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Comparing Nanofiltration and Ion Exchange for Reverse Osmosis Pretreatment in Industrial Water Treatment: A Techno-Economic Analysis

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Abstract – Water softening is a crucial process in various industrial applications, and the selection of an appropriate system involves balancing technical efficiency, environmental impact, and economic considerations. This paper presents a comprehensive analysis of two prominent industrial water softening systems, Nanofiltration (NF) and Ion Exchanger (IX), through a multidimensional lens. The system's design and sizing were simulated with computer assistance, using the DuPont's WAVE Water Treatment Design Software version 1.82. The technical evaluation, based on simulations, revealed that IX outperformed NF in total hardness removal (> 99%) at the expense of a slight increase in Total Dissolved Solids (TDS). In contrast, NF demonstrated a superior ability to reduce TDS, albeit with lesser total hardness removal. Environmental considerations highlighted trade-offs, with NF generating higher wastewater volumes and IX producing wastewater with highly concentrated TDS, necessitating complex treatment processes. Economically, NF generally incurred higher Total Annual Costs (TAC) at lower total hardness concentrations, while IX became costlier at higher concentrations. A selection chart is introduced to aid decision-making based on economic considerations. This research offers valuable insights for industries seeking an optimal water softening solution, balancing technical efficiency, environmental impact, and economic considerations. The findings provide a nuanced understanding to guide system selection based on specific water quality requirements and economic constraints.

Keywords: softening; ion exchange resin; nanofiltration; techno-economic; industrial water treatment.

Introduction

Reverse osmosis (RO) stands out as a widely adopted water purification technology in various industries. This membrane-based, pressure-driven process effectively separates dissolved solids (TDS) from water (Bergman, 2007). Its prevalence in industrial applications can be attributed to its energy efficiency in comparison to traditional thermal desalination methods (Fritzmann, 2007; Ismail *et al*., 2019). However, despite its widespread use, RO technology encounters operational challenges, notably membrane fouling and scaling. These issues contribute to elevated operating pressure, increased membrane pressure drop, and declining permeate quality. The consequences of increased pressure or pressure drop include heightened energy consumption and potential mechanical damage to the membranes (Kucera, 2015).

Membrane fouling occurs when contaminants or foulants enter the RO system, accumulating on the membrane surface and impeding water flow. These foulants consist of biological or colloidal matter, silt, and organic compounds (Pandey *et al*., 2012). Conversely, scaling arises from the deposition of mineral salts which surpass their solubility limit, forming scales on the membrane surface. The primary culprits for scaling in RO systems are calcium (Ca) and magnesium (Mg) scales, also known as hardness scales (Nalco Water, 2018).

Addressing membrane fouling and scaling typically involves chemical cleaning of the membranes. However, this method has drawbacks such as production downtime (Lipnizki and Jönsson, 2018) and the generation of chemical wastes (Luján-Facundo *et al*., 2016). An alternative approach is the installation of pretreatment units to eliminate foulant and scale-forming contaminants before they enter the RO system. Technologies like clarification, multimedia filtration, and carbon filters effectively remove foulants, while conventional methods such as lime softening and ion exchange resin (IX) are employed to eliminate scale-forming hardness ions (Kucera, 2015).

Other membrane technology, namely nanofiltration (NF) has also been used to remove hardness ions (Ca^{2+}, Mg^{2+}) from the water. Several studies on NF membrane softening capabilities have been successfully performed, such as by Ghizellaoui *et al*., (2005), Su *et al*., (2015), and Song *et al*., (2016). These studies prove that NF membrane is a strong alternative to the ion exchange softening technology. Furthermore, Straits Research (2023) reported that the global market-size of NF membranes is forecasted to grow steadily at approximately 5.85% within 2023-2031 period, which means that the use of NF membranes will most likely be increasing in the future. Therefore, it is important for the RO users in the industries to consider NF membranes as the alternatives for RO pretreatment.

Previous study by Canepa *et al.* (1996) presented the comparison between NF and IX, mainly in the technical aspects. Economical aspect, namely the operating cost, was analyzed, but the capital cost of each system was not considered. The environmental aspect was also not thoroughly examined. Moreover, the study was conducted more than two decades ago. Consequently, to anticipate the increasing NF usage in the industries, it is necessary to re-evaluate the study, to expand the research scope and to perform more thorough assessment. In this study, comprehensive analysis of two prominent industrial water softening systems, Nanofiltration (NF) and Ion Exchanger (IX), through a multidimensional lens was provided. While the previous study focused on either technical or economic aspects, this research combined both technical efficiency and economic considerations, along with an in-depth examination of environmental impacts. Additionally, the use of simulations, particularly employing DuPont's WAVE Water Treatment Design software, added a practical dimension to the analysis, allowing for accurate system design and sizing evaluations. This approach provides valuable insights into the performance of NF and IX systems in various scenarios, considering factors such as total hardness removal, Total Dissolved Solids (TDS) reduction, wastewater generation, and overall cost implications. Furthermore, the introduction of a selection chart to aid decision-making based on economic considerations is a novel contribution. This tool offers a practical framework for industries to navigate the complex trade-offs between technical efficiency, environmental impact, and economic constraints when selecting an optimal water softening solution. All in all, this study is expected to provide insight on which technology is preferred technically and economically for RO pretreatment, especially in the context of recent development in the industries and growing markets.

Materials and Methods

Basis for Design and Simulation

Various scenarios were selected by considering the total hardness of the raw water and the net soft water capacity produced by either the Nanofiltration (NF) or Ion Exchanger (IX). For each parameter—net capacity and raw water total hardness—three (3) values were selected. This resulted in a total of nine (9) scenarios for each technology. Given the presence of two technologies, the overall number of scenarios for evaluation amounted to 18. These scenarios are detailed in Table 1. The total hardness values were determined according to the categories established by Effendi (2003): 125 ppm $CaCO_3$ for moderately hard water, 230 ppm $CaCO_3$ for hard water and 360 ppm $CaCO_3$ for very hard water.

Table 1. Selected scenarios for this study

Net capacity	Total hardness					
	125 ppm $CaCO_3$		230 ppm $CaCO_3$		360 ppm $CaCO_3$	
15 m^3/h	(1) NF	(4) IX	(7) NF	(10) IX	(13) NF	(16) IX
50 m^3/h	(2) NF	(5) IX	(8) NF	(11) IX	(14) NF	(17) IX
80 m^3/h	(3) NF	(6) IX	(9) NF	(12) IX	(15) NF	(18) IX

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The system's design and sizing were simulated with computer assistance, using the DuPont's WAVE Water Treatment Design Software version 1.82. The simulation was executed on a PC equipped with an Intel ® Core™ i5-6200U processor running at 2.30 GHz, supported by 12 GB RAM.

The techno-economic assessment followed the methodology outlined in Figure 1. The primary objective was to gather technical data through computer-aided simulations and subsequently conduct an economic analysis based on the outcomes of these simulations.

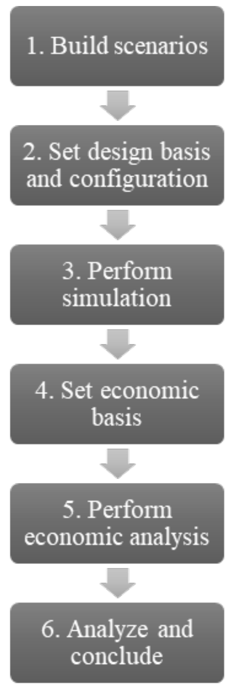

Figure 1. Methodology used in this study

NF System Design and Simulation

Figure 2 shows the process flow diagram of the NF unit. The design parameters and assumptions were set as follows:

1. Membrane type: DuPont FilmTec™ NF 90-400/34i (DuPont Water Solutions, 2020),
2. Design flux: 30-34 LMH (HDR Engineering, 2001),
3. Recovery: 75-80% (HDR Engineering, 2001),
4. Including chemical dosing unit (tank and pump): antiscalant, sodium bisulfite (chlorine scavenger), pH adjuster (acid or alkali) (Nalco Water, 2018),
5. Including membrane cleaning unit or Clean-in-Place (CIP) unit (DuPont Water Solutions, 2023a).

IX System Design and Simulation

Figure 3 shows the process flow diagram of the IX unit. The design parameters and assumptions were set as follows:

1. Resin type: DuPont AmberLite™ HPR1100 Na (DuPont Water Solutions, 2023b),
2. Total duration per cycle: 24 hours (22.3 hours of service and 1.7 hours of regeneration),
3. Including brine regeneration unit,
4. Source water for brine solution: product water.

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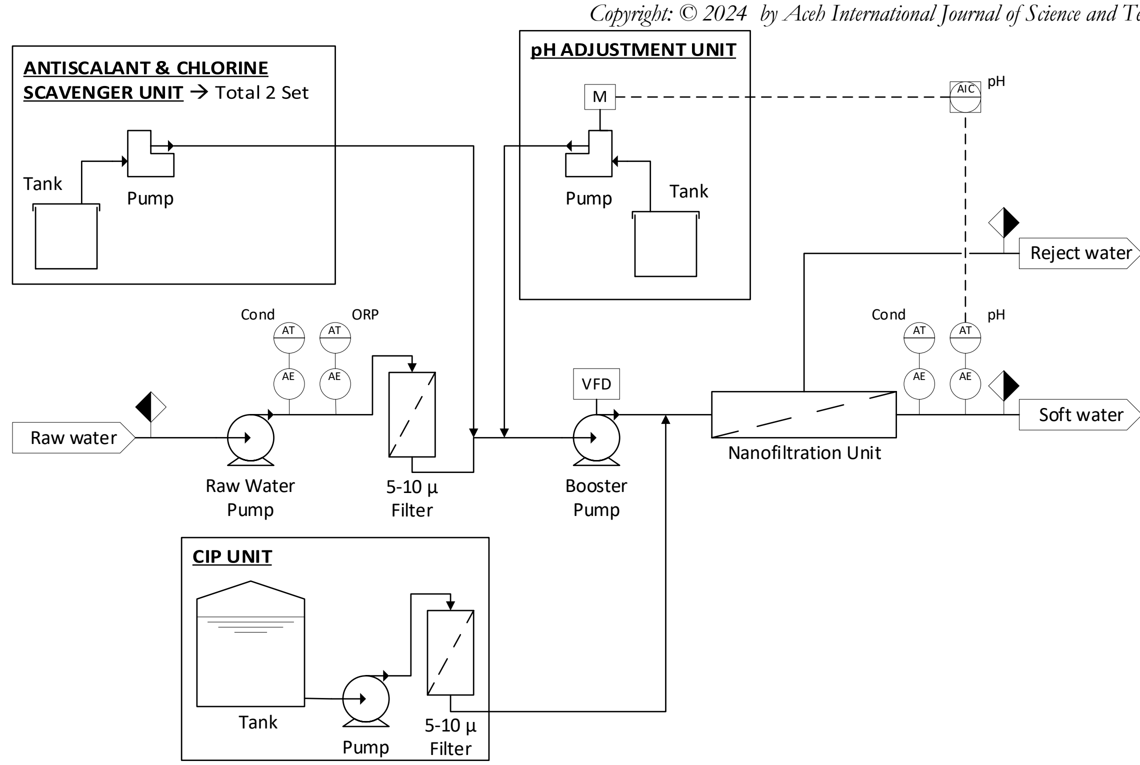

Figure 2. NF system process flow diagram

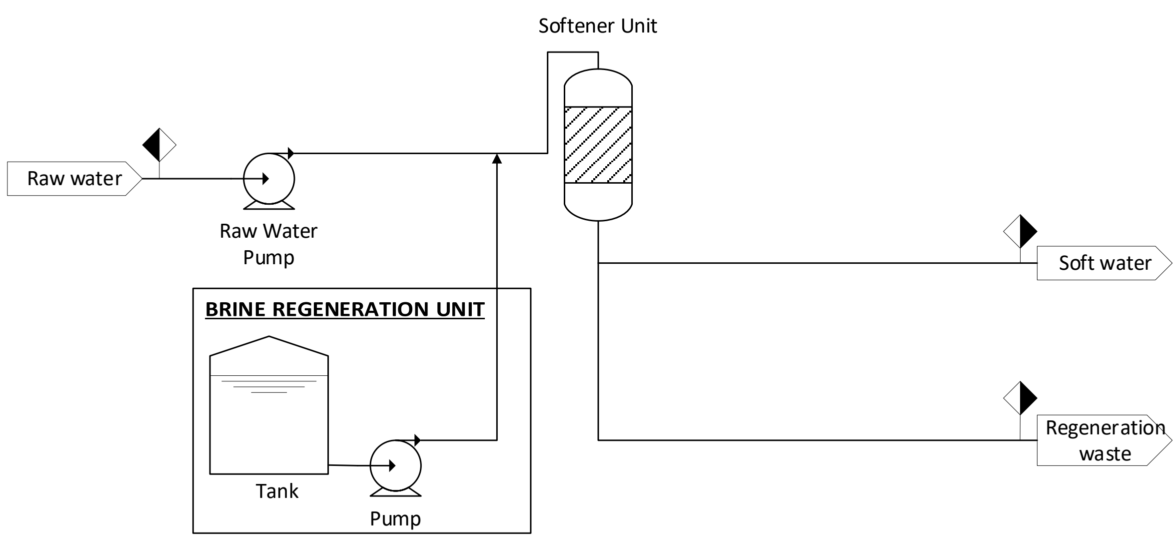

Figure 3. IX system process flow diagram

Basis for Economic Analysis

After properly simulating and sizing the NF and IX units, each design underwent a comprehensive economic evaluation. The economic analysis was evaluated based on the parameter Total Annual Cost (TAC), calculated as the sum of Annualized Capital Cost (ACC) and the Annual Operating Cost (AOC), as shown in equation (1).

$$TAC = ACC + AOC \quad (1)$$

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The NF and IX equipment were assumed to be in module form. The capital cost entailed a detailed estimation of the equipment module, encompassing tanks, pumps, membranes (NF) or resins (IX), valves, instruments, and module piping and auxiliaries as illustrated in Figure 2 and Figure 3. Next, this cost was annualized according to equation (2) (Smith, 2016),

$$Annualized\ Capital\ Cost = Capital\ Cost\ \times \frac{i(1+i)^n}{(1+i)^n+1} \quad (2)$$

where i is the interest rate (assumed at 9%), and n is the number of years (assumed at 10 years).

The operating cost mainly comprised of electricity for equipment driver, chemicals for NF dosing or IX regeneration, and consumables (membranes for NF or resin for IX). The cost estimation was based on 360 days per year of operation. It is important to note that the economic analysis was conducted within the context of Indonesia, and therefore, the Indonesian Rupiah (IDR) was considered as the base currency.

Results

Performance Analysis

The outcomes of the design simulation are outlined in Table 2. It is essential to highlight that the values presented in Table 2 represent the average values across all capacities corresponding to each hardness concentration.

In general, the total hardness of NF product water tends to be higher than that of the IX product water, with hardness removal ranging between 93.2%-94.6% for the NF system and over 99% for the IX system. Consequently, the IX system is preferred for applications that demand stringent total hardness quality.

Table 2. NF and IX design simulation results

No	Raw water total hardness	125 ppm $CaCO_3$		230 ppm $CaCO_3$		360 ppm $CaCO_3$	
	System	**NF**	**IX**	**NF**	**IX**	**NF**	**IX**
1	Product total hardness (ppm $CaCO_3$)	8.5	< 1	12.4	< 1	20.0	< 1
2	Hardness removal	93.2%	> 99%	94.6%	> 99%	94.4%	> 99%
3	Raw water TDS (ppm)	337.0	337.0	541.4	541.4	671.0	671.0
4	Product TDS (ppm)	34.4	350.3	42.3	564.5	48.9	703.7
5	Water recovery	80.0%	98.2%	75.0%	96.9%	75.0%	95.6%
6	Average wastewater TDS (ppm)	1,540	14,400	2,030	16,900	2,500	18,300

However, further observation on the results revealed another critical parameter that should be taken into account before choosing between NF and IX, namely Total Dissolved Solids (TDS). It can be observed that NF may reduce the TDS while IX may result in a slight increase in TDS. This disparity is attributed to the differences in the removal mechanism between NF and IX systems. In the IX system, the removed hardness ions are replaced with other ions (such as Na^+), whereas in the NF system, the removed ions are not replaced, causing a decrease in TDS. The percentage of removal depends on the initial hardness content of the raw water. High total hardness in the raw water, when removed, will cause a significant decrease in the TDS. Conversely, low total hardness in the water, when removed, may not cause a substantial decrease in TDS.

This distinction becomes particularly relevant in applications such as boiler water treatment, where precise control of TDS is essential (Spirax Sarco, 2019), contingent on the operating pressure. Soft water may suffice for low-pressure boilers (Amjad and Demadis, 2015). However, for medium to higher pressure boilers requiring more stringent water quality, i.e., lower TDS water, the NF system might be suitable. It is important to note that the NF system may not be suitable for very high-pressure boilers that mandate the use of high-purity or ultra-pure water.

Environmental Analysis

In addressing the environmental issues, it is important to examine the water recovery and contaminant concentration of the wastewater produced by each system, as shown in Table 2. The water recovery of NF system ranges approximately between 75 and 80%, indicating that an estimated 20-25% of the raw water is

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disposed as wastewater (reject water). This proportion is relatively higher than the wastewater generated by the IX system, which constitutes an estimated 1.8-4.4% of wastewater (with water recovery of approximately 95.6-98.2%). The minimal wastewater generated by the IX system is primarily attributed to the regeneration phase, where product water is employed (as outlined in previous section, **Error! Reference source not found.**).

Although the wastewater amount of NF is higher than IX, the handling or disposal of NF wastewater is relatively uncomplicated. Table 2 reveals that the average wastewater TDS of the NF system in this study ranges between 1,540 to 2,500 ppm. In accordance with Permen LHK No.5 Tahun 2014 (Kementerian Lingkungan Hidup, 2014), the maximum allowable limit for wastewater TDS is 2,000 ppm (Golongan I) or 4,000 ppm (Golongan II). It is therefore possible to dispose the NF reject water into water bodies without additional treatment, provided that other constituents in the reject water are within permissible limits. In cases where TDS exceeds the limit, simple treatments such as minor dilution are sufficient to meet disposal criteria.

Contrastingly, this is not the case for the IX system. IX wastewater contains significantly higher TDS, ranging from 14,400 to 18,300 ppm in this study. Diluting wastewater with such high TDS will require a relatively large amount of dilution water, which in this case, will increase the wastewater volume to approximately four to nine times (depending on the regulated disposal limit 2000 ppm or 4000 ppm).

Annualized Capital Cost Analysis

The estimated values of the ACC, AOC, and TAC are presented in **Error! Reference source not found.** for NF system and **Error! Reference source not found.** for IX system.

Table 3. Cost estimation of NF system

Total hardness (ppm $CaCO_3$)	Net capacity (m^3/h)	Scenario	Annualized Capital Cost (IDR/year)	Annual Operating Cost (IDR/year)	Total Annual Cost (IDR/year)
125	15	1	74,010,647	169,481,028	243,491,676
125	50	2	149,708,339	534,915,783	684,624,122
125	80	3	223,249,851	808,813,573	1,032,063,424
230	15	7	74,468,758	172,144,418	246,613,176
230	50	8	149,708,339	544,991,096	694,699,435
230	80	9	223,249,851	820,457,413	1,043,707,264
360	15	13	74,468,758	202,598,131	277,066,890
360	50	14	150,799,080	726,258,783	877,057,863
360	80	15	223,249,851	932,443,676	1,155,693,527

Table 4. Cost estimation of IX system

Total hardness (ppm $CaCO_3$)	Net capacity (m^3/h)	Scenario	Annualized Capital Cost (IDR/year)	Annual Operating Cost (IDR/year)	Total Annual Cost (IDR/year)
125	15	4	20,397,045	137,368,386	157,765,430
125	50	5	44,316,402	436,044,033	480,360,435
125	80	6	61,397,985	719,127,044	780,525,029
230	15	10	26,416,667	250,148,732	276,565,399
230	50	11	78,089,141	861,581,984	939,671,124
230	80	12	92,175,472	1,359,199,647	1,451,375,119
360	15	16	32,841,616	391,467,235	424,308,851
360	50	17	85,692,577	1,289,833,052	1,375,525,629
360	80	18	132,469,183	2,112,997,236	2,245,466,420

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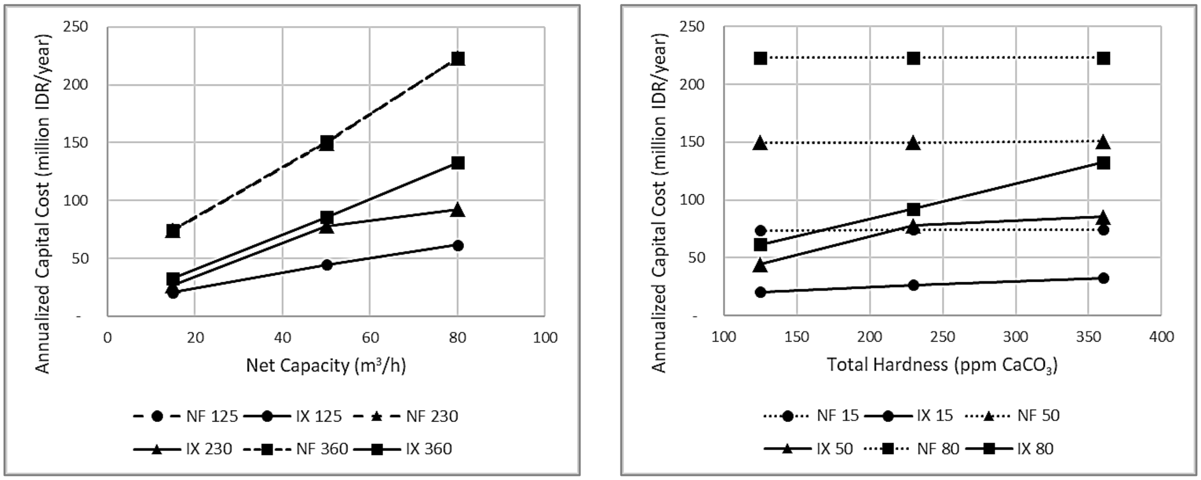
The ACC was plotted against the net capacity, as shown in Figure 4(a). As expected, the cost for both system increases with increasing capacity. Notably, the NF system generally exhibits a higher ACC compared to the IX system across varying capacities.



(a) (b)

Figure 4. Annualized capital cost (ACC) plotted against: (a) net capacity, (b) total hardness

In case of the IX system, at low capacity, there is only a slight cost difference among different total hardness. As the capacity increases, the cost difference expands. For example, the cost difference at 15 m^3/h (scenario 10 vs 16) is IDR 6,424,949 per year. As the capacity escalates from 15 m^3/h to 50 m^3/h, this difference increases to IDR 7,603,436 per year (scenario 11 vs 17), and when the capacity further increases from 50 m^3/h to 80 m^3/h, the difference significantly rises to IDR 40,293,711 per year (scenario 12 vs 18). This may be attributed to the increase in the number of IX units as the capacity becomes larger. When the total hardness in raw water increases, the required resin volume also increases proportionately. However, the IX vessel or tank has size limitations and therefore, when the resin volume exceeds the vessel's capacity, additional vessels are needed, leading to more piping and auxiliaries (such as valves and instruments). This results in higher capital costs, since at high capacity, multiple units need to be installed, whereas at lower capacity, a single unit is usually sufficient.

For the NF system, however, the overlapping points on the plot indicate that the ACC is not significantly affected by the total hardness. This is more clearly shown in Figure 4(b). Consequently, it may be concluded that the capital cost of NF system mainly depends on the size of the plant, i.e. capacity, while for the IX system, the ACC is influenced by both net capacity and raw water total hardness.

Annual Operating Cost Analysis

The AOC was plotted against the net capacity as shown in Figure 5(a). Similar to ACC, the AOC of both systems also increases as the capacity inreases. In the IX system, the cost difference exhibits a pattern akin to that observed in the ACC, where the difference is smaller at lower capacities and becomes more pronounced at higher capacities. For the NF system, the cost difference is unclear and therefore, the AOC is plotted against total hardness to provide a more unambiguous perspective, as shown in Figure 5(b).

Figure 5(b) shows that at lower hardness, the AOC of the NF system is generally higher than that of the IX system. However, as the total hardness in the raw water increases, this trend reverses, and the AOC of the IX system becomes increasingly and significantly higher than that of the NF system. Thus, it can be concluded that, similar to the capital cost, the operating cost of NF system mainly depends on its capacity, while the operating cost of IX system is influenced by both total hardness and capacity.

Aceh Int. J. Sci. Technol., 13(1) 19-30
April 2024
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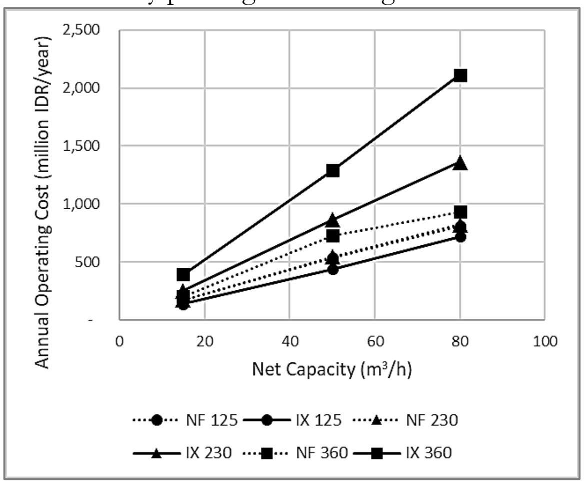
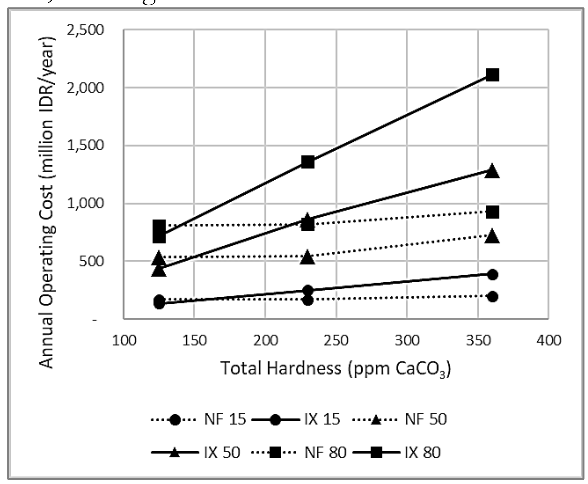
Total Annual Cost Analysis

Based on the ACC and AOC analysis, it may be expected that the total annual cost (TAC) of NF system is affected mainly by the capacity, while the TAC of IX system is influenced by both capacity and total hardness. This is shown by plotting the TAC against the total hardness, as in Figure 6.



(a)



(b)

Figure 5. Annual operating cost (AOC) plotted against: (a) net capacity, (b) total hardness

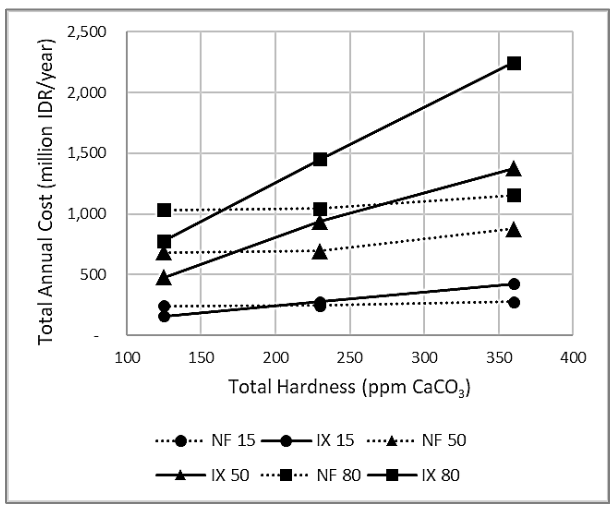


Figure 6. Total annual cost (TAC) vs total hardness

The plot in Figure 6 displays a trend which is similar to AOC. At lower total hardness levels, the TAC of the NF system is generally higher than that of the IX system. However, at higher total hardness, the TAC of the IX system becomes higher. This observation implies that at each capacity, there is an intersection point where such reversal happens. For example, the intersection point between NF 15 m^3/h and IX 15 m^3/h occurs at total hardness of 280 ppm $CaCO_3$. Below below this value, the TAC of the NF system exceeds that of the IX system, while above this value, the TAC of NF system becomes lower. All intersection points of the TAC at 15 m^3/h, 50 m^3/h, and 80 m^3/h are tabulated in Table 5.

Table 5. NF and IX TAC intersection point

Net capacity (m^3/h)	Total hardness (ppm $CaCO_3$)
15	280

50	222
80	204

NF vs IX Selection Chart

Next, using the data from Table 5, a graph was plotted and a trendline was drawn to facilitate the creation of a selection chart, as depicted in Figure 7.

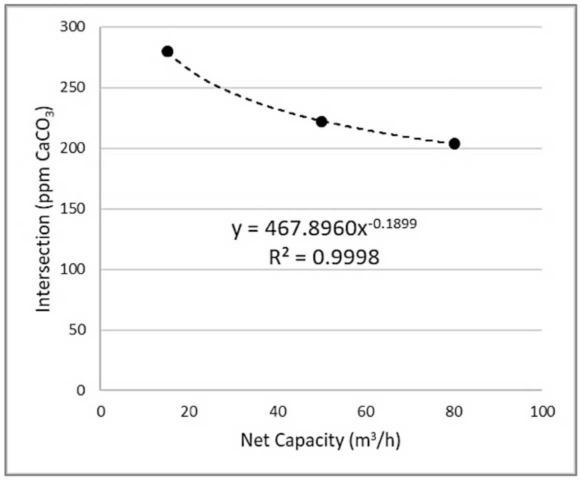


Figure 7. TAC intersection plot and trendline

Once the trendline was drawn, an equation may be generated, equation (3),

$$y = 467.896 \cdot x^{-0.189} \quad (3)$$

where x is the net capacity (m^3/h) and y is the total hardness (ppm $CaCO_3$) at which the TAC of IX becomes higher than NF and vice versa.

Now, using equation (3) and varying x from 10 m^3/h to 140 m^3/h, a selection chart can be generated along this range, as shown in Figure 8. To read this chart, one can simply decide the required capacity and measure the raw water total hardness, and then plot the point in the chart. For example, when an industry requires soft water as much as 120 m^3/h and the raw water contains a total hardness of 100 ppm $CaCO_3$, then it is economically recommended to select IX system over the NF system. However, if the raw water contains very high total hardness of 300 ppm $CaCO_3$, NF system is recommended.

The author recommends three points which require careful attention when using the selection chart. Firstly, since the overall cost is an estimation, there could be some uncertainties around the selection line drawn in Figure 8. For example, when an industry requires soft water at 100 m^3/h and the raw water total hardness is 200 m^3/h, the point is too close to the selection line and consequently, it is possible to select either NF or IX. Detail calculation should be performed for this case. Secondly, the selection chart only considers economical aspects and not technical aspects as discussed in previous section, **Error! Reference source not found.** and **Error! Reference source not found.**. Lastly, although the cost estimation was performed in Indonesian context and consequently, users might expect different results depending on each context, the chart was prepared by considering costs which could be applicable as global as possible.

Discussion

The present study conducted a comprehensive analysis comparing two prominent industrial water softening systems, Nanofiltration (NF) and Ion Exchanger (IX), across technical, environmental, and economic dimensions. The technical evaluation revealed that IX outperforms NF in total hardness removal (>99%), while NF demonstrates superior TDS removal. Environmental analysis highlighted trade-offs, with

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NF generating higher wastewater volumes and IX producing wastewater with highly concentrated TDS. Economically, NF generally incurs higher Total Annual Costs (TAC) at lower total hardness concentrations, while IX becomes costlier at higher concentrations.

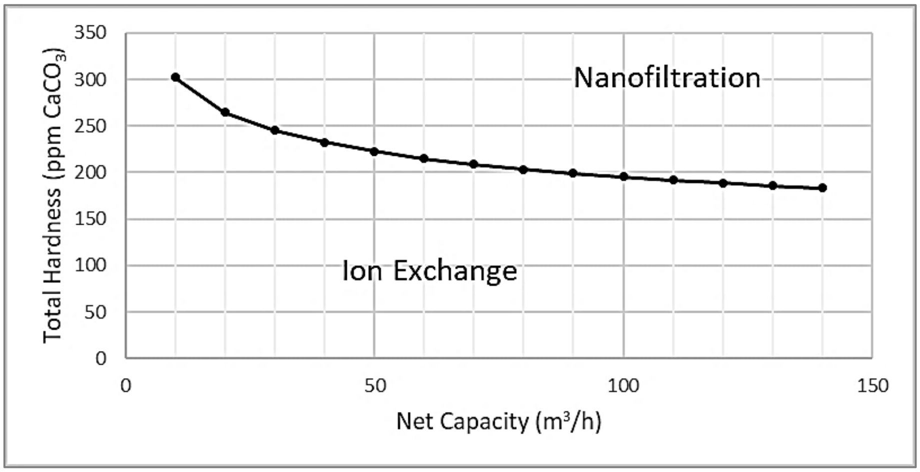

Figure 8. NF and IX selection chart based on TAC

Comparisons with previous studies reveal consistent findings regarding the technical performance of NF and IX systems in water softening applications. However, the present study extends the analysis by incorporating environmental and economic dimensions, providing a more holistic understanding of the trade-offs associated with each system. Previous studies may have focused solely on technical aspects, whereas this study integrates multiple perspectives to inform decision-making comprehensively.

The findings of this study have significant implications for industries seeking optimal water softening solutions. The superior total hardness removal offered by IX may be desirable for applications requiring stringent water quality standards. However, the environmental impact and economic considerations associated with IX, particularly at higher concentrations, underscore the importance of evaluating trade-offs. NF emerges as a viable alternative, offering substantial TDS removal and potentially lower environmental impact, albeit at a higher cost. The observed trade-offs between NF and IX systems highlight the need for a nuanced approach to system selection, considering specific water quality requirements, operational constraints, and budgetary considerations. The selection chart developed in this study provides a practical tool for decision-making, aiding industries in identifying the most cost-effective solution based on their unique circumstances.

One strength of the present study lies in its comprehensive evaluation of NF and IX systems across technical, environmental, and economic dimensions, providing valuable insights for decision-makers. The integration of simulation results, environmental analysis, and economic modeling enhances the robustness of these findings. Additionally, the development of a selection chart offers a practical tool for system selection. However, the study also has limitations. The analysis is based on simulations and modeling, which may not fully capture real-world variability and uncertainties. Further validation with experimental data could strengthen the reliability of the findings. Additionally, the study's scope is limited to a specific context, and findings may not be universally applicable across different industries or regions.

All in all, the comparative analysis of NF and IX systems presented in this study highlights the importance of considering multiple dimensions in water softening system selection. Decision-makers should carefully weigh the trade-offs between technical performance, environmental impact, and economic considerations to identify the most suitable solution for their specific needs. Based on these findings, I recommend industries to utilize the selection chart developed in this study as a practical tool for decision-making. Additionally, future research should focus on refining the modeling approach, incorporating real-world data, and expanding the analysis to include additional factors such as energy consumption and regulatory compliance. Overall, this study contributes to advancing understanding in the field of industrial water softening and provides valuable guidance for industries navigating the complex landscape of water treatment technologies.

Conclusion

NF and IX are two viable systems which can be used for industrial water softening. Both systems have been evaluated based on the technical, environmental and economical aspects. On the technical aspects, the simulation results reveal that IX exhibits a better removal of total hardness (> 99%), albeit with a potential slight increase in the TDS. In contrast, NF demonstrates less total hardness removal but excels in substantial TDS removal. On the environmental aspects, NF generates a higher volume of wastewater, but IX generates wastewater with highly concentrated TDS, which requires more complicated treatment. Turning to economic aspects, the total annual cost of NF generally surpasses that of IX at lower total hardness concentration. However, at higher concentrations, the total annual cost of IX overtakes that of NF. To assist in selecting NF or IX based on the economical aspect (total annual cost), a selection chart has been prepared accordingly. This chart aids in deciding between NF and IX, considering the total annual cost as a key determinant.

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