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Nanofiltration technology in water treatment and reuse: applications and costs

Arash Shahmansouri and Christopher Bellona

ABSTRACT

Nanofiltration (NF) is a relatively recent development in membrane technology with characteristics that fall between ultrafiltration and reverse osmosis (RO). While RO membranes dominate the seawater desalination industry, NF is employed in a variety of water and wastewater treatment and industrial applications for the selective removal of ions and organic substances, as well as certain niche seawater desalination applications. The purpose of this study was to review the application of NF membranes in the water and wastewater industry including water softening and color removal, industrial wastewater treatment, water reuse, and desalination. Basic economic analyses were also performed to compare the profitability of using NF membranes over alternative processes. Although any detailed cost estimation is hampered by some uncertainty (e.g. applicability of estimation methods to large-scale systems, labor costs in different areas of the world), NF was found to be a cost-effective technology for certain investigated applications. The selection of NF over other treatment technologies, however, is dependent on several factors including pretreatment requirements, influent water quality, treatment facility capacity, and treatment goals.

Key words | desalination, economic analysis, nanofiltration, wastewater reuse, water treatment

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LIST OF ABBREVIATIONS

AWWA: American Water Works Association
CNF: capillary NF membrane
CIP: clean-in-place
COD: chemical oxygen demand
DBP: disinfection by-product
EAA: equivalent annual annuity
GAC: granular-activated carbon
i (or ROI): rate of return
MACRS: modified accelerated cost recovery system
MBR: membrane bioreactor
MED: multiple effect desalination
MF: microfiltration
MSF: multi-stage flash desalination
MVC: mechanical vapor compression
MWCO: molecular weight cutoff
NF: nanofiltration
NF^2: dual pass nanofiltration
NPV: net present value
O&M: operation and maintenance
PAC: powder-activated carbon
RO: reverse osmosis
SWRO: seawater reverse osmosis
UF: ultrafiltration
USD: US Dollar
USEPA: United States Environmental Protection Agency
VC: vapor compression
ZLD: zero liquid discharge

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INTRODUCTION

The term nanofiltration (NF) appears to have been first used in the mid-1980s to describe membranes with characteristics that fall between ultrafiltration (UF) and reverse osmosis (RO) (Eriksson 1988). Because NF membranes are fundamentally similar to RO, the designation of a membrane as NF is based on various characteristics including effective pore size, molecular weight cutoff, and salt rejection (Simpson *et al.* 1987; Cadotte *et al.* 1988; Eriksson 1988; Conlon & McClellan 1989; Wang *et al.* 1995; Timmer 2001). Owing to characteristics including selective separation of salts, good organic removal, and relatively low pressure requirements, NF membranes are being increasingly employed in a wide variety of applications including water and wastewater treatment, and in several industries for product purification and treatment (e.g. dairy, chemical, beverage, food, pharmaceutical, pulp and paper, textile, and oil and gas). In 2004, it was estimated that NF makes up a tenth of the total membrane system revenue in the European municipal water market (Royan 2004). In 2006, the NF membrane market (including equipment) was estimated at $89.1 million and $97.5 million in 2007 (BCC Research 2007). BCC Research (2014) reported that the global market for NF membranes increased from $172.8 million in 2012 to $190.2 million in 2013, and is estimated to total $215.6 million by the end of 2014 and $445.1 million by 2019. Although NF could be an appropriate technology for many applications, the selection of NF over alternative processes should be based on technical and financial considerations. Typically, a feasibility study would be performed to determine the advantages of applying NF technology over other alternatives. An important concern in a feasibility study is the economic assessment, and any project regardless of size, should be economically viable. The purpose of this study was to review the application of NF technology in water and wastewater treatment and reuse. Furthermore, basic economic analyses were performed to investigate whether NF is a financially appropriate process to employ in drinking water treatment and wastewater reuse applications. It is worth noting, factors such as membrane fouling and chemical cleanings can significantly affect the economic assessment of membrane processes. Membrane fouling (including organic fouling, colloidal fouling, biofouling, and scale formation (Schaefer *et al.* 2005)) can impact membrane permeability and lifetime, rejection performance and, as a result, the cost benefits of employing NF. Researchers have demonstrated that certain membranes foul and experience greater flux decline than others (Peng *et al.* 2004; Bellona *et al.* 2008; Xu *et al.* 2010) and therefore, the impact of fouling on membrane performance should be evaluated before selecting a NF membrane for a particular application.

METHODS OF ECONOMIC ANALYSIS

Analysis methods

Several methods can be applied to perform an economic analysis, including the net present value (NPV) approach, equivalent annual annuity (EAA) approach, cost–benefit analysis, internal rate of return analysis, and payback period (PBP) analysis. These methods are well developed and described in various references. In this study, the EAA approach was employed to calculate and compare the unit water price for different alternatives at different flow rates. Using this approach, capital and operation and maintenance (O&M) costs were calculated and the capital cost was annualized. The total annual cost (consists of O&M and annualized capital costs) was then divided by the average flow rate of the treatment plant to calculate the unit water cost. It is worth noting that the average flow rate was considered to calculate O&M costs, whereas design capacity of treatment plants (1.3–2.5 times more than average flow rate depends on the capacity (USEPA 2006)) was used for capital costs calculations. Tax and depreciation were not considered in calculations of unit water costs. As an example to show the amount of profit from applying NF technology, water reuse in the textile industry was evaluated and NPV and PBP were calculated for textile industries with different capacities. Assumptions made to determine costs are listed in Table 1. Owing to the variability in cleaning

Table 1 | Assumptions for performing economic analyses

Parameter	Value/method
Life time of projects	25 years
Interest rate (*i*)	10%
Lifetime	25 years
Currency	All currencies were converted to US Dollar 2013 (USD 2013) using multipliers from The European Central Bank (2014) and Williamson (2014)
Ratio of design flow rate to average flow rate	1.3–2.5; based on the system capacity
Unit power (electricity) cost	$0.087 per kWh
Recovery of membranes	85% (unless otherwise noted)
NF membrane lifetime	5 years
Cartridge filter replacement cost	Calculated using equations reported by USEPA (2006)

practices, a standard rule of thumb of ($0.01 per 1,000 gallons of water produced) was used to account for NF chemical cleaning costs (USEPA 2006). Estimated costs for pH adjustment (acid) and antiscalant chemicals were also adopted from the United States Environmental Protection Agency (USEPA 2006).

Calculation of O&M and capital costs

Capital and O&M costs of the NF processes (except for desalination) were estimated using a procedure published by the USEPA) and details of cost calculation methods can be found in the report by the USEPA (2006). Capital costs were calculated based on membrane system costs, online monitoring costs, brine discharge pipeline costs and multipliers for housing, land, and operator training costs. For O&M costs, several factors were considered including clean-in-place chemicals, acid and antiscalant chemicals, NF membrane replacement, cartridge filter replacement, repair, maintenance, performance monitoring, power, labor, and costs for concentrate handling. For cost estimates of other processes (e.g. lime and soda, ozonation, activated carbon, etc.) and NF for desalination, data from different references were used, which are described in the appropriate sections.

NF IN WATER AND WASTEWATER INDUSTRY

Drinking water treatment

NF membranes are currently used for water softening (Bergman 1995; Schaep *et al.* 1998; Ghizellaoui *et al.* 2005) and the removal of color and disinfection by-product (DBP) precursors (Watson & Hornburg 1989; Ericsson *et al.* 1997; Khalik & Praptowidodo 2000; Mijatović *et al.* 2004; Lin *et al.* 2007; Chellam *et al.* 2008; Sobhani *et al.* 2012), mostly when the rejection of monovalent salts is of minimal importance and membranes that operate at low pressure (and energy) are desired over RO. NF is also preferred over RO due to a more dilute concentrate waste stream, and a product water requiring less stabilization to minimize distribution system corrosion (Beardsley & McClellan 1995). NF technology is reported to be the most appropriate process for hardness and organic removal although it is not always the most economical method (Yeh *et al.* 2000; Wilson Engineering 2013). Even though NF is reported to be an effective method for drinking water treatment at large facilities (Ventresque *et al.* 2000; Cyna *et al.* 2002), significant seasonal fouling events due to microbial activity and changes in organic matter properties have been reported for NF membranes (Her *et al.* 2007). NF has also been evaluated and/or employed for the removal of arsenic (Vrijenhoek & Waypa 2000; Nguyen *et al.* 2009; Harisha *et al.* 2010; Saitua *et al.* 2011), DBP precursors (Kim *et al.* 2007; Chalatip *et al.* 2009; Sentana *et al.* 2011), fluoride (Hu & Dickson 2006; Tahaikt *et al.* 2008; Padilla & Saitua 2010), heavy metals (Bouranene *et al.* 2008; Taleb *et al.* 2008; Murthy & Chaudhari 2009; Murthy & Choudhary 2011), inorganic carbon (Simpson *et al.* 1987; Padilla & Saitua 2010; Santafe-Moros & Gozalvez-Zafrilla 2010), nitrate (Santafe-Moros *et al.* 2005; Hayrynen *et al.* 2009; Santafe-Moros & Gozalvez-Zafrilla 2010), pesticides (Kiso *et al.* 2001; Van der Bruggen & Vandecasteele 2003; Bellona *et al.* 2004; Caus *et al.* 2009), oxyanions (e.g. bromate, perchlorate, phosphate, sulfate) (Kosutic *et al.* 2004; Yoon *et al.* 2005; Ballet *et al.* 2007; Listiarini *et al.* 2010), and various emerging organic contaminants (Nghiem & Coleman 2008; Bellona *et al.* 2011; Hajibabania *et al.* 2011; Shahmansouri & Bellona 2013).

To compare the costs of different options for water softening and color removal, unit water costs were calculated for three alternative processes over a range of flow rates including: (1) lime and soda ash softening; (2) lime and soda ash softening + ozone injection + granular-activated carbon ((GAC) for color removal); and (3) softening using NF membranes. Costs for water softening by NF membranes were calculated in two different ways including the EPA technique (method one; see section 'Calculation of O&M and capital costs'), and using NF water softening and color removal facility data from the literature (Bergman 1995; Ericsson *et al.* 1997; Costa & de Pinho 2006; Sobhani *et al.* 2012). To calculate costs for color removal by ozonation and GAC, data from Sobhani *et al.* (2012) were used. Capital and O&M costs for water softening using lime and soda ash were estimated using equations presented by McGivney & Kawamura (2008). Results (Figure 1) showed if only softening is important, lime and soda ash softening system would be marginally less expensive for large softening facilities (i.e. systems with capacity > 200,000 m^3/day). For smaller treatment plants, however, NF is a more cost-effective method as reported in the literature (Wilson Engineering 2013). Other advantages of NF over lime softening include small footprint, reduced chemical requirements, reduced chemical storage, increased organic matter removal, and no sludge production (Beardsley & McClellan 1995). If highly colored water is being treated, NF membrane

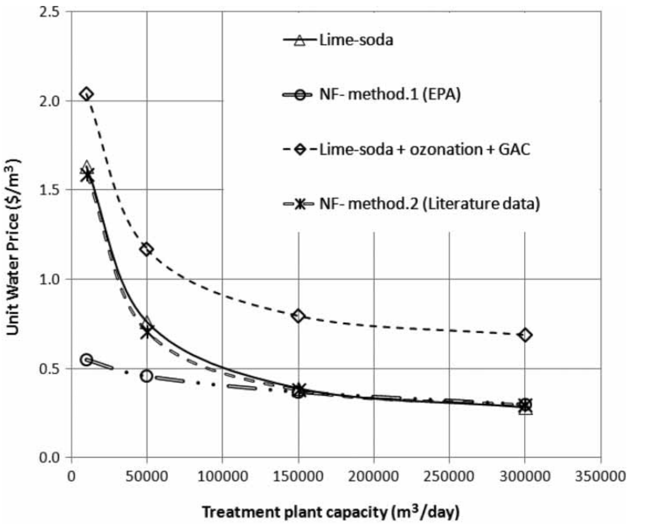

Figure 1 | Water cost for water softening and color removal alternatives; *i*: 10%; lifetime: 25 years; costs: 2013 USD; design flow rate to average flow rate ratio = 1.7 for capacity > 50,000 m^3/day and 2 for capacities ≤ 50,000 m^3/day.

systems produce water at a cheaper price compared to facilities using lime soda, ozonation, and GAC.

Wastewater treatment and reuse

The conventional approach for potable wastewater reuse applications (i.e. indirect potable reuse) is the use of an integrated membrane system (IMS) that employs microfiltration (MF) or UF pretreatment followed by RO, and usually, an advanced oxidation process (i.e. ultraviolet light with peroxide). Alternatives to conventional IMS include NF based processes as either a replacement for RO or hybrid systems, which are approaches that combine elements of two or more separate processes. Bench- and pilot-scale testing with low pressure and low fouling NF membranes have demonstrated that significant cost savings could be attained by using NF instead of RO membrane, although poor rejection of nitrate was observed (Bellona *et al.* 2008; Bellona *et al.* 2012). Several researchers have reported that NF is not as effective as RO for indirect potable reuse in terms of permeate water quality particularly with respect to inorganic nitrogen and unregulated organic contaminants (Bellona & Drewes 2007; Flyborg *et al.* 2010; Alzahrani *et al.* 2013), and more enhanced biological pretreatment methods may be necessary (Bellona & Drewes 2007). Several researchers have also investigated the applicability of hybrid processes employing NF membranes for indirect potable reuse applications (Flyborg *et al.* 2010; Kazner 2011; Alexander *et al.* 2012). Applying NF with GAC and powder-activated carbon (PAC) (Kazner 2011) and ozonation (Flyborg *et al.* 2010) has been reported to be a viable approach for wastewater reuse applications. Because the presence of particles could result in significant spiral wound NF module fouling when MF/UF pretreatment is not applied, Kazner (2011) used a capillary NF (CNF) membrane for the investigated hybrid NF systems.

Alternatives for the economic analysis of indirect potable reuse schemes include: (1) NF and UF (NF + UF), (2) CNF and PAC, (3) CNF and GAC, (4) CNF and ozonation, (5) conventional IMS (UF + RO), and (6) CNF as a stand-alone process. It was assumed that the same secondary wastewater treatment process was used for all alternatives and the economic evaluation was performed only for tertiary treatment. Systems with NF directly after secondary treatment were assumed to utilize CNF membranes with a low-molecular-weight cutoff (Kazner 2011). CNF membrane modules combine the cleaning characteristics (e.g. backwashing, air scouring) of capillary UF membranes with the favorable separation properties of spiral wound NF and enable raw water to be treated in a single step to produce high-quality permeate (Futselaar *et al.* 2002). However, because CNF is a relatively new process, it is not currently used for wastewater reuse applications.

The overall costs of hybrid CNF systems are mainly driven by the operational and capital costs of the NF elements and to a minor degree by carbon and ozone costs and consumption (Kazner 2011). Cost analysis was performed using the USEPA costing procedure for two scenarios, assuming the specific price of CNF membranes to be 5 and 15 times greater than spiral wound NF membranes (scenarios A and B, respectively). PAC injection with concentration of 50 mg/L was used in the analysis (Kazner 2011) with a cost of $1.95/kg. Construction costs for activated carbon systems were calculated using cost curves from McGivney & Kawamura (2008). For the ozonation system, the USEPA (2006) procedure was used for cost estimation assuming an ozone dose of 5 mg O_3/l. To calculate the capital cost of the RO system, the same procedure used for the spiral wound NF systems (i.e. USEPA procedure) was applied; however, it was assumed that cost of RO membranes was approximately 1.5 times less than spiral wound NF membranes (McGivney & Kawamura 2008). The same method used to calculate O&M costs for spiral wound NF was employed to estimate O&M costs for RO, with the only difference being the electricity cost. The portion of electricity used by process pumping was doubled for RO systems based on data presented by Bellona *et al.* (2012). Costs for UF systems were calculated using data and graphs provided by the American Water Works Association (2005).

Results of the cost analysis are presented in Figure 2(a) and (b). As was expected, unit water cost decreased as the treatment plant capacity increased. From an economic perspective, employing the UF + NF process is more beneficial for indirect potable reuse compared to the UF + RO process. Assuming that the CNF scenario A is feasible, facilities that use CNF membranes as a stand-alone process or as a hybrid process combined with ozonation are more cost-effective than facilities employing UF + RO. With CNF scenario A, the cost of indirect potable reuse by CNF + ozonation and the UF + NF processes are similar however; the former process is more cost-effective for facilities with average flow rates less than 150,000 m^3/day. On the other hand, for CNF scenario B, all scenarios that use CNF membranes are more expensive than scenarios that use an IMS. CNF + GAC would only be more cost beneficial than the UF + RO process for facilities with average flow rates less than 5,000 m^3/day. Results for hybrid processes using CNF and GAC or PAC are slightly lower than results from previous research that estimated the total cost for activated carbon/CNF processes in the range between (approximately) \$0.58 and \$1.06/m^3 (Kazner 2011).

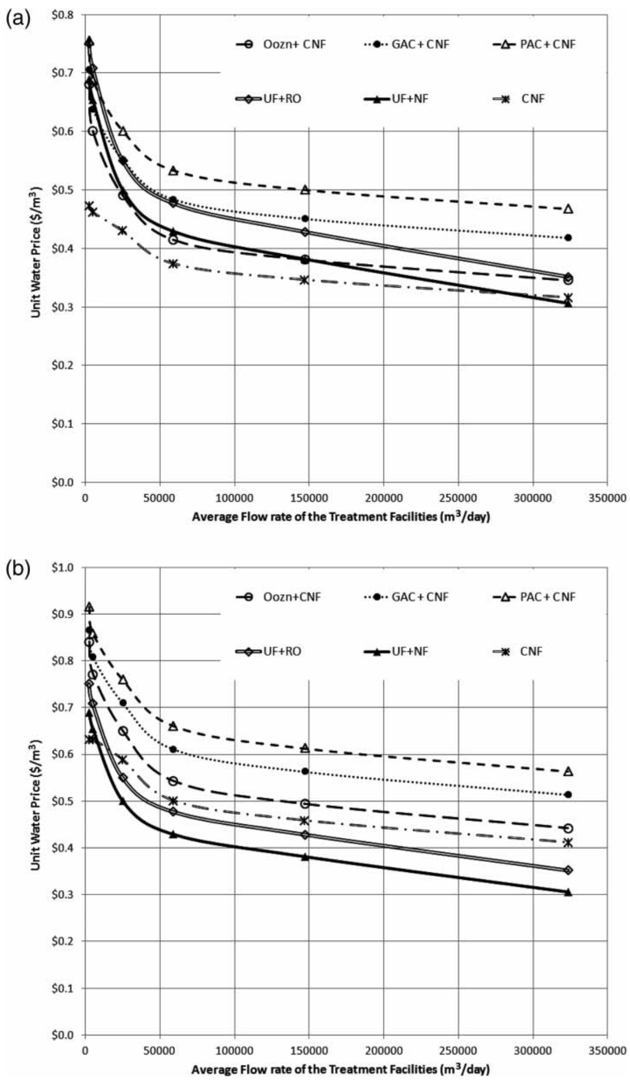

Figure 2 | Unit cost (\$/m^3) for tertiary treated wastewater for indirect potable water applications; *i*:10%; lifetime: 25 years; costs: 2013 USD; A: CNF/NF cost = 5, B: CNF/NF cost = 15; design flow rate to average flow rate ratio = 1.7 for capacity > 50,000 m^3/day and 2 for capacities ≤ 50,000 m^3/day.

Seawater desalination

The NF desalination market is currently very small due to the limitation of NF in removing monovalent ions. NF has been proposed for certain applications in the desalination industry both as a stand-alone process (Cheng *et al.* 2013) or a hybrid process (Hassan *et al.* 1998; Sarkar & SenGupta 2008; Song *et al.* 2011; Cheng *et al.* 2013). Cheng *et al.* (2013) investigated the application of RO-NF and NF^2 (two pass NF) and reported that the produced water met all current and anticipated drinking water regulations. Hassan *et al.* (1998) proposed using the NF membrane as a pretreatment for multi-stage flash desalination (MSF) and RO-MSF and stated that NF could significantly improve desalination processes from both an environmental and economic perspective. Introducing NF technology to RO and MSF desalination processes could reduce typical seawater reverse osmosis desalination costs by approximately 30% (Al-Sofi *et al.* 2000). Macedonio *et al.* (2007) reported that while NF can significantly increase the recovery of desalination systems, the cost savings are only marginal when energy recovery devices are used. In addition, Sarkar & SenGupta (2008) developed and tested an energy efficient hybrid method for desalination by combining ion exchange and NF.

Alternate technologies for desalination include distillation processes (MSF, multiple effect distillation and vapor compression), ion exchange, and membrane processes. According to McGivney & Kawamura (2008), large desalination facilities (>10 mg d) using RO produce less expensive water compared to those using distillation processes. Therefore, alternatives evaluated in this section were NF^2 (Cheng *et al.* 2013), NF-RO (Cheng *et al.* 2013), and RO. To calculate capital and O&M costs for NF^2 and NF-RO systems, data from Cheng *et al.* (2013) for 50 mg d facilities were used. Capital costs for non-membrane items and non-energy O&M costs were scaled according to the six-tenths power rule (Equation (1)) (Owen *et al.* 1995):

$$C_a = C_b \times \left(\frac{Q_a}{Q_b}\right)^{0.6} \quad (1)$$

where C_a and C_b are costs of plants to treat flows of Q_a and Q_b, respectively. For O&M related to energy and the membrane portion of capital cost, it was assumed costs change by the ratio of flow rates. Because the interest rate (i) and the electricity cost in the calculations by Cheng *et al.* (2013) were different, corrections were made and unit water price was recalculated. Corrections were also made to calculate capital and O&M costs based on design flow rate and average flow rate, respectively. Unit water costs for desalination systems are presented in Figure 3. Results indicate (as were also shown by Cheng *et al.* (2013) that if a single RO process is enough to meet the drinking water standards, using RO is more cost-effective than using the NF^2 system. However, in the case that desalinated water using single pass RO cannot meet regulations then the two pass RO-NF system may be necessary, although the NF^2 system was found to be more cost beneficial.

It is worth mentioning that there is no global standard for reporting desalination water costs and depending on the assumptions made during the cost analysis, the unit water for desalination systems can vary significantly. Costs shown in Figure 3 are based on assumptions made in this study. In the case that capacity and average flow rate of

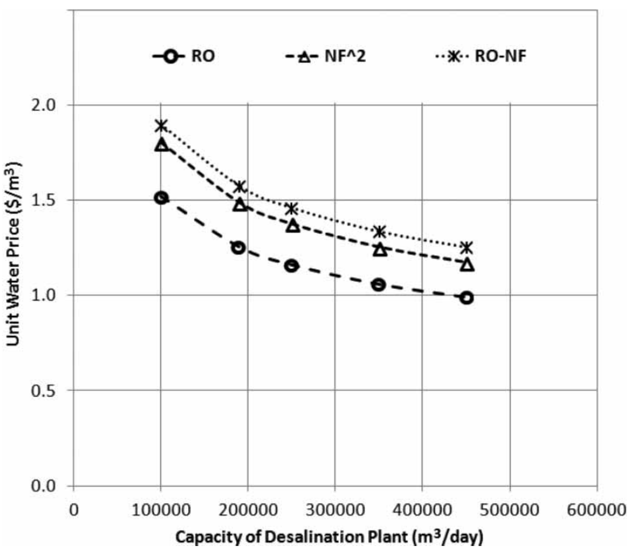

Figure 3 | Comparison of unit water price for RO, NF^2, RO-NF desalination facilities; i: 10%; lifetime: 25 years; costs: 2013 USD; design flow rate to average flow rate ratio = 1.3.

the desalination facilities are assumed to be the same, unit water price for RO desalination plants will be in the range of \$0.85–1.27/m^3. Pankratz (2009) reported that seawater desalination water costs during 2000 and 2010 in different areas of the world were between \$0.5 and \$1.85/m^3. Karagiannis & Soldatos (2008) reported that for plants with a size range of 100,000–320,000 m^3/day, the cost of RO desalination was \$0.45–0.66/m^3.

Wastewater treatment in textile industry

In the textile industry, two NF membrane applications include dye production and wastewater treatment and reuse. A few researchers have proposed NF membranes to replace precipitation and filtration (using a filter press) in conventional dye production (Yu *et al.* 2001; Mikulášek *et al.* 2006). Although there are limited data available in the literature, NF is reported to have been used for a dye-producing plant in China since 1993 (Yu *et al.* 2001). The most reported application of NF technology in the textile industry is to treat and reuse wastewater from dye baths and researchers have evaluated hybrid NF systems for treatment and reuse of textile wastewater (Van der Bruggen *et al.* 2004; Bes-Pia *et al.* 2005; Gozálvez-Zafrilla *et al.* 2008; Giwa & Ogunribido 2012).

The most common wastewater treatment processes in the textile industry are biological treatment (mostly activated sludge), precipitation, coagulation/flocculation, flotation, oxidation, and adsorption (Gozálvez-Zafrilla *et al.* 2008). Biological treatment is not effective for dye removal and for decolorizing textile effluents, adsorption using PAC is expensive and not completely efficient, and the aforementioned treatment methods are not capable of salt removal (Tang & Chen 2002; Gozálvez-Zafrilla *et al.* 2008). Currently, most studies have investigated combining different methods and using hybrid approaches for textile wastewater treatment, many of which, employ membrane processes (Tang & Chen 2002; Van der Bruggen *et al.* 2004; Bes-Pia *et al.* 2005; Gozálvez-Zafrilla *et al.* 2008). NF has been studied as a method to separate dyes, salt, chemical oxygen demand (COD), and other pollutants from dye-bath effluents (Jiraratananon *et al.* 2000; Van der Bruggen *et al.* 2004; Shu *et al.* 2005; Fersi & Dhahbi 2008; Alcaina-Miranda *et al.* 2009; Amar *et al.* 2009).

Because the composition of dye-facility wastewater can vary significantly, variable success has been reported when using NF as a treatment technology. Several challenges with implementing NF include fouling, secondary waste generation, insufficient dye rejection, and energy dissipation of hot process streams. High dye and COD concentrations can result in severe fouling and flux decline, higher energy requirements, and frequent chemical cleanings (Tang & Chen 2005; Tang *et al.* 2011; Ellouze *et al.* 2012). To reduce NF fouling, pretreatment methods such as adsorption, coagulation/flocculation, ozonation, and UF have been investigated (Bes-Pia *et al.* 2005; Chakraborty *et al.* 2005; Tang & Chen 2005; Fersi & Dhahbi 2008; Riera-Torres *et al.* 2010). Hybrid methods using NF are commonly employed with UF as pretreatment to improve the system's efficiency (Van der Bruggen *et al.* 2004; Bes-Pia *et al.* 2005; Fersi & Dhahbi 2008; Gozálvez-Zafrilla *et al.* 2008; Alcaina-Miranda *et al.* 2009; Giwa & Ogunribido 2012; Vergili *et al.* 2012). NF has also been investigated for zero liquid discharge (ZLD) applications for dye-bath effluent treatment and reuse, and salt recovery (Vishnu *et al.* 2008; Giwa & Ogunribido 2012). Vergili *et al.* (2012) performed a techno-economic analysis of a ZLD system for textile dye-bath wastewater treatment and reported that various IMS configurations (including UF/tight NF, loose NF/tight NF, loose NF/RO, and UF/tight NF/RO) were all 'technically feasible and economically viable' and have payback periods of less than 2.1 years.

Economic analyses were performed for two alternatives to evaluate the profitability of implementing NF for dye-bath effluent reuse. For alternative one, wastewater would only be treated biologically and discharged, and there is no investment and no profit for this alternative. For alternative two, however, an IMS (UF/NF) would be used to treat and reuse dye-bath effluent. Dye-bath effluent and wash water reuse is commonly discussed in the literature as using ZLD systems in which, salt, water, dye, and other materials are recovered. However, the economic analysis included calculating the profit a textile industry could make by reusing dye-bath effluent assuming a UF/NF system is an appropriate technology. For UF membrane calculations, costs from the American Water Works Association (2005) were used. Figure 4 shows the unit water cost for reused water which fluctuates between \$0.5 and \$4/m^3. As a comparison, Samhaber & Nguyen (2014) calculated the total mean treatment cost for a NF treatment plant with a capacity of 20 m^3/day and 100 m^3/day dye effluent and with an assumed membrane flux of 10 L/m^2·h and 365 operating days per year at US\$4.20/m^3 and US\$1.9/m^3, respectively. Samhaber & Nguyen (2014) reported that the costs decreased with increasing operating flux, plant capacity, and number of days of operation per year. It is worth noting that incinerator costs for concentrate disposal were not included in the calculations performed during this study. A simple calculation for incinerator cost using data from Vergili *et al.* (2012) revealed that incinerator costs could dramatically affect the water cost for the system.

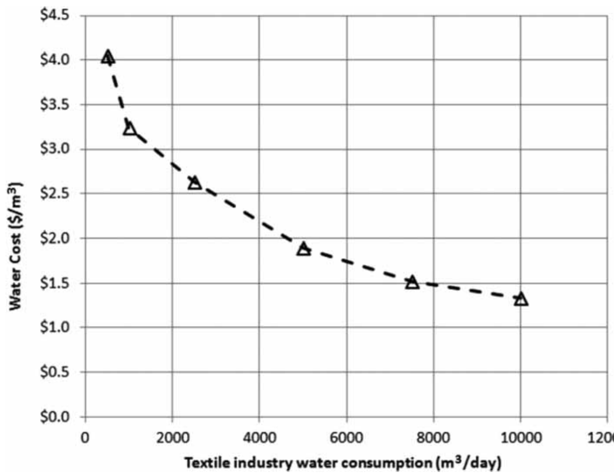

Figure 4 | Unit reused water cost for dye-bath effluent treatment by UF–NF system (*i*: 10%; lifetime: 25 years; costs: 2013 USD; design flow rate to average flow rate ratio = 2).

To estimate the profit from reusing dye-batch effluent, NPV and PBP for alternative two were calculated using the assumptions listed in Table 2. Assuming a unit water price of \$2/m^3 (water purchased for textile processes), savings were calculated using the flow rate and cost of producing reuse water. PBP and NPV for industries with NPV greater than zero are presented in Table 3. It is worth noting that because tax and start-up costs were included in the calculations, reuse systems which produce

Table 2 | Assumptions for economic analysis of dye-bath water reuse

Property	Value
NF recovery	85% (Vergili *et al.* 2012)
UF recovery	85% (Vergili *et al.* 2012)
Ratio of wastewater to influent water for textile industry	85% (Molen 2008)
Ratio of dye-bath effluent to total wastewater	8% (Vishnu *et al.* 2008)
Industry influent water range	500–10,000 m^3/day
Unit water price	\$2/m^3
Lang factor	4
Depreciation method	MACRS (Department of the Treasury: Internal Revenue Service 2014)
Tax portion	30% of income
Start-up cost	10% of total depreciable capital

Table 3 | Economic indicators for water reuse facilities of dye-bath effluent for large textile industries (*i*: 10%; lifetime: 25 years; costs: 2013 USD)

Total water consumption of the industry (m^3/day)	Dye-bath water effluent	NPV of water reuse facility ($)	PBP of water reuse facility
7,500	510	100,000	9 years
10,000	680	412,000	8 years

Note: Calculations account for tax, depreciation, and start-up costs as well as capital and O&M costs.

water with costs lower than $2/$m^3$ in Figure 4 did not necessarily have NPV greater than zero. For industries with a total water consumption of 7,500 m^3/day and more, PBP for the water reuse facility (UF/NF) would be less than 9 years (Table 3). For facilities with flow rates less than 7,500 m^3/day, dye-bath wastewater reuse is not profitable.

CONCLUSIONS

NF represents a relatively recent development in membrane technology that is being integrated into a number of industries for water treatment and separations. Profitability of NF technology depends on several factors such as pretreatment requirements, influent water quality, capacity of treatment facilities, and treatment goals. Limitations of current NF technology include incompatibility with chemical oxidants, narrow temperature range, limitations toward fouling mitigation, and waste generation. Development of more robust NF membrane materials with enhanced separation efficiencies as well as membranes with low fouling propensity will further increase areas of application and a greater market share of the membrane separation industry.

In this study, a literature review and economic analysis was performed to investigate the applicability of NF technology for several water and wastewater treatment purposes. For drinking water treatment, NF membranes could be more viable than other technologies, particularly when the removal of hardness, color, and DBP precursors is necessary. Several researchers have investigated the application of NF as stand-alone or as a part of hybrid systems for indirect potable reuse applications. For reuse applications, the UF/NF process is more cost-effective than UF/RO (assuming both processes can meet treatment goals); however, the cost-effectiveness of CNF as a stand-alone or in a hybrid process depends on the cost of CNF membranes. NF was generally not a cost effective process for seawater desalination; however, the NF^2 process may be economical when single pass RO cannot meet water quality guidelines.

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