

CONCENTRATION AND RECOVERY OF PROTEIN FROM TUNA COOKING JUICE BY FORWARD OSMOSIS

KHONGNAKORN W.^{1,*}, YOURAVONG W.²

¹Membrane Science and Technology Research Center, Department of Civil Engineering,
Faculty of Engineering, Prince of Songkla University, Hat Yai, Songkhla 90112, Thailand

²Membrane Science and Technology Research Center, Department of Food Technology,
Faculty of Agro-Industry, Prince of Songkla University, Hat Yai, Songkhla 90112, Thailand

*Corresponding Author: watsa.k@psu.ac.th

Abstract

Tuna cooking processing plants generate large amount of cooking juice containing a significant content of protein. Recovery and concentrating process of this valuable compound together with a low energy consumption process are of interest regarding full utilization concept and green process approach. Forward osmosis (FO) was employed in this work to recover and concentrate tuna cooking juice. FO process could increase the protein concentration up to 9% with an average permeate flux of 2.54 L/m²h. The permeate flux however tended to decrease as protein concentration increased due to the impact of osmotic pressure of the feed and fouling on the membrane surface. Since tuna cooking juice consists of protein and minerals, membrane analyses indicated that fouling was more severe compared to the fouling caused by standard bovine serum albumin pure protein. However, the presence of minerals rendered it a quicker and lower energy process by comparison. These results indicated that FO is a promising technique in the recovery and concentration of tuna cooking juice protein.

Keywords: Forward osmosis, Protein recovery, Fouling, Tuna cooking juice.

1. Introduction

Canned tuna industry is one of the major industries in Thailand. Among canning industries in the country tuna canning has an almost 80 % share. In 2014 more than 55,500 tons of canned-tuna is exported and its 5-year growth rate is reported to be 19 % p.a. [1]. Hundred thousand cubic meters of tuna cooking juice each year is an unavoidable by-product, and is commonly considered as a liquid waste,

along with some solid waste, producing a very high BOD loading to wastewater treatment. Tuna cooking juice, however, contains approx. 4 % of valuable protein [2, 3] and can be potentially utilized as a source of bioactive peptides, e.g. anti-oxidative, antimicrobial, antihypertensive peptides [4-7].

Methods for protein separation and concentration from tuna cooking juice include: precipitation, colloid gas aphrons (CGA), gel filtration chromatography, freeze-drying, spray-drying, drum drying, and evaporation [8-10]. One common disadvantage of these methods is contamination from chemicals and degradations of protein at high temperature. For protein separation, however, membrane technology is preferred and recommended [4, 8]. Forward Osmosis (FO) is a process of membrane separating in which it establishes one natural driving force called osmotic pressure. FO process is more advanced than other processes in terms of lower membrane fouling, low hydraulic-pressure operation and energy consumption [11-13]. The process has been applied in food industry, desalination, wastewater treatment and power generation [14-17].

The objective of this paper was to recover and concentrate valuable protein compounds in tuna cooking juice by FO process. The process operating conditions were investigated under various draw solution concentrations, feed velocities and temperatures for their effects on bovine serum albumin (BSA) solution. The set of optimum operating conditions derived was employed in the experiment with tuna cooking juice to recover and concentrate protein.

2. Materials and Methods

In this section, the methods used in characterizing the properties of industrial tuna cooking juice will be provided followed by description of type of FO membrane and the FO membrane system. Details on how to carry out the filtration experiment to study the effects of several important process conditions such as draw solution concentration, cross-flow velocity, temperature, etc., will also be provided. Experiments regarding the membrane surface fouling caused by protein and its characterization method will be also explained.

2.1. Preparation and characterisation of tuna cooking juice

Tuna cooking juice was obtained from Tropical Caning (Thailand) Public Company Limited, Hat Yai, Thailand. Numerous two-litre samples were prepared as homogeneous feed solutions, and stored at -20°C for further use. Those needed to be investigated would be thawed overnight for pre-treatment before the experiment; details can be found in Section 2.3.2.

Total protein and salt in the tuna cooking juice were determined using AOAC (1999) Method [18]. Total dissolved solids, pH, conductivity and COD were evaluated using the Standard Method [19]. Because of the interference of high NaCl concentration, organic concentrations in the feed solution and in the draw solution had to be measured by total organic carbon (TOC) by TOC Analyzer (Shimadzu TOC Analyzer TOC-L, Japan). Apparent viscosity was measured by capillary viscometer (Schott-instruments GmbH).

2.2. FO membrane and experiment setup

Cellulose triacetate (CTA) FO membranes were purchased from Hydration Technology Innovations (HTI, Albany, OR, USA). Approx. thickness of the flat sheet FO membrane is 50 μm , and the contact angle 64°. Embedded in the membrane is a polyester-mesh support layer. Performance of the membrane was characterized by its water permeability coefficient, pure water flux and salt rejection. The water permeability coefficient, salt permeability coefficient, and salt rejection were tested with RO mode.

Deionized (DI) water was supplied as feed solution at applied pressures ranging between 1-5 bars. The water and 10 mM of NaCl solution were respectively used for water flux testing and salt rejection testing [12]. The water flux (J_w), water permeability coefficient (A), salt permeability coefficient (B), and salt rejection (R) were calculated using Eq. (1) - (3), respectively.

$$J_w = \frac{\Delta \text{weight}}{\text{water density} \times \text{effective membrane area} \times \Delta \text{time}} \quad (1)$$

$$R = 1 + \left(\frac{(B)}{A(\Delta p - \Delta \pi)} \right)^{-1} \quad (2)$$

$$R = \left(1 - \frac{C_p}{C_f} \right) \times 100 \quad (3)$$

where A is in $\text{LMH} \cdot \text{bar}^{-1}$; ΔP is the pressure difference across membrane, in bar; and $\Delta \pi$ is the osmotic pressure across membrane, also in bar; C_p and C_f are the salt concentrations, in mg/L of the permeate solution and the feed solution, respectively.

The FO system was set up as shown in Fig. 1. The membrane module unit consists of two c-section cells, one on the permeate - or draw side - and one in the feed side of the membrane, combining into a channel. Each section is 200 mm in length, 100 mm in width (inner side), and 3 mm in the inner depth. Feed solution and draw solution were conducted in co-current mode, each by a peristaltic pump (EYELA MP-3N). The draw solution concentration was maintained constant. Pressure, temperature, flow rate and salt concentration were measured, respectively by a pressure transducer (TR-PS2W-2bar Lutron), Thermo couple (SR100KB1.5S, Caho), flow meters (MR3000, Key Instruments), and a conductivity sensor coupled with its transmitter (M200, Mettler Toledo). Programmable logic controller (PLC) was used to detect and control the system. Signals from all four sensors were translated to digital values and recorded directly to the computer. The permeate flux was weighed by a digital balance (AND GF-3000) connected to the computer.

2.3. FO performance

2.3.1. Effect of operating conditions

Three important variables; draw solute concentration, cross-flow velocity, and temperature, will be investigated in this section. The water solution used for the

membrane feed side was composed of 1 g/L BSA and kept constant under three different variables.

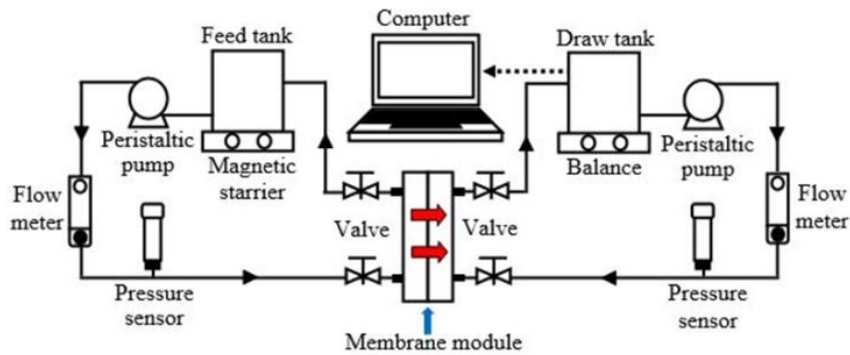


Fig. 1. Schematic of FO experimental setup.

Effect of draw solution concentration

The draw solution used NaCl concentrations of 0.5, 1.0, 1.5 and 2 M to investigate its effect. The FS and DS flows were operated in co-current mode at velocity of 20 mL/min on both sides and tested at a controlled room temperature of $25 \pm 0.5^\circ\text{C}$.

Effect of flow velocity

The draw solution here used a constant NaCl concentration of 2 M, and the temperature was controlled at $25 \pm 0.5^\circ\text{C}$. The FS and DS flows were operated in co-current mode under varying cross flow velocities of 16.7, 41.5 and 83 m/min.

Effect of temperature

The NaCl concentration for the draw solution was maintained at 2 M, and the FS and DS flows were operated in co-current mode at a fixed 100 ml/min. Temperatures were, however, varied to be at $25 \pm 0.5^\circ\text{C}$, $35 \pm 0.5^\circ\text{C}$ and $45 \pm 0.5^\circ\text{C}$.

2.3.2. Concentrate of tuna cooking juice

Before analyses, each sample was thawed at 4°C overnight and then filtrated with cotton fiber (100 μm pore size) to eliminate suspended matters which would increase membrane fouling. The FO process used to filtrate the tuna cooking juice under study employed the maximum 2 M NaCl as draw solution; FS and DS flows at the maximum cross flow velocity of 100 ml/min; and a temperature of $25 \pm 0.5^\circ\text{C}$, since these conditions yielded the optimum result. Protein concentration from the tuna cooking juice was determined using Lowry method employing BSA as a standard.

2.3.3. Membrane fouling and their characterization

In order to test fouling, BSA was chosen as the model for protein without other compounds to compare with the tuna cooking juice. The experiment was run for 9 hours and 36 hours for the tuna cooking juice and the BSA, respectively. In each run, either for the juice or the BSA, when the ratio of flux and the initial water flux (J/J_0) reached 0.5, the experiment was halted. Deionizer water was fed to clean the process at a velocity of 44 m/min for 20 min. The process was then re-filtrated until J/J_0 was 0.5 again. Once more the processed was paused to be cleaned by a regenerated chemical (1% citric acid and 0.5% NaOH) for 30 min at the same velocity of 44 m/min on both sides of the membrane module, and stopped finally when J/J_0 approached 0.5.

Membrane fouling morphology was characterized by a scanning electron microscope (SEM-Quanta, FEI Quanta 400) coupled with energy dispersive spectrometry (SEM-EDS). Roughness of the membrane was characterized by an atomic force microscope (AFM, NanosurfEasyScan2). Fouling behaviour found was applied to evaluate using the resistance series model according to the method proposed by Zhang et al. [20].

3. Results and Discussion

The findings of this work will be discussed in the following subsections according to the scope of the experiments as described in section 2.0.

3.1. Characterisation of tuna cooking juice

The characteristics of tuna cooking juice are presented in Table 1. The feed solution is mildly acidic, low in viscosity, but high in total organic carbon (TOC) loading. The main valuable component is protein; having approx. 5% concentration. The total solid concentration is still high though it was cotton-filtrated. This high value correlates with high conductivity and high salt concentration.

3.2. Flux permeability and salt rejection of FO membrane

The pure water permeability of cellulose triacetate (CTA) forward osmosis (FO) flat sheet membrane was about 0.74 LMH/bar; and for the salt, 0.68 LMH. The CTA membrane NaCl salt rejection value of 88% is considerably higher than normal mean values of 50% in other RO membranes. In the FO mode experiment, the water flux and the reverse salt flux used DI water as feed solution, and 2 M NaCl as draw solution. The water flux value was 5.08 LMH while that of the reverse salt flux was 0.27 mol/gMH.

3.3. Effect of draw solute concentration

In the FO process operation, systematic experiments were conducted on the effect of draw solution's NaCl concentration, varying between 0.5 M and 2 M, on the water flux and the salt reverse flux. As NaCl concentration increased the water

flux also increased in the feed solutions using either DI water or BSA solution; increasing from 4.34 LMH to 6.63 LMH when using the former, and from 3.93 LMH to 6.11 LMH when using the latter. Greater osmotic pressure resulted from higher concentration rendered the water fluxes high, but it also increased salt leakage from the draw solution across the semi-permeable membrane [21]. The reverse salt when using DI water increased from 1.45 gMH to 3.57 gMH, and from 1.34 gMH to 3.53 gMH when BSA solution was used, and this is one of the phenomena that decreased the water flux. Internal concentration polarization (ICP) in the support layer was reported to be the cause of the decrease of the water flux [12]. From these results, the optimal draw solution concentration was concluded to be the 2 M NaCl because of the relatively higher flux and the salt reverse flux obtained.

Table 1. Physico-chemical characteristics of tuna cooking juice.

Composition	Tuna cooking juice		
	Feed solution	Concentrated	Diluted DS
pH	5.79	5.76	5.57
TOC (g/L)	30.28	60.28	0.24
Protein (w/v %)	5.51	9.02	ND.
Viscosity (mPa.s)	1.11	1.16	1.00
Salt concentration (mg/L)	11,390	19,957	13,357
Total solid (mg/L)	11,450	12,237	350
Conductivity (mS/cm)	16.2	19.0	132.2

Note: DS: Draw Solution and TOC: Total Organic Carbon.

3.4. Effect of flow velocity

Using the draw solution at 2 M NaCl concentration the effect of cross-flow velocity, varying between 16.7 to 83 m/min, was investigated on the water flux, both when DI water and BSA solution were used. Either using DI water or BSA solution, the water flux was observed to increase with increasing cross-flow velocity. However, the flux when using BSA initially increased slightly - from 4.57 to 5.47 LMH (62% to 74%) when flow velocity increased from 16.7 to 41.5 m/min - and then to 6.28 LMH (85%) at 83 m/min. These results when BSA was used are in the same pattern as that reported by P. Zhao et al. [22]. Altaee and Tonningen [23] had found that, in both the feed solution and the draw solution, high feed velocity increased the water flux and decreased fouling since hydrodynamic shear forces increased with increasing feed flow rate. From these results, the optimal flow velocity was concluded to be 83 m/min in order to obtain a higher flux because of high turbulence in the module. Higher cross flow velocity seemed to have decreased the boundary layer thickness and thus the decreased absorption of BSA on the membrane surface.

3.5. Effect of temperature

Temperature plays a significant role in the FO process; influencing the thermodynamic properties of both the feed solution (FS) and the draw solution (DS) [24]. When temperature increased from 25 °C to 45 °C the water flux increased from 6.78 LMH to 8.42 LMH when using DI water and from 6.28 LMH

to 7.63 LMH when using BSA solution. An increase in temperature decreases water viscosity and increases its diffusivity that affects the concentration gradient at the membrane surface. This result is similar to that reported by Phuntsho et al. [24] which studied the effect of working temperature on FO separation performance; that higher temperature induced higher initial flux, higher water recovery and higher concentration factors. These results revealed that BSA recovery and water flux increase with increasing flow velocity, temperature and DS concentration, and decreasing salt reverse flux. High water flux obtained seems to be mainly dependent on crossflow velocity that impacts on the hydrodynamic shear force at the membrane surface. Higher flow velocity decreases the boundary layer thickness and thus decreased absorption of protein at the membrane surface.

3.6. Concentrate of tuna cooking juice

Figure 2 presents the relationship of water flux, protein concentration and viscosity during membrane filtration of the tuna cooking juice. Initially the water flux decreased steeply and then tapered off to be rather constant around 2.54 LMH at time 200 min. At this value of water flux the rising protein concentration with time went up to 9% w/v. The viscosity gradually and slowly rose from 1.11 mPa.s at time zero to 1.16 mPa.s at time 300 min. The decreasing permeate flux with processing time is thus due to the impacts of increasing protein concentration and increasing viscosity. The increased protein concentration at the membrane surface, concentration polarization, diffusivity and fouling consequently increase the osmotic pressure on the feed side. As a result, the effective driven osmotic pressure across the membrane reduces.

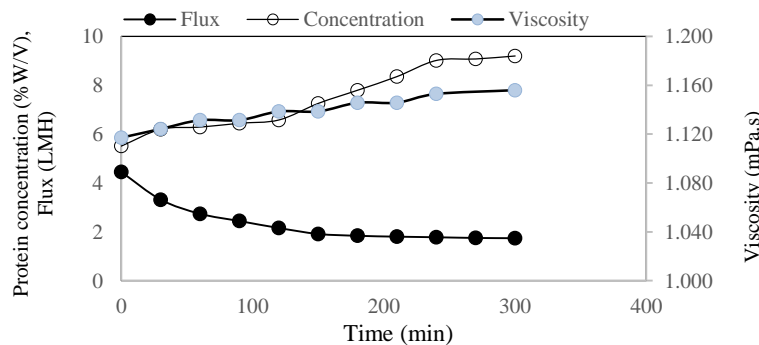


Fig. 2. Relationships of water flux, protein concentration and viscosity versus time of membrane filtration of tuna cooking juice.

3.7. Membrane fouling and their characterization

Figure 3 describes developments of membrane fouling in the FO filtration of BSA (upper part), and of the tuna cooking juice (lower part). The water flux in BSA solution filtration initially declined slightly then decreased more sharply but again tapered off. This behavior is in accordance with published mechanisms on organic fouling of BSA accumulation and adsorption on membrane surface [22, 25]. For

the tuna cooking juice filtration, the water flux decreased steeply from the beginning then became more or less asymptotic. The declining curves are clearly different since the tuna cooking juice contains much more organic and inorganic composites and compounds, and hence fouled up more quickly than BSA that contains only pure protein. The rapid decline in the case of tuna cooking juice was mainly attributed to the decrease of the effective driving force in FO caused by both the increasing salinity and viscosity on the feed side.

The phenomena of membrane fouling on the feed side, with the decline of flux with time, was due to accumulation on the active or selective layer. Membrane fouling from different types of foulant can be confirmed by the resistance serie model Eq. (4). CTA membrane resistances of FO filtration: Total resistance R_t , Membrane resistance R_m , Pore plugging resistance R_p , and Cake layer resistance R_c , for both the BSA and the tuna cooking juice, are shown in Table 2.

$$J = \frac{\Delta P}{\mu R_t} = \frac{\Delta P}{\mu(R_m + R_c + R_p)} \quad (4)$$

In Table 2, R_p was found much higher than R_c ; indicating accumulation of organic compound (gel) which diffuses some organic molecules and accumulates in the pores while some part of protein is absorbed in the active layer. R_c , presented in inorganic form, and in terms of scaling, accumulates on the surface and blocks the surface pores. On the contrary, Zhang et al. [20] observed, for municipal wastewater treatment, that R_p was lower than R_c ; indicating that the cake layer is the dominant contributor to membrane fouling in that case.

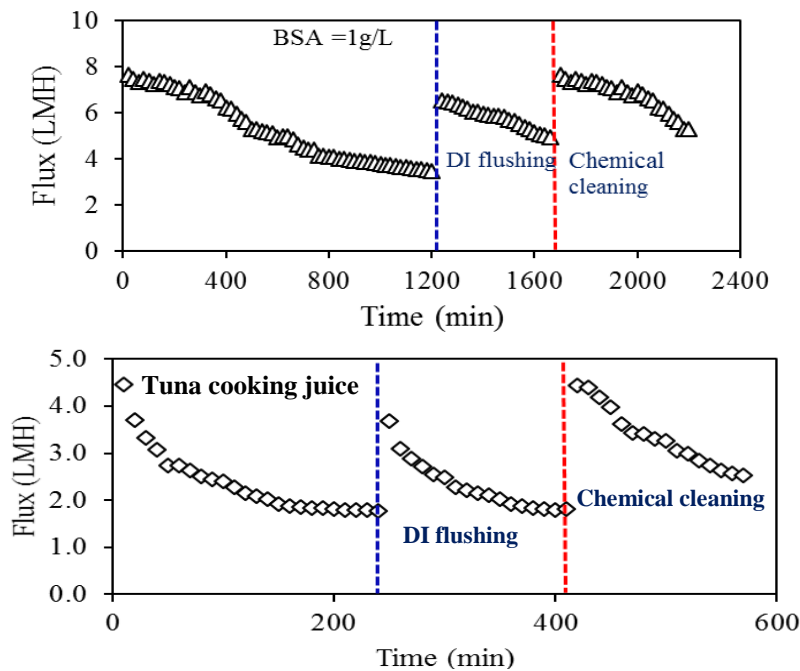


Fig. 3. Evolution of BSA (upper graph) and tuna cooking juice (lower graph) filtration.

The R_p is higher than R_c that indicated the accumulation of organics compound (gel) which diffuse some organic molecule and accumulate in the pore and some part of protein absorb in the active layer. The R_c present the inorganics form in terms of scaling, was accumulated and block the surface pore. In contrary, Zhang et al. [20] observed the R_p is lower than R_c which indicated that cake layer is the dominate contributor to membrane fouling for municipal wastewater treatment. Figure 4 illustrates SEM-EDX results confirming scaling accumulations at the membrane surface. Membrane scaling occurs due to inorganic crystallization of ionic calcium, sodium and magnesium from tuna bone degradation during the process.

Table 2. Membrane resistance of FO filtration for the BSA and the tuna cooking juice.

Type of solution	CTA membrane resistance of FO filtration ($\times 10^{11}$ 1/m)			
	R_t	R_m	R_p	R_c
BSA	17.28	6.97	9.29	1.02
Tuna cooking juice	29.53	6.97	21.19	1.37

Note: Subscripts t, m, p, and c for resistance R stand for, respectively, Total, Membrane, Pore plugging, and Cake layer

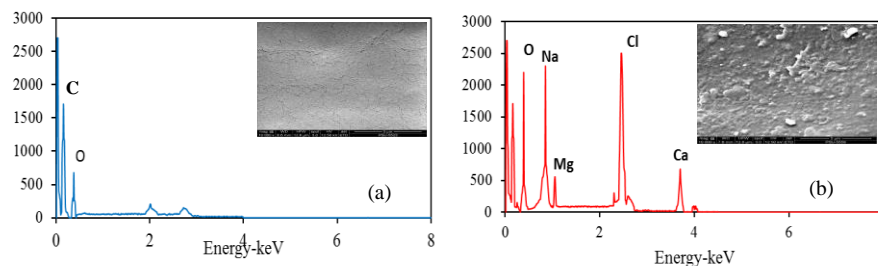


Fig. 4. SEM-EDX results of CTA membrane, (a) before and (b) after tuna cooking juice filtration.

In general, the water flux declines with time because of pore blocking and gel accumulation on the membrane surface; so-called external concentration polarization (ECP). However, membrane ECP fouling from the tuna cooking juice, besides tuna meat scraps, also composed of some water soluble materials such as gelatine and calcium.

The atomic force microscopy (AFM) used to study the characteristic of roughness of membrane surface revealed images of a smooth surface on the top layer, with a mean roughness (R_a) of 5.52 nm for a virgin membrane, and 12.25 nm for the fouled membrane (Fig. 5). Thus, roughness is correlated to accumulation of foulant or scaling; the more roughness value the more clogging, and hence the decrease in water flux.

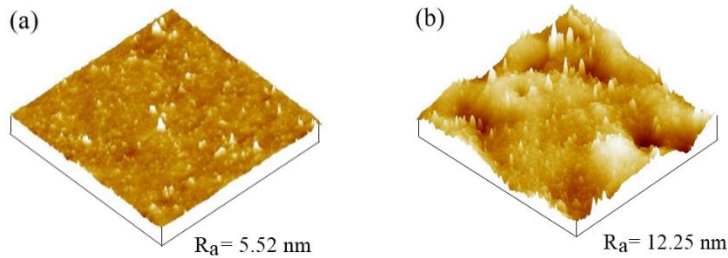


Fig. 5. AFM images of CTA membrane, (a) virgin membrane and (b) fouled membrane.

4. Conclusions

Effects of operation conditions and fouling on protein recovery from tuna cooking juice by FO process were investigated. The average permeate flux obtained was 2.54 LMH; and the protein recovery, 9% (w/v). The water flux output declined due to combined fouling from soluble organic and inorganic compounds, gel accumulation in the pore and scaling on the membrane surface. However, foulants require DI water flushing, and especially chemical cleaning to enhance the water flux. The membrane resistance model results for tuna cooking juice filtration indicated that gel in pore blocking is the dominant contributor to membrane fouling.

Acknowledgement

This work was supported by the Revenue Budget of the Prince of Songkla University (PSU) through its Faculty of Engineering (ENG 550348S). The authors are grateful to all members of the PSU Membrane Science and Technology Research Centre (MSTRC) at the Faculty of Science for supporting the collaboration. I would like to thank Prof. Wiwat Sutiwipakorn for grammatically correction.

References

1. Ministry of Commerce Thailand. (2015). Retrieved January 25, 2015, from <http://www2.ops3.moc.go.th>.
2. Prasertsan, P.; Wuttjumngong, P.; Sophanodora, P.; and Choorit, W. (1998). Seafood processing industries within Songkla-Hat Yai region: The survey of basic data emphasis on wastes. *Songklanakarin Journal of Science and Technology*, 10, 447-451.
3. Vandanjon, L.; Cros, S.; Jaouen, P.; Quéméneur, F.; and Bourseau, P. (2002). Recovery by nanofiltration and reverse osmosis of marine flavors from seafood cooking waters. *Desalination*, 144, 379-385.
4. Walhaa, K.; Amara, R.B.; Bourseau, P.; and Jaouen, P. (2009). Nanofiltration of concentrated and salted tuna cooking juices. *Process Safety and Environmental Protection*, 87(5), 331-335.

5. Kasiwut, J. (2012). *Antioxidative, Angiotensin I-Converting Enzyme (ACE) Inhibitory and Ca-binding Activities of Peptides Produced from Tuna Cooking Juice and Spleen Extract-protease*. Master Thesis. Prince of Songkla University, Thailand.
6. Walha, K.; Amar, R.B.; Masse, A.; Bourseau, P.; and Cardinal, M. (2011). Aromas potentiality of tuna cooking juice concentration by nanofiltration. *LWT-Food Science and Technology*, 44, 153-157.
7. Hsu, K.C.; Lu, G.H.; and Jao, C.L. (2009). Antioxidative properties of peptides prepared from tuna cooking juice hydrolysates with orientase (*Bacillus subtilis*). *Food Research International*, 42, 647-652.
8. Hajiham, M.; and Youravong, W. (2013). Concentration and desalination of protein derived from tuna cooking juice by nanofiltration. *Jurnal Teknologi*, 65, 1-6.
9. Afonso, M.D.; and Borquez, R. (2002). Review of the treatment of seafood processing wastewaters and recovery of proteins therein by membrane separation processes-prospects of the ultrafiltration of wastewaters from the fishmeal industry. *Desalination*, 142, 29-45.
10. Khetprathum. (2008). *Production and Physicochemical Properties of Fish Wash Water in Surimi Industry using Ultrafiltration and Spray Dry*. Master Thesis. Prince of Songkla University, Thailand.
11. Bootluck, W.; Khongnakorn, W.; and Youravong, W. (2014). *Effect of different concentration of draw solution on BSA recovery by forward osmosis*. 3rd International Conference on Environmental Engineering, Science and Management. Bangkok, Thailand, 26-28 March.
12. Khongnakorn, W.; Bootluck, W.; and Youravong, W. (2014). CTA-FO membrane by CO₂ plasma treatment. *Jurnal Teknologi*, 70(2), 71-75
13. Mi, B.; and Elimelech, M. (2010). Organic fouling of forward osmosis membranes: Fouling reversibility and cleaning without chemical reagents. *Journal of Membrane Science*, 348, 337-345
14. Castello, E.M.G.; Cutcheon, J.R.M.; and Elimelech, M. (2009). Performance evaluation of sucrose concentration using forward osmosis. *Journal of Membrane Science*, 338, 61-66.
15. Ginnis, R.L.M.; and Elimelech, M. (2007). Energy requirements of ammonia-carbon dioxide forward osmosis desalination. *Desalination*, 207, 370-382.
16. Achilli, A.; Cath, T.Y.; Marchand, E.A.; and Childress, A.E. (2009). The forward osmosis membrane bioreactor: A low fouling alternative to MBR processes. *Desalination*, 239, 10-21.
17. Achilli, A.; Cath, T.Y.; and Childress, A.E. (2009). Power generation with pressure retarded osmosis: An experimental and theoretical investigation. *Journal of Membrane Science*, 343, 42-52.
18. AOAC. (1999). *Official methods of analysis*, 16th edition, Association of Official Analytical Chemists, Arlington, VA.
19. APHA. (2012). *Standard methods for the examination of water and wastewater*, 20th edition. American Public Health Association, Washington, USA.

20. Zhang, X.; Ning, Z.; Wang, D.K.; and Costa, J.C.D. (2014). Processing municipal wastewater by forward osmosis using CTA membrane, *Journal of Membrane Science*, 468, 269-275
21. Lutchmiah, K.; Verliefde, A.R.D.; Roest, K.; Rietveld, L.C.; and Cornelissen, E.R. (2014). Forward osmosis for application in wastewater treatment: A review. *Water Research*, 58, 179-197.
22. Zhao, P.; Gao, B.; Yue, Q.; and Shon, H.K. (2015). The performance of forward osmosis process in treating the surfactant wastewater: The rejection of surfactant, water flux and physical cleaning effectiveness. *Chemical Engineering Journal*, 281, 688-695.
23. Altaee, A.; Zaragoza, G.; and Tonningen, H.R.V. (2014). Comparison between forward osmosis-reverse osmosis and reverse osmosis processes for seawater desalination. *Desalination*, 336, 50-57.
24. Phuntsho, S.; Vigneswaran, S.; Kandasamy, J.; Hong, S.; Lee, S.; and Shon, H.K. (2012). Influence of temperature and temperature difference in the performance of forward osmosis desalination process. *Journal of Membrane Science*, 415-416, 734-744.
25. Kim, Y., Lee, S.; Shon, H.K.; and Hong, S. (2015). Organic fouling mechanisms in forward osmosis membrane process under elevated feed and draw solution temperatures. *Desalination*, 355, 169-177.