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Techno-economic investigation of water recovery and whey powder production from whey using UF/RO and FO/RO integrated membrane systems

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ABSTRACT

As a by-product of dairy industry with high pollutant capacity, uncontrolled discharges of cheese whey result in serious pollution problems in the environment. Besides, recovery of water and whey powder in a whey stream has come to the fore as an important one of whey control strategies in environmental pollution. In that sense, the feasibility of water recovery and whey powder production from whey using integrated membrane processes was techno-economically investigated in this study. The study was focused on three case studies including different process scenarios were executed with laboratory-scale experiments in order to determine the technical performances of processes. The process scenarios were selected as following: the ultrafiltration/reverse osmosis (UF/RO), the forward osmosis/reverse osmosis (FO/RO) with NaCl draw solution and forward osmosis/reverse osmosis including thermolysis (FO/T/RO) at 60˚C for concentrating NH_4HCO_3 draw solution. The real-scale costs for the processes were estimated separately for each scenario using the process modeling and cost estimation software program. The results revealed that UF/RO system is an effective option in whey treatment. FO/T/RO process supplied relatively low-economic performance with 9 years payback, $353,000 net present value (NPV) and moderate water recovery value with 47.7%. However, FO/RO process seemed to be a featured alternative with the highest water recovery of 77.4%, the whey powder production of 98,874 entity/year, and NPV of $12,347,000 and also an inevitable result of 0.8 years payback lower than that of UF/RO. These results proved that FO/RO system with NaCl draw solution could be successfully employed for both water recovery and whey powder production from whey when compared to UF/RO system known as widely used.

Keywords: Forward osmosis; Integrated membrane systems; Water recovery; Whey powder production

1. Introduction

Cheese whey is a by-product of the cheese manufacturing processes and contains about 93–94% of water and the following nutrients from the original milk: lactose (4.5–6.0%), soluble proteins (0.6–1.1%), minerals (0.8–1.0%), lactic acid (0.05–0.9%), and fats (0.06–0.5%) [1]. The type and composition of whey mainly depends upon the processing techniques used

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for casein coagulation from liquid milk and generally referred as sweet (the casein coagulation occurs at pH 6.5 with the rennet) and acid whey (the casein is coagulated with addition of organic or mineral acids at $pH < 5.0$) [2]. Cheese whey management is very important issue because of the extremely high organic content. Due to high pollutant capacity depending on rich nutrient content, the whey cannot be directly discharged to the receiving environment because of serious environmental problems [3].

Generally, three different options can be used for cheese whey treatment technologies: the valorization technologies for the recovery of valuable compounds such as proteins and lactose, the biological treatment technologies for the production of lactic acid, ethanol or hydrogen with controlled fermentation processes and the physicochemical treatment methods such as the thermal techniques, coagulation–flocculation, thermocalcic precipitation, acid precipitation, electrochemical oxidation, membrane separation, etc. [1]. In recent years, the membrane processes are extensively used for the concentration of proteins and lactose from cheese whey, and they also provide the water reuse and valuable ingredients recovery [4,5]. Nanofiltration can be used to separate lactose and mineral salts for the demineralization of whey stream with the lactose retention values above 89% [6–8]. Therefore, the reverse osmosis process could be used for demineralization of whey and also the purification of lactose in the concentrated whey [9]. Microfiltration and ultrafiltration processes have lower lactose retention values below 40%, but these processes are mainly used to remove fat and proteins [4,10]. However, high pressure-driven membrane technologies have some limitations such as higher cost because of high operating pressures. Additionally, the whey protein concentrates might present a lack of uniformity in the composition [11].

Forward osmosis (FO) membrane process could be a potential alternative or complementary step to the pressure-driven membrane processes in certain applications such as the seawater desalination, wastewater reclamation, drinking water production, brine concentration, protein concentration, liquid food processing, and dehydration of alcohols [12,13] and has been gaining popularity in recent years. Basically, FO process uses a concentrated draw solution to generate high osmotic pressure gradient, which creates the driving force for water transport across a semi-permeable membrane from the feed solution [14,15]. The solute molecules in draw solution are then separated from the diluted draw solution to recycle the solute, as well as to produce clean product water [16]. Using FO processes in different areas has considerably increased, and thus, it requires further technical and economic analysis. Especially, the cost analysis is very important step for the selection of membrane processes. The different configurations of membrane processes could be made possible for gaining economic benefit by processing special products in industrial waste liquids. At the same time, the successful and economical designs of hybrid or integrated membrane systems are a challenging task that can be facilitated by the use of computer-aided process design and simulation tools [17]. For making a reliable economic analysis, various costs such as operating or investment cost should be taken into account.

The objective of this study is to investigate the techno-economic analysis of whey concentration and water recovery with different membrane processes scenarios. Three scenarios were chosen as ultrafiltration/reverse osmosis (UF/RO), forward osmosis/reverse osmosis (FO/RO) with NaCl draw solution, and forward osmosis/reverse osmosis including thermolysis (FO/T/RO) with NH_4HCO_3 draw solution. Several key parameters were technically determined with bench-scale experiments in continuous operation. The technical performances of each membrane process were simulated with the process modeling and cost estimation software. Also, a full economic analysis including both water recovery and whey powder production was carried out by complementing the scenarios with whey powder production line. Consequently, the real-scale costs were estimated individually for each scenario.

2. Materials and methods

2.1. Materials

FO experiments were executed using flat-sheet cellulose triacetate FO membrane (Hydration Technologies Inc., OR). UF and RO experiments were carried out using polyethersulfone UP010 (Microdyn-Nadir GmbH, Germany) and composite polyamide CPA-3 (Hydranautics Inc., CA) membranes, respectively. Analytical grades (NaCl, NH_4HCO_3, and NH_4OH 25%) were obtained from Merck. Cheese whey was supplied from industrial facilities of Cayirova Milk and Milk Products Inc., located at Kocaeli, Turkey. The characteristics of raw cheese whey and whey concentrated by integrated membrane systems were presented in Table 1.

2.2. Methods

2.2.1. Experimental systems

2.2.1.1. FO membrane system. A laboratory-scale FO system shown in Fig. 1(a) was employed in the experiments. The cross-flow membrane module was a

Table 1
Characteristics of raw whey and concentrated whey by UF/RO, FO/RO, and FO/T/RO integrated membrane systems

Parameters	Unit	Raw whey	UF/RO		[a]FO/RO	[a]FO/T/RO
			UF	[b]RO		
pH	-	4.83 ± 0.40	5.03	5.17	4.86	8.38
Cl^-	mg/L	1,742 ± 841	1891	2,639	9,350	3,819
Osmolality	mmol/kg	336 ± 43	476	514	1,174	1,070
Conductivity	mS/cm	8.19 ± 2.04	7.97	5.27	18.92	31.8
Density	g/cm^3	1.021	1.0316	1.0512	1.0794	1.0411
SCOD	mg/L	67,579 ± 9,070	96,181	64,680	174,876	100,381
NH_4-N	mg/L	107 ± 7	154	151	225	5,967
NO_2-N	mg/L	0.16 ± 0.02	0.27	2.01	0.40	0.15
NO_3-N	mg/L	242 ± 2	362	77	529	282
TKN	mg/L	1,166 ± 525	1,451	353	2030	9,002
Org-N	mg/L	1,059 ± 527	1,298	202	1805	3,035
TN	mg/L	1,408 ± 525	1813	430	2,559	9,284
TP	mg/L	490 ± 81	652	725	936	781
Total protein	%	2.26 ± 0.15	4.52	5.95	9.54	4.96
Fat	%	0.27 ± 0.11	1.49	1.78	1.89	0.36
SNF (fat-free dry matter)	%	6.48 ± 0.34	11.96	15.48	25.82	12.57
Total solid content	%	6.75 ± 0.42	13.45	17.41	27.71	12.93
Lactose	%	3.36 ± 0.23	6.71	8.83	14.17	7.38
Minerals	%	1.41 ± 0.32	1.10	1.30	3.51	4.40

[a]means that whey was concentrated by FO process in FO-included systems.
[b]UF permeate was the feed stream of RO process defined as the first step RO in the scenario.

custom made cell with equivalent flow channel at both sides of the membrane. The membrane module made from Delrin acetal resin material (DuPont, Delaware) has an effective membrane area of 140 cm^2. Two speed controllable peristaltic pumps (EW 77111-67, Cole Parmer, IL) were used to pump the solutions. Two flow meters with maximum flow rate 10 $L\,min^{-1}$ were separately placed on the feed and draw lines of the setup in order to enable the desired same flow rates on each line. The setup was also equipped with a constant temperature water bath (462-7028, VWR Scientific, IL) to maintain the same temperature at both the feed and draw solutions during FO tests. The operations of two different FO processes inside of FO/RO and FO/T/RO systems for whey concentration were separately carried out using the same FO system shown in Fig. 1(a). In both of FO processes, salt concentrations in draw solutions were kept constant during the experiments.

In FO/RO system, FO process was operated with 2 M NaCl draw solution at the conditions of feed and draw volumes of 3.5 L, cross-flow rate of 300 L/h (0.5 m/s), temperature of 25 ± 0.5˚C, reverse membrane orientation mode (the active layer in contact with the feed), and co-currently flow in the channels. The whey concentration was maintained at sequentially three times within 14 h. At the end of each operation period, the fouled membrane was subjected to cleaning along 15 min by using de-ionized water as the feed and fresh 2 M NaCl as the draw solution, after turning the membrane to the normal mode (the active layer faced on the draw, while it was on the whey side during operation).

In FO/T/RO system, 2 M NH_4HCO_3 with supplementary NH_4OH was used as the draw solution in which molar ratio of NH_4^+ to HCO_3^- was adjusted to 2. The process operation (draw volumes, cross-flow rate and membrane orientation) was employed at the same conditions of the FO process with NaCl, except for temperature of 30 ± 0.5˚C, operation time of 18 h and counter-currently flow in the channels. The whey concentration was maintained at sequentially three times within 18 h operation time. Although membrane cleaning was also done at the same conditions of the FO process with NaCl, fresh 2 M NH_4HCO_3 in $NH_4^+/HCO_3^- = 2$ was used as draw solution instead of 2 M NaCl. Thermal decomposition of NH_4HCO_3 draw solution at 60˚C was carried out in a separate reactor vessel of 250 mL with a semi-continuous operation of 15 h for each FO operation cycle.

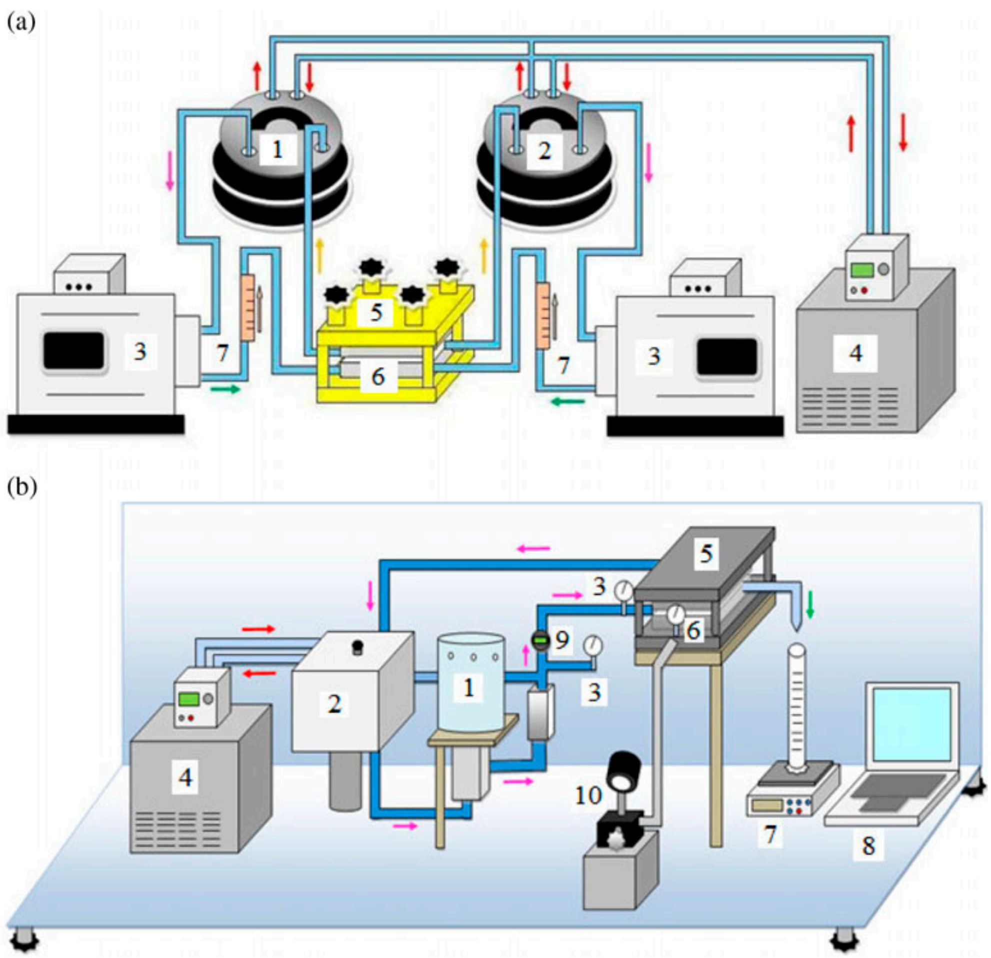

Fig. 1. Experimental membrane system setups ((a) FO system (1: feed tank, 2: draw tank, 3: peristaltic pumps, 4: water bath, 5: clamp, 6: membrane module, 7: flow meters), and (b) pressure-driven membrane system (1: high pressure pump, 2: feed tank, 3: pressure gauges, 4: water bath, 5: clamp, 6: membrane module, 7: balance, 8: computer, 9: digital flow meter, 10: clamp driver).

During both FO/RO and FO/T/RO experiments, no solution change was made for the course of either operation or cleaning.

2.2.1.2. Pressure-driven membrane system. UF and RO experiments were executed using laboratory-scale pressure-driven membrane system (Fig. 1(b)). The system had a flat-sheet cross-flow membrane module having an effective membrane area of 140 cm^2 (GE Osmonics, MN). It was equipped with a feed tank, high-pressure pump of 100 bar with a flow volume 330 L h^{-1} (Bosch, Germany), flow splitter, digital flow meter (max 720 L h^{-1}) (Honsberg, Germany), and manual oil pump for clamping the module. In the experiments, the processes were employed in the concentration mode, which means that permeate solutions were not returned into the feed tank while the retentate was. The flow rates of the permeate solutions collected in a beaker were measured by an electronic balance (Precisa XT2220 M-DR) and recorded by a computer.

In UF/RO system, the experiments were conducted at the conditions of 40 ± 1 and 25 ± 1 °C temperature, 4.5 and 2.25 L feed volume, 10 and 40 bar transmembrane pressure, and 12 and 1 h filtration time for UF and RO, respectively. Cross-flow rate was set to 2.5 m/s by using 17-mil thick spacer in the flow channel during either experiment. In UF experiment, whey was concentrated at two equivalent operation sequences of 6 h by the replacement of the membrane.

In FO/RO system, RO filtration of draw solution was employed as the first step RO in FO-included scenarios and run along 18 h with 40 bar transmembrane pressure, 2.5 m/s cross-flow rate, 25 ± 1 °C temperature and 3.5 L feed volume. The steady-state water flux of the first step RO at the end of 18 h was determined as

1.79 L/m^2.h, and the water recovery performance of the process in simulations was applied with a recovery rate of 80%. Due to the deficiency of the permeate volume obtained from the first-step RO implementation, the performances of the second-step RO were not experimentally investigated with bench-scale research. Hence, the second RO in FO/RO system and RO of FO/T/RO system were considered as the same process of which the performance was assumed as COD: 98.4%, NaCl: 98.5%, NH_4HCO_3 and NH_4OH: 99.2%, water flux: 40 L/m^2 h, and recovery rate: 50%.

Analytical procedure concerning the measurement of water quality parameters in the feed and draw solutions was defined in Aydiner et al. [18]. The principles on the determination of technical performances of FO, UF, and RO processes were given in Aydiner et al. [19].

2.2.2. Economic analysis

In accordance with the performance results obtained from laboratory-scale researches for the scenarios, a comprehensive cost analysis was carried out using a software (*Intelligen's SuperPro Designer® v7.5*). *SuperPro Designer* is a process simulator to provide an efficient design with modeling and optimization of integrated processes [20]. As intended for estimations of real-scale costs of laboratory-scale processes, *SuperPro Designer* was successfully used for integrated membrane processes in different wastewater systems [8,12]. At the scope of economic evaluation of the scenarios, the technical performances associated with each integrated system were individually simulated in the software for a lifetime of 15 years, 7,920 h annual exploitation, and 100 m^3/day design flow rate. The simulations were essentially based on verifying the experimental mass balances of the processes. The dimensions and numbers of units in the scenarios were determined in respect of design limitations known from instances in practice (Table 2). Thereafter, the economic performances of the scenarios were estimated by the software using the price knowledge obtained from the literature survey and market researches for equipment, consumables, utilities, whey powder and water (Table 3). In Table 3, recycled water saving, wastewater disposal, electricity and membrane disposal costs and labor salaries were implemented to the economic analysis as local prices in Turkey. UF and RO membrane purchase costs were obtained from Turkey branch office of an international membrane company. Stand-alone FO membrane cost selected as $12 per FO membrane material corresponds to $55–60 per m^2 of FO membrane in FO membrane module as a result of module purchase cost of $1,000, module construction cost of $500 and direct cost components for the FO process. This value is some above the known values of FO membrane in literature in which $45 per m^2 of FO membrane in the system given by Cath et al. while $30 per m^2 of FO membrane in FO membrane module assumed by Yangali-Quintanilla et al. [21,22].

Table 2
Unit numbers required for each process in whey treatment systems together with unit dimensions required for membranes

Unit	Unit numbers		
	UF/RO	FO/RO	FO/T/RO
UF (m^2)*	31 (9.73)	–	–
RO in the first step (m^2)*	8 (9.34)	91 (39.59)	–
RO in the second step (m^2)*	4 (7.76)	3 (26.87)	8 (37.26)
FO (m^2)*	–	27 (39.56)	20 (39.31)
Raw whey storage (2.5 m^3)	2	2	2
Concentrated whey storage (1.5 m^3)	3	2	4
Spray dryer (3.5 m^3)	4	2	5
Silo (1 m^3)	2	2	2
Packaging (7 package/h)	2	2	2
Condenser (15,000 m^2)	3	2	4
Thermolysis (20 m^3)	–	–	21
Cooler (2.5 m^2)	–	–	4

*Those in parenthesis are the required membrane areas belonging to the corresponding membrane process in treatment scenarios. Module numbers concerning both membrane processes in UF/RO system were specifically increased for safety operation by decreasing the required membrane areas compared with other two scenarios.

Table 3
Unit prices for constituents required during whey processing via disposal costs and working life of membranes

Constituent	Remark	Unit price
Recycled water saving	\$/ton	1.80
Wastewater disposal	\$/ton	0.25
Whey powder selling	\$/entity	32.50
Package purchase	\$/package	0.20
Electricity	\$/kWh	0.10
Labor		
Technician (full-time)	\$/h	4.0
Engineer (part-time)	\$/h	11.0
Membrane disposal	\$/m^2	5
Membrane purchase		
UF	\$/m^2	100
FO	\$/m^2	12
RO	\$/m^2	30
Membrane life		
UF and RO	year	3
FO	year	5
Auxiliary chemicals/materials		
NH_4OH	\$/kg	0.50
NH_4HCO_3	\$/kg	0.20
NaCl	\$/ton	41.00
Chilled water	\$/ton	0.40
Cooling water	\$/ton	0.05
Freon	\$/ton	0.15
Steam	\$/ton	12.00

The total capital cost, which consists of direct fixed capital, working capital and start-up costs, was calculated in a series of steps using the software. Operating cost was separately estimated by the software based on subcategories such as labor, facilities, consumables, disposal and utility-dependent factors. While the total capital and operating costs were calculated as described in detail before in a previous study [23], the total revenue was estimated from unit revenues obtained from recycled water and whey powder selling. The return on investment, payback time and net present value (NPV) were determined in the cash flow analysis conducted using the software. For this purpose, 3 year loans at a fixed interest rate were assumed for a period of 15 years of operation.

3. Results and discussion

3.1. Technical performances

In FO processes in FO/RO and FO/T/RO systems, the time-dependent variations of osmotic pressures of feed (π_f) and draw (π_d) solutions and the osmotic pressure differences as net (difference among osmotic pressure of draw and feed solutions, $\Delta\pi_{net} = (\pi_d - \pi_f)$) and normalized net (net osmotic pressure difference per osmotic pressure of feed solution, $\Delta\pi_{normalized\ net} = (\Delta\pi_{net}/\pi_f)$) were shown in Fig. 2(a) and (b), respectively. Despite same draw concentration, NaCl yielded some higher driven force with osmotic pressure of 103 bar compared with 90 bar of NH_4HCO_3. Because of the increasing of osmotic pressure in the feed depending on concentrating whey, the net pressure difference decreased from 95 to 70 bar at FO/RO and from 81 bar to 58 bar at FO/T/RO. Each FO process resulted in a linear decrease in normalized net pressure difference.

Fig. 3(a), (b), (c), and (d) indicate volumetric water permeation, water flux, salt flux and whey solid content in FO-integrated systems. It can be seen from Fig. 3(a) that 2.7 L and 1.6 L of initial 3.5 L of whey passed to the draw solution at FO/RO and FO/T/RO, respectively. The water flux decreased with time and operation period in spite of membrane cleaning which carried out by back-washing at both process (Fig. 3(b)). The last water fluxes of FO in FO/RO were determined as 7.9, 2.3, and 3.5 L/m^{2}h at the end of

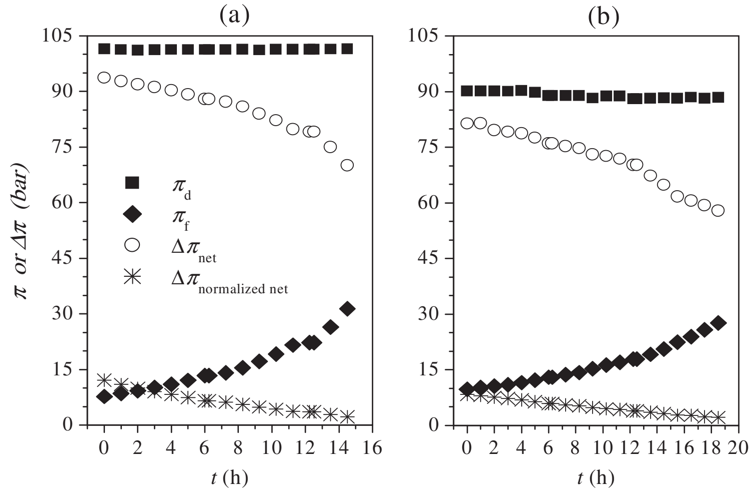

Fig. 2. Time-dependent variations of osmotic pressures at draw (π_d) and feed (π_f) and of osmotic pressure differences as net ($\Delta\pi_{net}$) and normalized net ($\Delta\pi_{normalized\ net}$) in FO process ((a), FO/RO and (b) FO/T/RO), ($\Delta\pi_{normalized\ net}$, normalized net osmotic pressure difference, was determined by dividing $\Delta\pi_{net}$ with π_f).

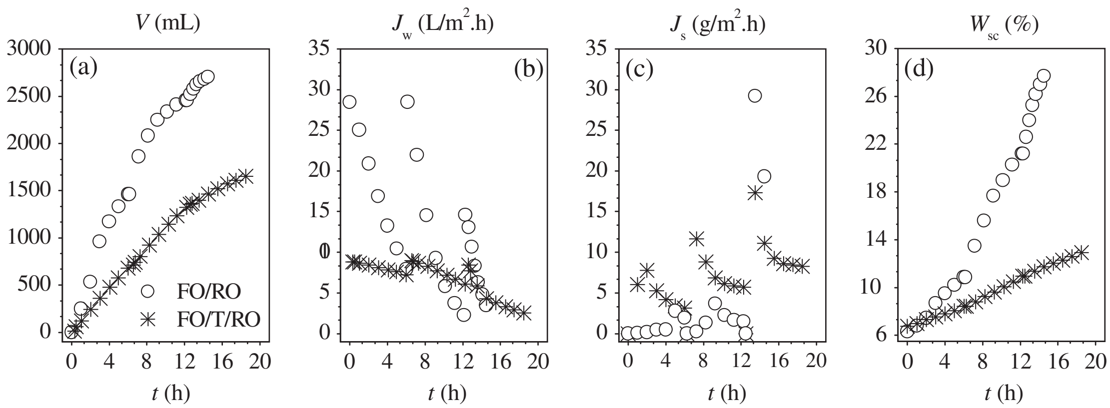

Fig. 3. Time-dependent performances of FO process on water permeation and whey concentration in FO-integrated systems ((a), volumetric water permeation; (b), water flux; (c), salt flux; and (d), whey solid content).

periods I, II, and III, respectively. On the other hand, those of FO in FO/T/RO were found to be 7.3, 6.1, and 2.5 L/m^2 h. From Fig. 3(c), the last salt fluxes of FO processes in FO/RO and FO/T/RO systems were found as 1.95, 1.50, and 19.30 g/m^2 h, and 3.16, 5.66, and 8.30 g/m^2 h at the end of periods I, II, and III, respectively. The whey solid content reached to 10.85, 21.21, and 27.71% at FO/RO and 8.44, 10.94, and 12.93% at FO/T/RO (Fig. 3(d)). From these results, it can be said that FO/RO system was operated more efficiently than FO/T/RO, so the production of whey powder in a spray dryer system could be accomplished more economically using FO/RO.

Fluxes belonging to UF and RO in whey concentrating by UF/RO system were depicted in Fig. 4(a) and (b), respectively. Although UF was operated under two sequential periods, same fluxes of 10.3 L/m^2 h were observed at the end of both periods. After UF processing of whey, the whey permeate was filtrated by RO and permeate flux of 33.4 L/m^2 h was obtained. The using of RO process after UF exhibited a high water permeation performance in whey concentrating.

The rejection performances of integrated systems were shown in Table 4. In FO/RO system, the rejection values of nitrogen compounds were in the range of 51.3–77.3% in addition to the complete rejection of total phosphorus. But high salt concentration in the draw led to low RO performance with a rejection of 50.7% as well as lower COD rejection of

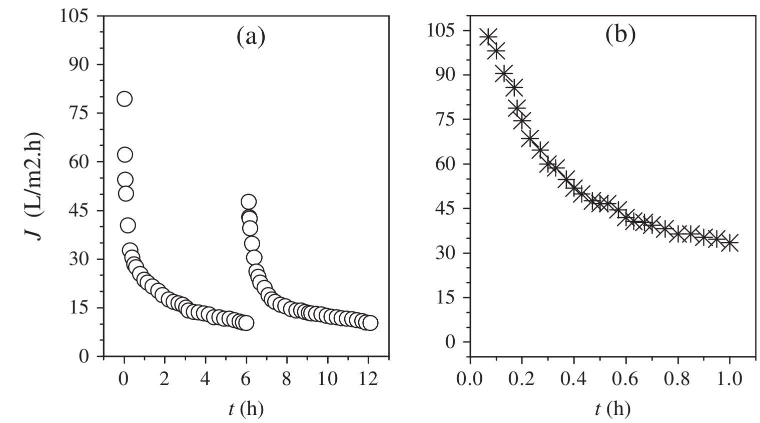

Fig. 4. Flux evolutions vs time in UF (a) and RO (b) processes during whey processing by UF/RO system.

Table 4
Experimental performances related to UF, RO and thermolysis processes in the corresponding integrated systems along with qualities in FO draw solutions at the end of FO processing of whey

Parameters	Unit*	UF/RO		FO/RO[a]		FO/T/RO[a]	
		UF, *R* (%)	RO, *R* (%)	FO draw	RO, *R* (%)	FO draw	T, *R* (%)
pH[b]	–	5.06	5.09	6.10	6.15	8.45	7.5
Cl^-	mg/L	−25.6	96.7	65,028	50.7	–	–
Osmolality	mmol/kg	25.0	97.1	3,400	35.6	3,148	93.3
Conductivity	mS/cm	−20.6	86.2	132.8	30.0	115.8	92.6
COD	mg/L	66.8	99.3	1923	34.2	3,952	−145.0[d]
NH_4-N	mg/L	97.6	95.9	5.5	60.0	40,175	88.8
NO_2-N	mg/L	0.0	69.1	0.08	62.0	–	–
NO_3-N	mg/L	89.0	94.4	5.7	51.3	–	–
TKN	mg/L	82.4	54.6	61.8	75.8	–	–
Org-N	mg/L	80.7	23.7	56.3	77.3	–	–
TN	mg/L	83.7	61.5	67.6	73.7	–	–
TP	mg/L	45.5	99.9	2.67	100.0	14.5	4.5
ΔV[c]	%	–	–	–	–	–	80.0

*These units were given for only the FO draw solutions in FO-included scenarios.
[a]In laboratory-scale studies, RO process was implemented as the first-step RO for FO-included scenarios.
[b]pH was presented in the actual values.
[c]ΔV is the decrease in the water volume of FO draw solution by water vaporization during thermolysis of NH_4HCO_3 at 60°C.
[d]means that COD increased during thermolysis process due to vaporization of some soluble organics concurrently with water, NH_3 and CO_2. At the end of the process, 10,670 mg COD/L was recycled into the draw solution.

34.2% due to low-molecular-weight soluble organics passed from whey into the draw. In UF/RO system, RO process in single step provided to produce high-quality water in spite of relatively lower nitrogen removal performance. Stand-alone thermolysis process after FO process did not make possible to produce clean water from the draw due to vaporization of some soluble organics concurrently with water, NH_3, and CO_2. This meant that a complementary implementation of RO process after thermolysis is required.

3.2. Economical performances

Integrated membrane systems' investment, operation and analysis of the total cost of components were carried out using *SuperPro Designer* software. Fig. 5 depicts the flow charts of (a) UF/RO, (b) FO/RO, and (c) FO/T/RO systems. The performances belonging to whey treatment simulated by the scenarios were presented in Table 5.

The water recoveries of 77.4 and 47.7%, respectively, for FO/RO and FO/T/RO indicated that water

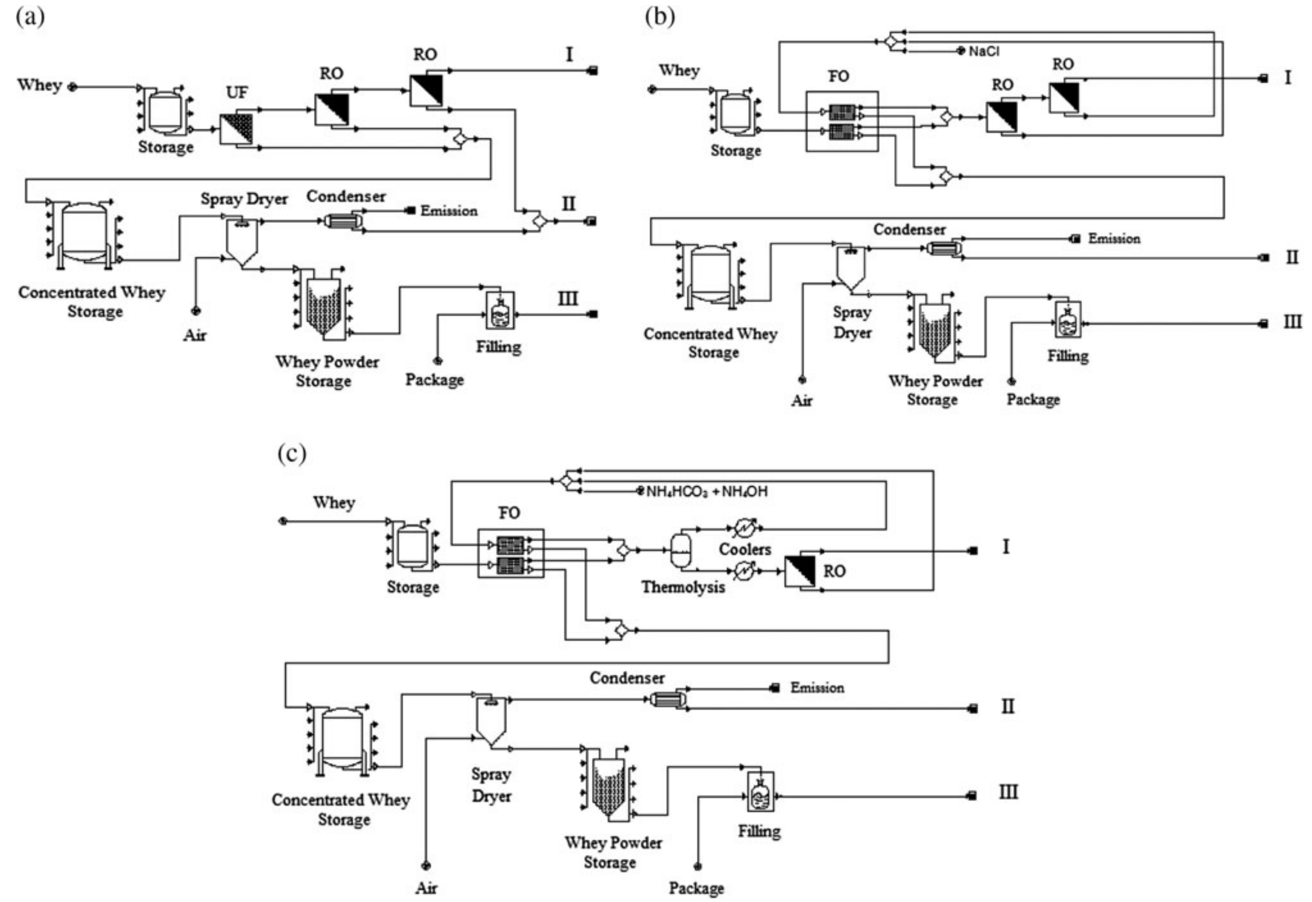

Fig. 5. Process flow representations including both water recovery and whey powder production for integrated membrane systems ((a), UF/RO; (b), FO/RO; and (c) FO/T/RO), (I: water recovery line, II: centralized wastewater treatment line, and III: packaged whey powder product line).

recovery in high volume could be obtained when compared to UF/RO (29.7%) which has been widespread used in whey treatment. The simulation results showed that FO/RO produced the whey powder which had almost same of dry matter content in UF/RO, but better moisture availability. FO/T/RO produced comparatively low quality of whey powder. COD of water recovered by FO/RO was estimated as 50 mg/L and lower than UF/RO (63 mg/L). While the quality of the recovered water in FO/T/RO was determined lower than the other two options. Although constituent concentrations in wastewater to be treated with a centralized treatment facility in FO/RO system estimated to be worse than those in UF/RO and FO/T/RO (except for NaCl), mass loadings were determined better than those of both systems.

Table 6 indicates the economic performance of the scenarios and so the results can be evaluated by comparing with each other. The economic performance of FO/RO system was better than UF/RO. In other words, FO/RO system can be applicable as a new whey treatment alternative to UF/RO system for concentrating whey and producing clean water. Although FO/RO system provides high enough quality and economic gains comparable with UF/RO, the payback time of FO/T/RO system was predicted as 9 years. There were two main reasons for the 9-fold increase in payback time for FO/T/RO system with respect to FO/RO system: (1) Despite the system inflow of 100 m^3/day, the flow coming to the thermolysis unit was the sum of inflow and the return flow from RO unit that brought about an inflow of 580 m^3/day into the thermolysis unit in accordance with the simulated mass balance as about six times more than total whey inflow into the system. This increase produced a need for 21 thermolysis units for the evaporation of wastewater and thereafter four cooler units. Also the number of spray drier units rose from 2 to 5 due to high input rate of concentrated whey in the system.

Table 5
Simulated performances for flow rates and qualities of water in raw whey line (RWL), water recovery line (WRL) and centralized wastewater treatment line (CWTL), together with quality of whey powder (WP) produced

Parameters	Unit	UF/RO				FO/RO				FO/T/RO			
		RWL	WRL	CWTL	WP	RWL	WRL	CWTL	WP	RWL	WRL	CWTL	WP
Vol. flow	m^3/day	100.00	29.80	62.60	–	100.00	77.40	16.06	–	100.00	47.70	44.80	–
Temperature	℃	40.00	25.87	22.79	–	25.00	25.26	25.00	–	25.00	25.34	0	–
Solid cont.	%	7.14	0.0063	0.26	93.31	6.32	0.0044	0.39	93.59	6.78	0.019	0.15	90.75
Moisture	%	–	–	–	4.45	–	–	–	2.43	–	–	–	6.14
NaCl	mg/L (%)*	1,668	7,373	234	(2.04)	1,187	293	0	(3.78)	2,709	1,193	0	(2.91)
COD	mg/L	70,875	62.50	2,601	–	72,816	50.31	4,508	–	61,451	174	1,363	–
TKN	mg/L	988	0.87	36.30	–	732	0.50	45.20	–	939	2.66	20.8	–
TP	mg/L	455	0.40	16.70	–	421	0.30	26.10	–	432	1.22	9.6	–
NH_4OH	mg/L	–	–	–	–	–	–	–	–	106.60	10.80	0	–
NH_4HCO_3	mg/L	–	–	–	–	–	–	–	–	0	61.70	0	–

*Those in parenthesis are the percent amounts (w/w) in whey powder obtained from the scenarios while mg/L gives the concentration values in the lines.

Table 6
The results of overall economic analyses for whey treatment scenarios

Cost remark/indicator	Unit	UF/RO	UF/RO*,a	FO/RO	FO/RO*,b	FO/T/RO
Whey powder production rate	entity/year	98,016	87,024	87,610	98,874	96,915
Whey powder production cost	$/entity	4.45	4.99	4.59	4.10	30.99
Return on investment	%	113.27	99.62	108.58	123.50	11.07
Payback time	years	0.88	1.00	0.92	0.81	9.04
Total operating cost	$	436,000	434,000	402,000	405,000	3,003,000
Total capital cost	$	1,565,000	1,565,000	1,459,000	1,459,000	2,135,000
Total revenues	$/year	3,230,000	2,873,000	2,893,000	3,259,000	3,178,000
Net present value (at 7.0% interest)	$	12,065,000	10,490,000	10,742,000	12,347,000	353,000

*,a and b indicates respectively that, initial solid contents of whey belonging to UF/RO and FO/RO scenarios were correspondingly equalized with each other in the simulations to make a comparable economic analysis among them.

Consequently, total capital investment increased about 45%. (2) In order to handle the thermolysis inflow in high volume, large amounts of steam and freon had to be utilized in thermolysis for evaporation and cooler for cooling, respectively. Therefore, the utility costs under the operating costs rose up to 25-fold which in turn resulted in an increase of 750% in operating cost.

In addition to the UF and RO systems which have widespread usage, FO systems were included to this study for their innovative usage opportunities in whey processing. It is well known from literature researches and land applications about UF and RO processes that there is enough knowledge for full scale applications of them. However, as oriented to their real case membrane implementations, FO systems have been started to be utilized for recovery and reuse of industrial wastewaters in the last decade. Thus, inadequate know how about design and operation of FO systems in full scale necessitates more efforts on the selection of appropriate one among various technologies for their use of intent. So the impacts of various treatment options together with their economics in recovery and reuse could be more precisely assessed by using one of engineering methods such as decision-making tools. For this, environmental and social indicators as well as technology and economics should be taken into account in distinctive selection of most appropriate technology among the studied.

4. Conclusion

As already known from its usefulness and usability in real-world, UF/RO was ascertained to be an effective system for whey treatment. Despite moderate water recovery of 47.7%, FO/T/RO performed quite low economic performance with 9 years payback and

$353,000 NPV. However, FO/RO seemed to be a very interesting choice in which the highest performances for water recovery, whey powder production and NPV were acquired with 77.4%, 98,874 entity/year, and $12,347,000, respectively, together with some better payback of 0.8 years. These results proved that when compared to UF/RO system, FO/RO in whey processing could also be effectively employed for all the investment intended for both water recovery and whey powder production. Future work will be comparison study which includes a comprehensive technology assessment focused on selecting the most appropriate one among various innovative membrane systems for whey powder production and water recovery in dairy industry, in light of technical, economic and environmental aspects of the systems.

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