Membrane Water Treatment, *Vol. 6, No. 6 (2015) 477-488*
DOI: http://dx.doi.org/10.12989/mwt.2015.6.6.477

Applicability of low pressure membranes for wastewater treatment with cost study analyses

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(*Received October 04, 2015, Revised October 23, 2015, Accepted October 28, 2015*)

Abstract. This study demonstrates that low pressure membranes are the ideal choice for industrial and/or municipal wastewater treatment by showing some promising experimental results, understanding different membrane filtration models, studying the potential of membrane bioreactors (MBRs), considering ceramic membranes fabrication and illustrating the role of nanotechnology in membranes. Cost study calculations are included to determine the treatment cost as well as the initial cost of various membrane types. Results showed that integrated membranes are preferred over MBR in case of average capacities. However, higher capacity situations are the most economical choice for MBR. It is shown that the least treatment cost in MBR was about $0.13/m^3. However, the $0.13/m^3 is the theoretical cost which is very small compared to the actual average MBR treatment cost of $0.5/m^3.

Keywords: MBR; treatment cost; membrane technology; RO; MF; UF; filtration model; nanoparticles; ceramic membrane fabrication; treatment experiments

1. Introduction

Nowadays, wastewater quantities are increasing dramatically due to high demand on numerous industrial products that require the use of water such as oil and paper industries. Recently, membranes are considered as excellent alternatives for wastewater treatment compared to other purifying techniques because it does not require a large installation space and there is no side pollution effects. Membrane is a porous layer of polymeric or metal material that can allow the passage of fluid with restrictions to specific particles based on their chemical, physical properties and molecule size. In other words, membrane is a selective barrier that separates between two phases such as removing salts from a salty water where permeability and selectivity depend on particles' pore size.

Theoretically, wastewater treatment process by membranes goes through four key stages with

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http://www.techno-press.org/?journal=mwt&subpage=7 ISSN: 2005-8624 (Print), 2092-7037 (Online)

association to particles' diameter size. First, microfiltration (MF) process in which particles with diameter between 0.9-90 microns are separated. Second, ultrafiltration (UF) stage that usually .have pores in the range of 10 to 1000 A. Third, nanofiltration (NF) method for removing particle pore size around 0.5 to 1.5 nanometers. Finally, reverse osmosis (RO) technique where minerals, salt and organics can be separated from water.

In fact, water pollutants differ based on the wastewater source. For example, industrial wastewater is characterized by a high amount of chemicals, especially sulfur, but municipal wastewater will have more organic pollutants such as bacteria and viruses. However, the focus of the theoretical section of this research is on the effectiveness of the industrial wastewater treatment by membranes by critically evaluating previous studies.

On the other hand, another area has been investigated which is related to cost analyses of various membrane plants from different studies. The cost estimations include membrane types like membrane bioreactors (MBR), reverse osmosis (RO) and microfiltration (MF). The major interests were in calculating membrane treatment costs, initial and operating & maintenance expenses in association with membrane efficiency, total plant capacity and other specifications.

2. Membrane treatment experiments

2.1 Esfahani Study: *Tehran Refinery*

Esfahani *et al*. (2014) studied membranes as a new effective way for treating industrial effluent of wastewater or oil. The method of Esfahani experiments initiated by using the disposal rate of some substances in RO, UF, NF membranes besides applying different mathematical formulae on fluid flow inside cavity, flow rate per unit area, pores per centimeter of membrane and flux rate. In the first experiment, Esfahani tested the ability of RO membrane to remove particles from industrial wastewater and he explored that RO membrane can remove between 90 to 99% of total dissolved solid (TDS) in water. Secondly, UF membrane were applied to a system to remove solids from liquid solvent. Yet, UF removal percentage was lower than RO but much better in membrane fouling and concentration polarization conditions. In Esfahani's third experiment, NF rate of oil separation was about 97% and NF found to be easy to apply for wastewater treatment in petrochemical units to remove organic pollutants as Esfahani studied NF membrane in the effluent of Tehran Refinery API unit.

According to Esfahani, there would be a huge demand on using membranes for industrial wastewater treatment within the next few years. Similarly, by using membranes we can avoid various major negative sides of other treatment options with high costs, side pollution and too much installation space. On the other hand, Esfahani found that membranes are very optimal in eliminating unwanted materials such as salt, organics, ions and other molecules. In addition, membrane technology is the best alternative to purify industrial water without harming the environment.

2.2 Konieczny Study: *Filtration Models*

Membrane and membrane modules used for water treatment should have high surface area (packing density) and consume minimum amount of energy. However, fouling is a negative impact that comes from overuse of the same membrane. Thus, fouling occurs when contaminants block membrane surface resulting in lowering permeate flux rate. The adsorption of natural organic substance, pollutants, on the membrane surface and pores is a major issue that cause flux fluctuations. Filtration cyclic process and regeneration of membranes will happen to maintain the flux rate. Many chemicals can be applied on the membrane surface to free organic pollutants in order to restore permeate flux rate and regenerate the system. In fact, several models can describe the association between fouling and the reduction of permeate flux which is mainly responsible for the treatment efficiency.

Konieczny and Rafa (2000) studied the verification of the model of the membrane filtration process of natural water with variable flux $J = f(t)$ under constant pressure conditions. In addition, reasons for declined efficiency of membrane filtration process were analyzed. Different parameters were discussed to overcome the fouling issue which caused reduction in the overall membrane treatment efficiency. Therefore, experiments were carried out to compare the treatment effectiveness of membranes application in both ultrafiltration (UF) and microfiltration (MF) for ground and surface water with various membrane configurations such as flat, tubular and capillary made from different polymer materials. Studies included two major filtration model verifications. First, model based on the change of volumetric flux in time and its relation to the efficiency drop. Second, model in the conditions of constant pressure.

As a result, there was a good connection between the low permeate flux, resulting from fouling, and the treatment efficiency. In constant pressure conditions, proportional relation stated between the filtrate volume and the blocked membrane surface. Konieczny concluded that fouling is a key parameter in changing filtration time, filtrate volume and efficiency of membranes for natural water treatment. Filtration models of permeate flux and constant pressure conditions can be achieved for large plants through different experiments with different membranes to have less fouling problems.

2.3 Marrot Study: *Membrane Bioreactors* (*MBR*)

Membrane bioreactors are systems that consist of a biological reactor for degradation of organics and a membrane for separation of microorganisms. There are several advantages that make MBR unique compared to membrane systems only. Marrot *et al*. (2004) studied previous conclusions regarding industrial wastewater treatment in membrane bioreactors by comparing bioreactors to conventional processes and discussing the characteristics of membrane bioreactors. Marrot comparison technique showed that MBR had several advantages. For instance, MBR allows the biomass concentrations to be higher meaning that the treatment efficiency will be higher. Therefore, the aeration tank volume can be reduced since there is a high biomass concentration settled in the bioreactor. Furthermore, sludge production decreased by a factor of 2 to 3 and membrane was perfectly integrated with the reactor allowing for water reuse and reduction in the overall cost.

However, fouling issue associated with MBR is a crucial characteristic because it will affect directly on the treatment efficiency. According to Marrot, membrane fouling can be eliminated by aeration or by chemical washing. The complexity of bioreactors made it harder to understand fouling. Yet, Marrot realized that the use of a greater membrane roughness would be able to decrease fouling. Moreover, operating bioreactors at lower critical flux will prevent sudden fouling. In case of membrane washing, Marrot determined that backpulsing is better than backwashing because it eliminates fouling totally. More investigations proved that membranes are a fruitful choice for industrial wastewater treatment.

2.4 Parma Study: Ceramic Membrane Fabrication

Fabrication of membranes becomes more convenient in both industrial and personal use. As a result, wastewater treatment can be achieved easier than before without depending on specialized corporations for designing membranes with expensive options, instead it can be done locally with cheap materials and easy steps. To approve this, Parma and Chowdhury (2004) prepared his own ceramic membrane for oily wastewater treatment from very simple, low cost and available materials in India. Parma believed that ceramic membranes have an excellent thermal and chemical stability with a good separation efficiency. Thus, Parma utilized kaolin with other additives to fabricate his simple membrane.

Ceramic membranes are capable to remove crude oil from oily wastewater from refineries. The raw materials used by Parma to build his membrane was clay, 300 μ mesh screen and 300 μ mesh clay powder. Different chemicals like sodium carbonate were added to increase the membrane mechanical strength. Parma was able to fabricate his membrane over circular discs of aluminum foil with sintering temperatures of 500℃, 600℃, 700℃ and 800℃. Membrane characterization obtained by using SEM and powder SRD in order to get the average pore size and distribution of pores.

After that, Parma evaluated the permeability of these pores by having a water permeation test in batch mode. Initially, the flux was high, but then it decreased over time while pressure increased. Parma found that membrane porosity declined around 25-15% with the increase in sintering temperature. Around 500 pore diameters was measured by ImageJ software where it was determined that the average pore size increased with the increasing temperature due to pores overlapping. At last, Parma tested his membrane and got a rejection percentage about 52% for oil from oily water. The conclusion was that ceramic membranes could be prepared inexpensively with flexible pore sizes for industrial wastewater treatment meaning that membranes could be an optimal treatment technique with the use of very cheap materials and preparation processes.

2.5 Parchi Study: Nanoparticle Materials

Nanoparticles is an advanced technology used in membranes for wastewater treatment. It is a promising method due to many advantages. Membranes that are structured with nanomaterials are more capable to absorb, react and interact because of the huge number of small atoms at the membrane surface which will increase the treatment performance. It is realized that nanoparticle materials are one of the most important techniques which can be utilized to treat wastewater from toxic organics and metal ions.

Gautam and Madathil (2013) explored that there are different types of nanoparticles. For example, nanosorbents like carbon-based, polymeric and nano-networks. Polymeric materials are used to remove organic and inorganic contaminants while nano-network nanosorbents have a great structure for eliminating metal ions. On the other hand, nanocatalysts are widely used for water treatment due to it is high surface area which increases the catalytic activity for more degradation rate.

Additionally, there are more advanced membrane technologies like biomimetic membrane, which is similar to reverse osmosis (RO) for removal of salt, and molecularly imprinted polymer that is considered for various applications in biology, pharmacy and environment sciences because of its high selectivity. Prachi concluded that membranes nanotechnology approach for wastewater treatment is promising, durable, friendly and very effective. Moreover, nanoparticle membranes

Table 1 Summary of previous membrane experimental studies with their final results

Membrane Type	Theoretical (Pore Size)*	Esfhani Study (Esfhani *et al*. 2014)	Konieczny Study (Konieczny and Rafa 2000)	Marrot Study (Marrot *et al*. 2004)	Parma Study (Parma and Chowdhury 2014)
Microfiltration (MF)	0.1-10 μm (1-1000 nm)	> 96.6% TSS	Fouling resulted in lowering flux, and reduced efficiency	Membrane Bioreactors (MBR); *Advantages*: Higher efficiency Reduced Sludge Lower cost *Disadvantages*: Higher fouling	Ceramic Membrane; 52% oil rejection, Simple clay inexpensive materials
Ultrafiltration (UF)	0.01-0.1 μm (1-100 nm)	COD < 90%, with better fouling control			
Nanofiltration (NF)	< 0.001 μm (< 1 nm)	~ 97% COD and TOC, preferred in petrochemical	N/A		
Reverse Osmosis (RO)	< 0.001 μm (< 1 nm)	> 90-99% TDS	N/A		

*Wagner 2001 and US EPA 2005

are easy to manufacture, design and operate in both lab scales and large industry scales. Similarly, different membrane types showed that there are other significant advantages such as cost-effectiveness, no waste generation, recycled films materials, low energy and less time consumption.

3. Cost study analyses

The cost estimation technique was established mainly to observe the differences in prices between one membrane type and another. Also, MBR membrane was our focus to identify the treatment cost for several membrane plants with different capacities. The total membrane cost calculated based on both initial and operating costs. Recently, a huge decrease in the membrane design prices occurred due to the great advancements in membrane technologies. The design prices dropped from $400/m^2 to $50/m^2. Therefore, membrane cost analyses are important to illustrate the latest technologies with a comprehensive comparison with respect to the treatment cost. This will help us to have an optimal selection in treating wastewater with higher efficiency and lower cost.

3.1 Methodology

The calculation method for studying membrane cost started by reviewing numerous articles related to the treatment cost and the total membrane cost. Besides the data of various membrane plants, experimental models were also considered to be successful in addressing the real cost as well. Afterwards, an extensive critical review was done for five different membrane types. The review included information regarding membrane specifications, assumptions, efficiencies and treatment costs. All of these were taken into account to generate results that are more accurate.

3.2 Data and equations

The collection of data was not an easy task due to the lack of information in many kinds of membranes. However, due to the fact that MBR is the ideal selection for wastewater treatment since it can produce a higher water quality in lower cost compared to MF, UF or RO; five membrane types were considered in the cost study calculations. Three of them are MBR and the other two have an integration between two different membranes to enhance the water treatment. UF-RO and MF-RO are the integrated membrane systems that were considered in our calculations. The primary use of this integration is to show that the treatment cost could be lowered to a value that is lower than the MBR treatment cost. Moreover, the fouling issue can be reduced dramatically by using this integration since most contaminations are going to be purified in the first membrane, either UF or MF. This is a perfect situation for RO membranes where it can increase the lifetime of the RO.

As mentioned previously, the major cost calculations were for the membrane treatment cost and the total cost. Below, you can find the main equations used to identify those two expenses.

$$\text{Total Cost (\$)} = \text{CAP} + \text{O\&M} + \text{Design Cost} \tag{1}$$

$$\text{Treatment Cost (\$/m}^3\text{)} = \text{Average value of the given range} \tag{2}$$

3.3 Assumptions

To simplify our calculations, there are a set of assumptions that will be considered to evaluate the five membrane models in a way that is more appropriate.

- Consider N/A capacities to be at 20,000 m^3/day
- Calculations of aerobic MBR are neglected because of the lack of information about treatment costs
- High capacity model is also taken to be at 20,000 m^3/day because there is a negligible difference in the treatment cost between the lower and higher capacity units (3,785 and 37,850 m^3/day)
- In case of MBR and UF–RO, average values are considered for cost estimations
- MF–RO is not included in our calculations due to inconsistency in the capacity
- In the total cost analysis, we will neglect all other specifications related to each membrane and consider the total cost values only (CAP + O&M + Design Cost)
- Average values of cost range for CAP and O&M costs were considered
- UF–RO and Anaerobic MBR CAP and O&M costs are not calculated due to lack of information
- MF–RO is taken at its highest capacity for total cost estimations
- Theoretical aerobic MBR highest and lowest models CAP and O&M where calculated at \$400/m^2 and \$50/m^2, respectively
- Theoretical aerobic MBR highest and lowest models CAP and O&M calculated at the same experimental aerobic MBR area of 15,000 m^2
- The design costs and capacities or both experimental and theoretical aerobic MBR are considered to be equal at \$1,824,000 and 1,900 m^3/day, respectively
- BOD, COD and TSS rejection efficiency calculations were performed while neglecting all the specification differences between membranes.

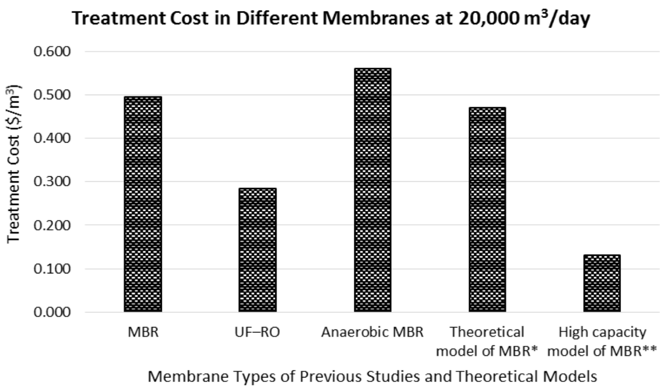
3.4 Notations

Table 2 Membrane technology characteristic symbols

Symbol	Meaning	Symbol	Meaning
Sub	Submerged	*GFD*	Gallons/Ft^2 Day
SS	Side-Stream	*MLSS*	Mixed Liquor Suspended Solid
P&F	Plate and Frame	BOD_5	Biochemical Oxygen Demand (5-days)
HF	Hollow Fiber	*COD*	Chemical Oxygen Demand
T	Tubular	*TSS*	Total Suspended Solids
SOTE	Standard Oxygen-Transfer Efficiency	*TDS*	Total Dissolved Solids
PS	Polysulphone	*TOC*	Total Organic Carbon
PE	Polyethylene	*NTU*	Nephelometric Turbidity Units
M	Million	*K*	Thousand
RO	Reverse Osmosis	*O&M*	Operating and Maintenance Cost
UF	Ultafiltration	*CAP*	Capital Cost
PVDF	Polyvinyl Difluoride Membrane	*AnSMBR*	An Anaerobic Thermophilic Submerged Membrane Bioreactor
MF	Microfiltration	*VFA*	Volatile Fatty Acids
PA	Polyamide	*NF*	Nanofiltration
mg-N/L	mg Nitrogen in one Liter of water	*MBR*	Membrane bioreactor

3.5 Results and Discussions

The cost analyses show the differences in treatment prices between several membrane types. Comparison between the membranes models were included in Table 3. The comparison table illustrated a lot of information regarding each membrane that has been taken from various experimental studies. Some of the data were also taken from actual membrane plants.



[*] US Environmental Protection Agency (EPA) fact sheet shows that MBR operating cost is $0.47/m^3

[**] EPA illustrates other MBR operating cost for low and high capacity MBR wastewater

Fig. 1 Comparison between the treatment costs in different membranes

Table 3 Data summary for different membrane types

Type	Specifications	Assumptions	Efficiency	Cost
Aerobic MBR (Gander *et al.* 2000)	**SS**: Fine bubble aerators, SOTE 25-40% **Sub**: Coarse bubble aerators, SOTE 19-37% **Pore size**: 0.2-0.5 μm for different membranes **Configuration**: P+F or HF **Materials**: PS or PE **Flow type**: Cross flow **Capacity**: 1900 m^3/day **Calculation model**: 150 units, 0.4 μm **Life-span**: 7 years	*Municipal wastewater* *Treatment of TSS, COD/BOD*	*COD/BOD* **SS**: PS, P+F, 88-94.5% **Sub**: PE, HF, 0.3 and 0.1 86-97% **Sub**: PS, P+F, 0.4, 92%	*Aeration*: **SS**: 20% **Sub**: 90% *Retentate pumping*: **SS**: 60-80% **Sub**: ≤ 28% *Design cost*: \$121.6/m^2 *CAP*: \$6.07 M
MBR (DeCarolis *et al.* 2007)	*Full-scale MBR facilities* **Temperature**: 25℃ **Flux rates**: Sub, 15-19 GFD and SS, 30 GFD **Capacity**: 4,000 and 20,000 m^3/day **Inlet water quality**: **MLSS**: 8 g/L **BOD_5**: 290 mg/L	*Municipal wastewater* *Typical for*: BOD_5 290 mg/L NH_3 30 mg-N/L TSS 320 mg/L *5% interest*	Complete oxidation of $BOD_5 < 2$ mg/L Complete nitrification of $NH_3 < 1.0$ mg-N/L Treatment % is N/A	*Treatment*: 4,000 m^3/day \$0.53-0.68/m^3 20,000 m^3/day \$0.44-0.55/m^3 *CAP** \$7.99–9.85 M *Annual O&M** \$218–302 K
UF–RO (Bick *et al.* 2012)	*Primarily for agricultural irrigation* **Capacity**: 20,000 m^3/day **Recovery**: 95% **Operating flux**: (Liter/m^2-hour) **UF**: 27 and RO: 34 **Feed pressure**: (bar) **UF**: 4 and RO: 12.5	*Properties*: Disinfected water Turbidity < 2 NTUs < 5 Coliform < 2.2 per 100 mL BOD_5 < 20 mg/L TSS < 30 mg/L	BOD_5 ~ 85% COD ~ 100% TSS ~ 100%	*Treatment*: \$0.15-0.42/m^3

Table 3 Continued

Type	Specifications	Assumptions	Efficiency	Cost
MF–RO (Valizadeh *et al*. 2015.	*Integrated membrane system* (*IMS*) **Pore size**: 0.45 μm **Materials**: Hydrophilic PVDF for MF and PA for RO **Capacity**: 1.66–416.66 m^3/day **MF pump efficiency**: 80% **Flow type**: Cross flow **RO recovery**: 79-85% **RO flux**: 22-27 Liter/m^2-hour	*Pretreatment stages*: Sand filter Activated carbon block Cartridge filter *O&M ~ 2% of capital cost*	TDS > 98% COD > 94% BOD_5 > 91% TOC ~ 91% TSS > 98%	*Treatment*: 1.66 m^3/day \$1.02/m^3 CAP and O&M \$65 M 416.66 m^3/day \$0.55/m^3 CAP and O&M \$365 M
Anaerobic MBR (Jeison and Van Lier 2008)	*The AnSMBR operated continuously for 300 days* **Critical flux**: 7 Liter/m^2-hour **Temperature**: 55°C **Configuration**: MBR was fitted with tubular polysulphone MF 4 tubes of 36.7 and 0.9 cm of length and diameter **Membrane area**: 0.042 m^2 **Lifetime**: 3 years **Biomass concentration**: TSS < 35 g/L **Compressor efficiency**: 60%	Electricity price: \$0.067/kW·h	VFA removal usually over 98%	*Treatment*: \$0.56/m^3 *MBR configuration*: Generally, Sub < SS but, if fluxes 3 times higher Sub > SS

* This total capital cost and O&M is for 20,000 m^3/day capacity

The treatment costs of different membranes are shown below in Fig. 1. The data in Tables 3 and 4 were also utilized to get an idea about the total experimental aerobic MBR costs and it was compared with the highest and the lowest costs of MBR theoretical models (Fig. 2). Also, BOD, COD and TSS rejection percentages of the integrated membranes were observed at their original conditions (Fig. 3).

Table 4 Membranes capacities vs. treatment costs

Membrane type	Capacity (m^3/day)	Treatment cost (\$/m^3)
Aerobic MBR	1900	Only design cost is calculated
MBR	4,000 and 20,000	0.53-0.68 and 0.44-0.55, respectively
UF–RO	20,000	0.15-0.42
MF–RO	1.66–416.66	1.02 and 0.55, respectively
Anaerobic MBR	N/A	0.56
Theoretical model of MBR*	N/A	0.47
High capacity model of MBR**	3,785 and 37,850	0.11-0.15 and 0.10-0.15, respectively

* US Environmental Protection Agency (EPA) (United States Environmental Protection Agency 2015) fact sheet shows that MBR operating cost is \$0.47/m^3
** EPA (CostWater 2015) illustrates other MBR operating cost for low and high capacity MBR wastewater

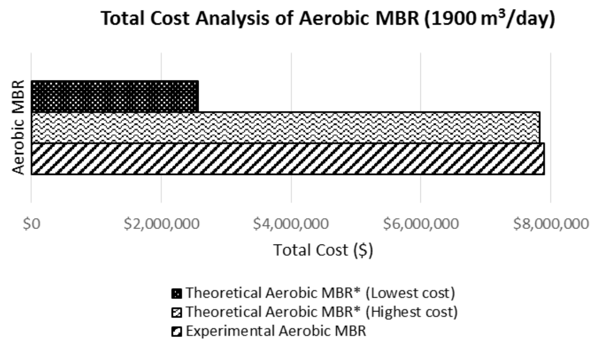


Fig. 2 Aerobic MBR cost analysis

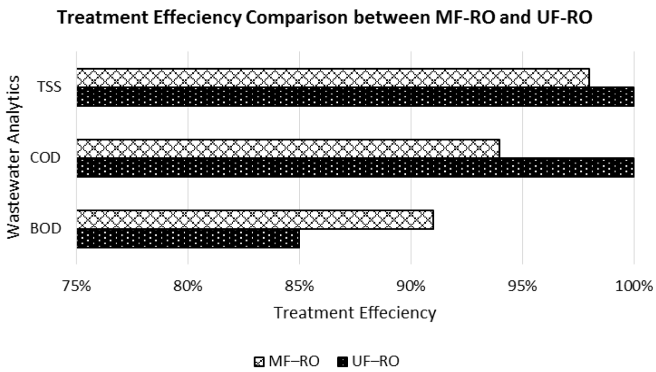


Fig. 3 Efficiencies in the integrated studied membranes

The above figures and calculations could verify many facts that need to be considered in future studies. For example, higher capacities in MBR plants will reduce the treatment cost needed for wastewater. And this is actually true for all other membrane types. An integrated membrane like UF-RO is found to be much economical than MBRs at average capacities. It is shown in Fig. 2 that the experimental aerobic MBR is approximately having the same cost amount of the highest theoretical MBR model. This indicates that there are many other factors that are neglected in the theoretical model (highest or lowest). These factors contribute in raising the experimental price to be similar to the higher model. This could be also associated with the low capacity of this plant which, if increase, it will obviously decrease the total cost of that plant over the next year. Considerations of the flux rate, fouling and operating conditions are very crucial in shaping the total treating cost and/or the capital cost of any membrane.

4. Conclusions

In conclusion, Esfahani experiments in the three different types of membranes (RO, UF, NF) confirmed that membranes are an optimal choice for removal of pollutants from industrial wastewaters. In addition to that, the use of MBR where we have an integration between reactors and membranes would greatly enhance the treatment efficiency as mentioned by Marrot. Even though fouling issue can be an obstacle for selecting membrane as an alternative to treat industrial wastewater, Konieczny and Rafa established two filtration models of permeate flux and constant pressure conditions that can be utilized in large wastewater plants for having less fouling problems. On the other hand, the investment in membrane business becomes much easier for industries because the fabrication technique is not limited to huge corporations, instead persons may fabricate their own membranes like the ceramic membrane that is designed by Parma. Understanding nanotechnology science seemed to be useful to select the ideal membrane for a perfect removal of the unwanted materials.

The cost study proved that MBR is considered to be the optimal treatment option for both industrial and wastewater treatment. However, the treatment costs decreased by using integrated membranes such as UF-RO that will also allow us to have much longer life span for the membrane. Wastewater treatment plants with a very high treatment capacity should not care about the MBR specifications because it is found that at upper capacity values the treating cost does not change that much. Moreover, the initial cost depends on the treatment capacity. The high advancement in membrane technologies reduced membrane expenses in the last few year. Thus, more extensive research and reviews should be considered to have the most cost-effective membrane for wastewater treatment.

Acknowledgments

The authors would like to express their gratitude toward their families for their continued support, without which this research would not have been possible.

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