli C	Total Coliform C
PPW (MPN/100 mL)	> 24196000	> 24196000	> 24196000	> 24196000	> 24196000	> 24196000
Permeate (MPN/100 mL)	345	68670	308	92080	115	29090
Removal %	99.999	99.7	99.999	99.6	99.999	99.9

(A) 40 psi TMP (B)70 psi TMP (C) 110 psi TMP

3.3.2 Particles Removal

As stated earlier, the SSUF efficiently removed pollutants from the PPW. Over 90% of TSS, oil & grease were removed at the three TMPs. Initially, the PPW pH was around 6.2 for most of the samples taken, but the SSUF reduced the acidity as the average pH recorded for the permeate was about 7.6. Fig. 9(a-c) shows the percentage removal of the particle by the SSUF at different TMP. The SSUF was efficient in the removal of oil & grease and TSS. At both 70 psi and 110 psi TMP, up to 99% removal of TSS and oil & grease was achieved. The removal of BOD and COD was up to 90% operating at 110 psi (minimum achieved was above 85%), while at 70 psi TMP, the BOD and COD removal was from 75% to 85%. At 40 psi TMP, COD and BOD removal was as high as 85% but could be as low as 65%. The figures show that the TMP influences the removal of BOD and COD. The higher the TMP, the higher the removal of COD and BOD. Other parameters measured are soluble BOD which was removed up to 60%, and TKN up to 75%. The ammonia removal on the other hand, shows different behavior. At 70 psi TMP, the ammonia increased on two occasions, whereas when the operating pressure was 40 psi and 110 psi TMP, the quantity of ammonia reduced even though it was minimal.

The average results observed at the different TMPs were compared with the monthly average result obtained from the treatment facility at Tyson Food Inc. The data shows the monthly average of three parameters (BOD, TSS, and ammonia) recorded for the effluent of the second DAF. Meanwhile, the sample used for this project was taken from the influent of the first DAF. Fig. 9d compares the industrial result with the results obtained from this study. Despite undergoing two DAF at the facility, the percentage removal of TSS and ammonia obtained from Tyson Food Inc. is comparable with the result obtained from the SSUF. However, the percentage removal of BOD is lower than that obtained from the facility.

Fig. 10 shows the sample of the PPW before the first and the second DAF and their corresponding treated water. From the figure, the treated water before the 2nd DAF is clearer because the water has undergone treatment from the first DAF.

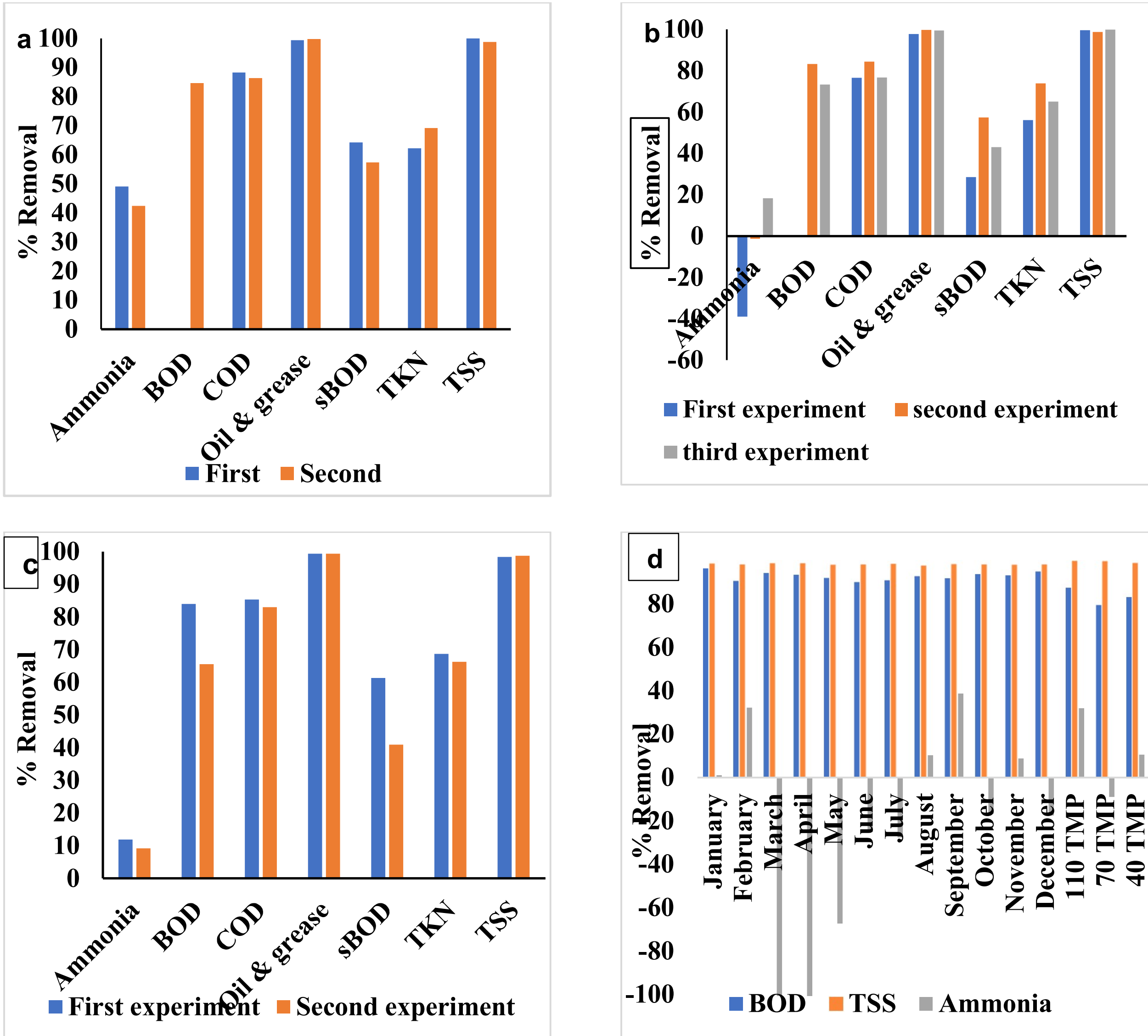


Figure 9: Removal efficiency of SSUF at (a) 110 psi TMP (b) 70 psi TMP (c) 40 psi TMP (d) comparison with industrial wastewater treatment plant effluent

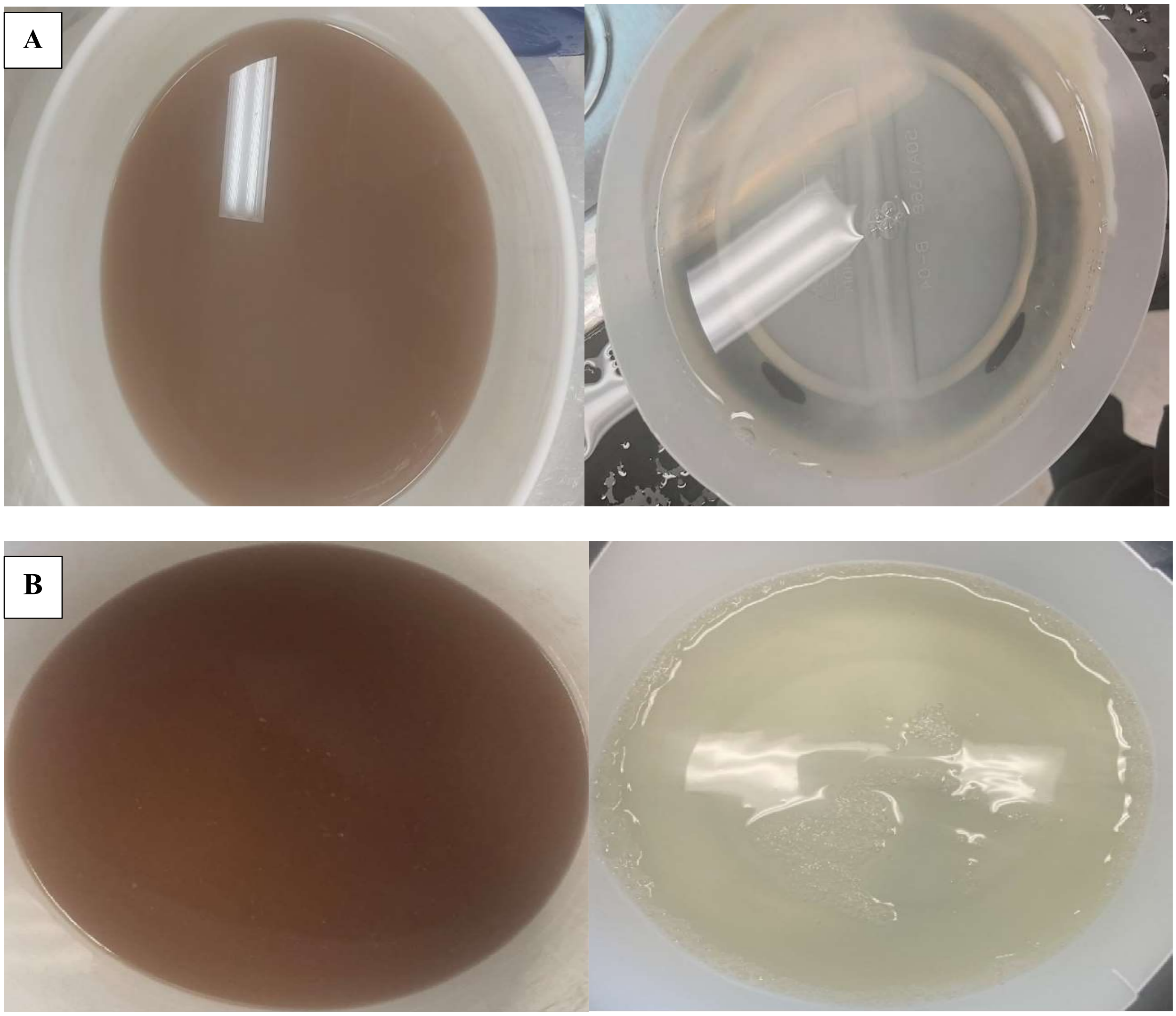


Figure 10: (A) PPW sample before 2nd DAF and corresponding treated water (B) PPW sample before 2nd DAF and corresponding treated water

After each experiment, the performance of the membrane reduced drastically due to fouling. This was confirmed by checking the DI water flux after the experiment and comparing it with the initial DI flux. The membrane was regenerated using Protease A, NaOH, and HCl [21]**.** After the regeneration, the DI water flux was measured to determine the cleanliness of the membrane. Fig. 11 shows the plot of the DI water flux of the regenerated membrane against time after different experiments. Over 80% of the initial flux was recovered using the regeneration technique developed for this study.

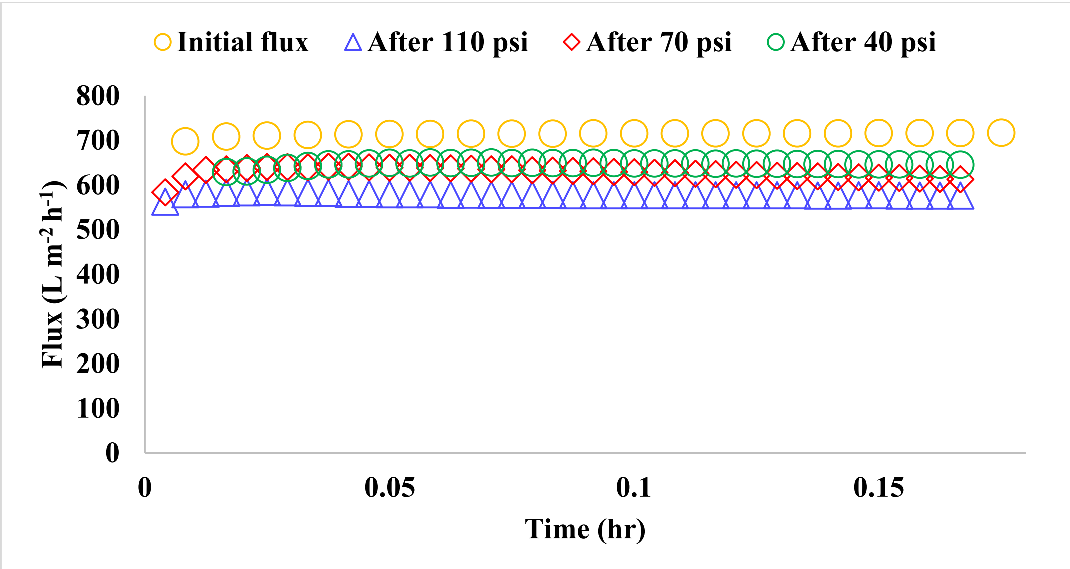


Figure 11: DI water flux at 40 psi after experiments at different TMP

3.4 Critical Flux

Figure 12 presents the results of the SSUF critical flux measurement at a cross-flow velocity (CFV) of 1.90 m s^{-1}. The CFV was made constant all through the study. Two methods were used to determine the critical flux. First, we measure the flux at a specific TMP for a specific time. After, the TMP was increased, and the flux was recorded before the TMP was returned to the initial value. The result showed the behavior of the SSUF at the interchanging TMPs, and we deduced that the critical flux is between 3.5 and 5 psi. In Fig. 12a, the flux was recorded at 5 psi for 2 hours before the TMP was increased to 7.5 psi. The TMP was returned to the initial TMP after an hour. For the first two hours, there was a gradual reduction in the flux, but on increasing the TMP to 7.5 psi, the flux decline became spontaneous. After one hour of flux observation at 7.5 psi, the TMP was returned to the initial value (5 psi) to observe if the flux would be steady. Although the flux continued to decline after reducing the TMP, it was noticed that the flux reduction was less than what was observed at the initial stage. It was deduced that the critical pressure is around 5 psi. Further studies were carried out by reducing the TMP. The same procedure was repeated in Fig. 12b, but the TMP was alternated between 4.5 psi and 5.5 psi. The observed flux shows that the flux reduction was lower than what was observed in the preceding study. Despite the reduction in TMP, the flux noticed was slightly higher than the observed flux when the TMP was alternated between 5 psi and 7.5 psi. The continuous slight decline in flux after alternating the TMP necessitated reducing the TMP, as presented in Fig. 12c and 12d. The results show steady flux after the TMP was returned to its initial values, although the volume recovered decreased. A repeated study was carried out at 3.5 psi for a more extended period; the result is presented in Fig. 12e. Similar to the observation in Fig. 12d, steady flux was recovered despite performing the study for longer. The results showed that the flux was repeatedly steady after repeated return to 3.5 psi. This showed that the critical flux is around 3.5 psi.

The critical flux was determined by **Chan et al.** [27] by considering the last flux on a straight line when the flux was changed, and the corresponding TMP was measured. An analog of that method was used in this study as the second method in measuring critical flux. We gradually increased the TMP, and the corresponding change in permeate flux was measured. In Fig. 12f, the point at which the flux deviates from linearity is the critical flux, and the corresponding TMP is taken as the critical pressure at that CFV. The result shows that the flux increases linearly for the first 30 minutes (up to the 5.5 psi TMP). Above 5 psi, the flux became constant and was not impacted by increased TMP. From the figure, the critical flux at a CFV of 1.90 m s^{-1} is estimated to be about 47.7 L m^{-2} h^{-1}, and the corresponding TMP is about 5 psi.

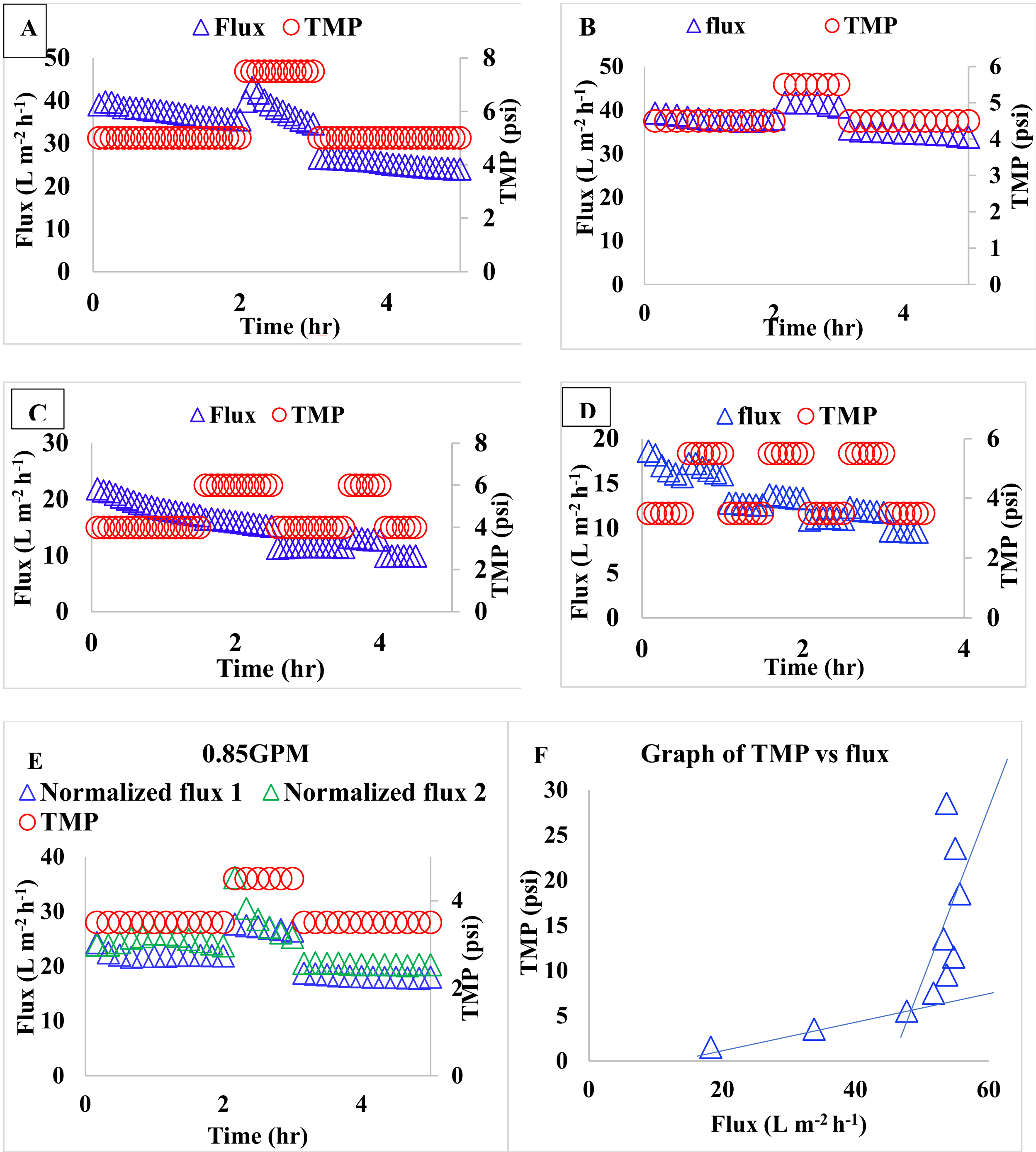


Figure 12: Critical flux at 1.90 m s^{-1}

CHAPTER 4

CONCLUSION AND FUTURE WORKS

4.1 Conclusion

This project aimed to intensify the PPW treatment unit by replacing the current treatment method with stainless steel ultrafiltration (SSUF) membrane. We investigated the use of SSUF membrane to treat poultry processing wastewater (PPW) taken before the first DAF and before the second DAF at three different transmembrane pressure (TMP). More emphasis was laid on using SSUF for treating the PPW before the first DAF to fully understand if the SSUF can replace the entire treatment unit. Analyses of the permeate flux, pollutants removal, and pathogen removal were carried out. The SSUF showed promising behavior in PPW treatment. A single SSUF removed over 99% of the pathogens with no pretreatment. The membrane was successful in the removal of oil & grease and TSS up to 99%. Other parameters measured were BOD, sBOD, TKN, ammonia, and pH. The results showed that operating the SSUF at 70 psi TMP with the PPW taken before the second DAF produced high flux, while for the treatment of PPW taken before the first DAF, operating at 40 psi TMP produced the highest flux. Although the pathogen removal at 110 psi is higher than other TMPs, the percentage removal was not significantly different. Importantly, the quantity of pathogen in the permeate is higher than the permissible limit, and a pretreatment may be needed to achieve the standard. Also, the permeate produced has an odor that may warrant other treatment.

Additionally, we investigated the possible ways of cleaning the membrane after usage, and two methods were used. The membrane was tested with DI water, and the flux shows that over 80% of the membrane was regenerated, and this was done repeatedly. Finally, the critical flux was estimated using two techniques. The first method was to examine the transmembrane pressure where the critical flux is obtained, and we estimated the critical flux to be between 3.5 psi and 5 psi, while the second method shows that the critical flux is 48 L m^{-2} h^{-1}at 5 psi.

4.2 Future Works

From the results, the SSUF performance showed steady flux after two hours, and the flux value is about 30 L m^{-2} h^{-1}. This value shows that the flux is lower than the typical flux of UF. As part of this work, some studies were performed using DAF-pretreated PPW. Although the efficiency was not verified, higher flux was recovered compared to the PPW without pretreatment. Also, we used 0.1 µm SSUF membrane to treat PPW without pretreatment (not reported), and a higher flux was recorded. It is recommended that future works should study the use of 0.02 µm SSUF membrane coupled with a pretreatment method (electrocoagulation). SSUF with larger pore sizes should also be studied with and without pretreatment.

Another objective of this project was to develop a cleaning procedure for the membrane, and two methods were developed. The first method requires soaking the membrane for 12 hours. Industrially, the first method will significantly increase the production time, which led to the development of the second cleaning method that requires cleaning for less than 3 hours. The second method was developed after a year of using the SSUF membrane. Future works should study the efficiency of the second method in cleaning the membrane from the early stage.

Finally, the critical flux experiments were conducted after several uses of the membrane. The membrane had been used for up to a year before the critical flux experiments were conducted. There is a high chance that some particles are already in the membrane pore. It is recommended that the critical flux experiment be studied with a virgin membrane.

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