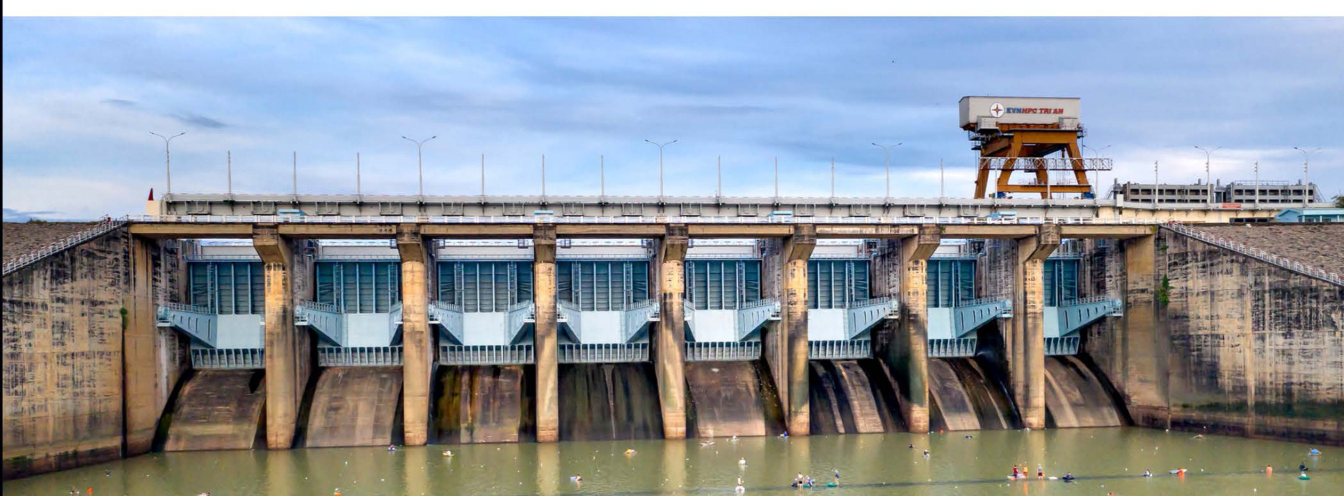
Nanofiltration for Sustainability

Reuse, Recycle and Resource Recovery

EDITED BY
ABDUL WAHAB MOHAMMAD,
TEOW YEIT HAAN AND NIDAL HILAL

CRC Press
Taylor & Francis Group



Nanofiltration for Sustainability

This book provides a novel exploration of the application of nanofiltration membrane technology for sustainability in various industries, situated in view of recent breakthroughs and the use of reuse, recycle and resource recovery approaches.

Moving from a comprehensive discussion of nanofiltration membrane processes to case studies and real-world applications of nanofiltration technology across society, both successes and potential limitations are considered.

Features:

- Detailed discussion of the fundamentals of nanofiltration technology
- The concepts of reuse, recycle and resource recovery using nanofiltration technology are explored in combination with other technologies to advance circular economy
- Considered across a range of industries, such as textiles, oil, gas, agriculture and pharmaceutics

Written in a thoroughly detailed manner, this book is an essential guide for industry professionals interested in sustainability and working toward a circular economy. Comprehensive discussions of the fundamental processes underpinning nanofiltration technology also make this book particularly appealing to students of industrial chemistry.

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CRC Press
Taylor & Francis Group
Boca Raton London New York

CRC Press is an imprint of the
Taylor & Francis Group, an **informa** business

Designed cover image: © Canva

First edition published 2024
by CRC Press
6000 Broken Sound Parkway NW, Suite 300, Boca Raton, FL 33487-2742

and by CRC Press
4 Park Square, Milton Park, Abingdon, Oxon, OX14 4RN

CRC Press is an imprint of Taylor & Francis Group, LLC

ISBN: 978-1-032-19949-8 (hbk)
ISBN: 978-1-032-20002-6 (pbk)
ISBN: 978-1-003-26182-7 (ebk)

DOI: 10.1201/9781003261827

Typeset in Times
by codeMantra

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1 Role of Nanofiltration Process for Sustainability in Industries

Reuse, Recycle, and Resource Recovery

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CONTENTS

1.1 INTRODUCTION

According to the United Nations, as much as 2 billion of the world's population are facing with the issues of water security, where dwindling clean water resources and limited water supply could threaten the health and social development of the affected community [1–3]. The drastic increase in demand for clean water associated with the rapid population growth and accelerated industrialization and urbanization, as well as the illegal discharge of pollutants to the waterways and uncontrollable climate change have severely upset the capability of the water utilities to produce clean water that meets the demand of people and economy [4,5]. The water crisis requires collective efforts from all stakeholders to prevent the situation from further deteriorating and harming the ecosystems and human well-being.

Sustainable development could be one competitive strategy to address the issues of water scarcity. Back in 2015, Agenda 2030 for Sustainable Development that includes 17 Sustainable Development Goals (SDGs) has been endorsed and embraced by all United Nations Member States to attain sustainable development [6]. In response to the issues of water scarcity, SDG 6 has been dedicated to water, with the aim to ensure availability and sustainable management of water and sanitation for all. This can be achieved through various approaches, such as to supply safe and affordable drinking water for

DOI: 10.1201/9781003261827-1

all, to reduce water pollution through wastewater treatment and minimum release of hazardous chemicals and materials to waterway, to improve water use efficiency across all sectors, and to promote integrated water resource management and reuse technologies [7]. Considering industrial water use composed of a huge portion of total water consumption worldwide, systematic and proper management of industrial effluent could significantly contribute to sustainable development in water industry.

Wastewater management strategies of various hierarchical can be adopted to achieve sustainable development and meet the call for Agenda 2030. For instance, proper treatment of wastewater could prevent the release of harmful pollutants from entering waterways, protecting the ecosystem and water resources [8]. Technological advancement in the past decades not only further improves the wastewater treatment efficiency but also enables the reclamation of treated water for reuse purposes. This could help to cut down the demand on clean water for operation and minimize wastewater discharge from the industries, which is a major step toward sustainable water management in the industry sectors [9]. Recently, a paramount shift has been observed toward the management of wastewater, where wastewater is no longer seen as a waste but could be an alternative source for various resources or valuable compounds. This is particularly interesting as apart from water, wastewater contains certain constituents (e.g., nutrients, organic compounds, and minerals) that could be recovered and reused, provided a proper treatment system is installed to manage the effluent [10]. Such recovery and reuse of resources from wastewater meet the concept of circular economy, align well with the model of production and consumption highly promoted by the government to achieve the aim of sustainable development.

All the aforementioned sustainable wastewater management strategies could contribute to sustainable development in water industry, and nanofiltration (NF) membrane process could directly or indirectly play a key role in attaining the sustainability status in water industry. Past studies have indicated the capability of NF system to function as a treatment process for the removal of pollutants and recovery of water and other valuable resources for reuse purposes or act as an intermediate/enabler process to alter the composition of the effluents into separate streams for subsequent treatment and reclamation purposes [11].

Furthermore, NF process could also be an alternative option over existing conventional processes which are less environmentally friendly. The replacement of conventional processes by NF will enable the industry to operate more sustainably, such as having lower energy consumption, releasing lesser greenhouse gases, and preserving the quality of products. Though not as widely adopted as NF being employed for wastewater treatment, the utilization of NF in industrial processes reflects the potential of NF in promoting sustainable industrialization. Overall, by employing NF in the treatment process or in operation process, it can help various industry sectors such as textile, food, oil and gas, tannery, pharmaceutical, and biorefinery to attain sustainable development.

1.2 SUSTAINABILITY ASPECTS

In this section, the role of NF process in promoting sustainable practices in various industries will be discussed in two categories: NF as enabler for resource recovery and reuse and NF as enabler for alternative sustainable operation and process. The former category is the application of NF to recover valuable resources from various medium, particularly industrial wastewater, for reuse purposes or as a feedstock for other industries. The second category highlights the potential of NF process as an alternative option to the current conventional processes in the industry, in which the NF process could be more sustainable especially in terms of energy consumption and preservation of products' quality. It has to be reminded that this chapter only discusses the contribution of NF process in various industries toward sustainable development. Technical details of the processes would be covered in Chapter 2.

1.2.1 Enabler for Resource Recovery and Reuse

In this section, the role of NF in assisting various industries to achieve resource recovery and reuse from industrial effluents will be discussed. The basic level of wastewater management is the prevention of pollutants from entering waterways by removing it from wastewater. This is to ensure the discharged wastewater complies with the stringent regulation set by the authority and free from pollutants that could harm the ecosystem and living organisms. For instance, NF has been shown to be capable of rejecting various pollutants and preventing those compounds from passing to treated water, such as dyes in textile effluent [12], dissolved solids in dairy effluent [13], phenolic compounds in olive mill wastewater [14], dissolved minerals in produced water [15], metal ions in acid mine drainage [16], tannins in tannery effluent [17], and multivalent ions in pulp and paper industrial effluent [18]. The rejection of pollutants by NF could help to protect the waterways and minimize the impact of industrial wastewater on the environment.

Realizing that wastewater is a source for alternative valuable resources, industry operators have started to seek for the recovery of these resources for reuse purposes. In most cases, NF has been integrated with other treatment technologies to deliver satisfactorily overall removal and treatment efficiencies, which will be further elaborated in Chapter 2. The most widely accepted practices are the recovery of treated water for reuse inside or outside the plants with the aim to cut down the consumption of fresh water. For instance, treated water (through integrated NF process) meeting the desired quality could be reused for housekeeping (equipment washing and floor cleaning) [19–21], irrigation and landscaping [22–24], feedwater for cooling water and steam generation [13,25,26], and processing [15,27–31]. Unlike reverse osmosis membrane that could basically reject all impurities, NF membrane has a constraint in removing pollutants with size smaller than its pores. Nonetheless, the reduced quantity of pollutants in the permeate could be eliminated by integrating post-treatment process after the NF, such as UV irradiation or ozonation which could be installed to further degrade the resilient compounds in NF permeate [32].

For some other cases, the treated water contains constituents that could enable specific reuse purposes. Religa et al. showed that the negatively charged NF membrane could facilitate permeation of chloride ions, and the chloride-rich permeate could be reused as pickling baths in the tannery industry [33]. Agtas et al. demonstrated that the installation of NF after ultrafiltration (UF) treatment has resulted in higher contaminant removal efficiency when treating textile wastewater [34]. The interesting part of their study was that NF, being a membrane that allows the passage of monovalent ions, enabled at least 50% sodium recovered in the permeate. The recovered caustic solution could be reused in the causticization process, which could potentially contribute to caustic recovery of 480 m^3/year, while caustic usage cost could be reduced by 50% if the recovered caustic solution is reused in the processing.

Similar economic benefit has also been reported by Santos et al. where the NF pilot plant was shown to be capable of recovering caustic solution from spent caustic solution in crude oil refinery [35]. The purified permeate caustic solution can be recycled back for further reuse in the refinery process, and economic analysis revealed that such strategy could save about 1.5 M€ per year for the oil refinery industry. The special characteristic of NF membranes that reject larger impurities but allow the passage of monovalent ions and water molecules also benefits the mining industry. Studies have shown that NF allowed high HSO_4^- anion permeation (>82%) when treating mining effluent, producing permeate stream rich in sulfuric acid which was further concentrated by reverse osmosis to 99% [29,36]. The recovered sulfuric acid with high purity could be reused in the mining production process. Hence, it can be shown that the incorporation of NF process enables the recovery of other important compounds from the wastewater, and the reuse of these resources could lead to cost savings and sustainable resource consumption for the industries.

There are other compounds in wastewater that could be recovered as valuable products. Phytotoxic phenolic compounds are normally found in olive mill wastewater. Their antioxidant and anti-inflammatory properties have attracted the attention of food and cosmetic industries. In this context, NF could be employed to separate phenolic compounds from other impurities in olive mill effluent by allowing them to pass to permeate side [37]. Upon further purification, the phenolic compounds could be recovered as value-added feedstock for cosmetic and pharmaceutical industries. However, further study has to be conducted to validate the economic feasibility of recovering phenolic compounds from olive mill effluent. In another study, Seip et al. employed NF as pre-treatment process prior to ion-exchange sorbents for lithium recovery from flowback-produced water [38]. Even though NF membrane did not directly take part in recovering the lithium, its presence as pre-treatment process enabled the removal of small organic molecules that could disrupt the sorbent of lithium in the ion-exchange process. Indirectly, the efficiency of lithium recovery could be enhanced, and this contributes to sustainable resource management since lithium is of high demand with the surge of battery production for electric cars.

A major percentage of phosphate from wastewater is normally transferred into the sewage sludge during the treatment process. This indicates that the phosphorus locked in the sewage sludge could be recovered and reused as fertilizer. Blöcher et al. have developed an integrated phosphorous recovery process consisted of low-pressure wet oxidation, UF, and NF [39]. The dissolved phosphate ($H_2PO_4^-$) ended in NF permeate since the membrane could not remove monovalent ion. However, after passing through the UF and NF processes, the filtered permeate was free from other impurities. This enabled up to 54% phosphorus recovery and the costs of the entire integrated process were as competitive as conventional sewage sludge disposal. Furthermore, additional benefits such as recovery of valuable phosphorus resource and reduced greenhouse emission could also be attained.

Generally, the unwanted impurities in wastewater are rejected by NF membrane and collected as retentate for subsequent treatment and disposal. The impurities concentrated in retentate stream enable the reduction in treatment volume and cost of other technologies. For instance, NF membrane could retain up to 99% of perfluorohexanoic acid (persistent contaminant) in retentate stream, which facilitated the subsequent electrooxidation process to degrade the pollutants into harmless compounds [40]. Without the concentration effect of NF membrane, electrooxidation process will have to deal with a huge volume of wastewater with trace amount of pollutants, which does not appear to be economically feasible. Similar benefit brought by NF process has also been reported in the handling of pharmaceutical pollutants. The presence of NF process helped to concentrate the pharmaceuticals in retentate and subsequently facilitated more efficient degradation of advanced oxidation processes (such as photo-Fenton and ozonation) [41–43]. This reflects that the incorporation of NF in the treatment process could aid in reducing physical footprint and cost of other treatment technologies since the effluent has been conditioned to smaller volume.

On the other hand, the rejected impurities could also be turned into valuable resources for other applications. For instance, NF membrane is known to be a process with great capability in rejecting multivalent ions and retaining the heavy metals in retentate. These heavy metals could be recovered and utilized in the industry. Muller et al. showed that NF membrane treating acid mine drainage could help to recover valuable metals such as copper in the retentate stream [16]. It was estimated that copper loss of around $69,000/year could be saved if the heavy metals were recovered. Chromium ions that have been used in tanning process in tannery industry could also be recovered by NF in retentate stream [33,44]. The chromium-rich retentate could be reused in tanning process after further purification, assisting the tannery industry to cut down the expenses on fresh chromium resource. Chen et al. reported that NF membrane could retain lactose in retentate when filtering dairy wastewater [45]. The lactose-rich retentate was found to be a better source for anaerobic fermentation to produce a higher proportion of volatile fatty acids and biogas for further utilization. Lupanine – a toxic alkaloid found in lupin beans – wastewater could be a valuable resource in pharmaceutical industry since it can be utilized as starting material for the production of other alkaloids (such as sparteine) [31]. The capability of NF membrane to reject as much as 99.5% of lupanine from lupin beans wastewater could produce a feedstock stream of lupanine for pharmaceutical industry once the retentate is further purified and extracted with other technologies.

NF could be used to recover sulfate ions (in retentate) from acid mine drainage and tannery effluent. With its >99% rejection of sulfate ions from acid mine drainage, the tight NF membrane produced retentate rich in sulfate content (~4,000 mg/L) that could be mixed with flowback water to remove barium and strontium ions from flowback water via sulfate precipitation process [25]. Galiana-Aleixandre et al. estimated that with 97% sulfate retention by NF when treating tannery

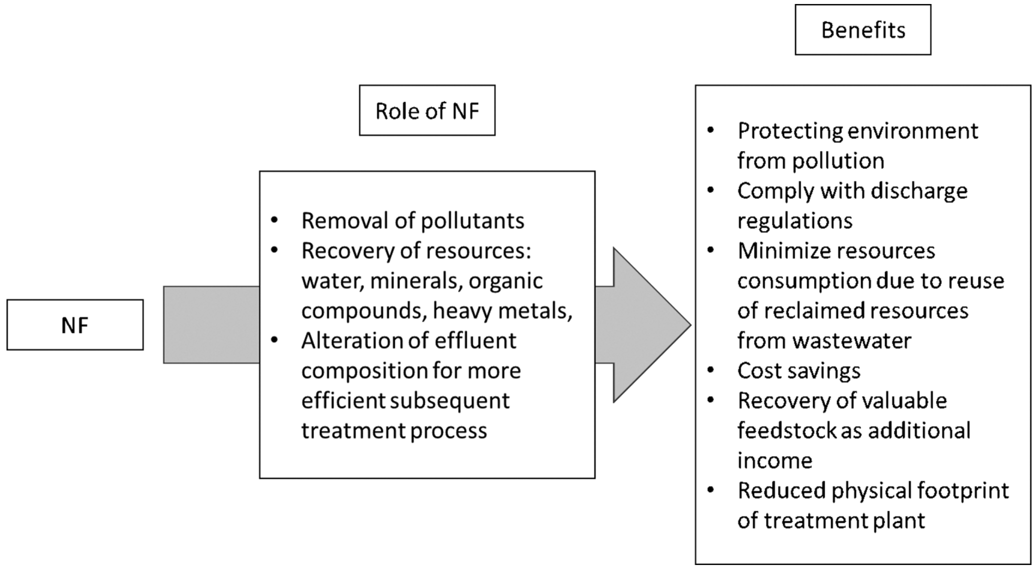

FIGURE 1.1 Role of NF and benefits obtained with the utilization of NF in the processing.

effluent could lead to the recovery of 61.63 t of sulfate per year which can be recycled and reused in tanning drums [46]. This indicates the huge potential to save the operational cost in the processing if NF membrane is installed to enable the recovery and reuse of resources from effluent. In textile industry, the dye effluent consists of high concentration of dyes and salts that would be a waste if treatment process adopted is to degrade and dispose the effluent. However, NF process could be utilized to fractionate the dye and salts, and enable the recovery of water, dye, and salts for reuse purposes. Lin et al. showed that NF process was capable to enrich the dye in retentate from 2.01 to 17.9 g/L while allowing most NaCl to pass through it [47]. The permeate rich in NaCl was then further processed by electrodialysis to separate NaCl from water. Eventually, the integrated process enabled resource extraction and reuse from high-salinity textile wastewater.

Lactic acids and amino acids are two main components that can be found in biorefinery fermentation broth. Both these acids are useful precursors with a wide variety of applications in pharmaceutical, food, and biotechnology products. Separation of these compounds from the fermentation broth is required for subsequent purification and utilization. In this scenario, NF membrane could be used to recover lactic acids and amino acids from fermentation broth, and then separated them into permeate and retentate streams, respectively, for further processing [48]. The NF membrane was also shown to be capable to concentrate the purity of lactic acid up to 85.6% [49]. Figure 1.1 summarizes the role of NF process and the associated benefits with the incorporation of NF in the processing.

1.2.2 Enabler for Alternative Sustainable Operation and Process

As discussed earlier, NF process enables the recovery of resources for reuse or other applications and alters the constituents in permeate or retentate for subsequent treatment or handling of impurities. The contribution of NF process to sustainable development in industry could also be reflected through the replacement of conventional processes by NF process that appears to be more operationally friendlier, for instance, the recovery of xylose from hemicellulose hydrolysate stream. The conventional method of xylose separation is through chromatographic method where the separation process is considered tedious and complex. To address these issues, Sjöman et al. showed that NF could be used to enrich xylose in permeate with xylose as up to 78%–89% of the total dry solids in permeate [50]. The purity of xylose was reported to increase by 1.4–1.7-fold after the NF process, reflecting the separation potential of NF for the xylose recovery from hemicellulose hydrolysate.

Conventional thermal process for the clarification and concentration of juices or liquid products is known to consume a large amount of energy and result in the thermal degradation of beneficial compounds [51,52]. Membrane process (including NF) could be an alternative process that offers several benefits such as less manpower requirement, greater concentration efficiency, shorter processing time, and better quality preservation for compounds susceptible to thermal degradation. For instance, NF has been shown to concentrate various fruit juices such as watermelon, bergamot, orange, pomegranate, and roselle and increase the amount of useful bioactive compounds (e.g., lycopene, flavonoid, ascorbic acid, anthocyanins, and phenolic contents) [53–57]. The elevated concentration of bioactive compounds in the juices with preserved antioxidant activity will be beneficial to the consumers. NF process could also remove haze precursors for juice clarification. Due to its selective property, haze precursors will be retained by NF while allowing the passage of sugars to permeate [58]. This maintains the taste, stability, storage ability, and lightness of the clarified juices.

NF membrane is also found to be an alternative yet competitive process to handle organic solvent separation and purification applications. The membrane process is also known as organic solvent nanofiltration (OSN) and has a great potential to be applied for the management of organic solvents in fine chemical, pharmaceutical, petrochemical, and food industries [59–61]. The advantages of OSN over conventional processes (e.g., preparative chromatography, distillation, extraction, and crystallization) include energy efficiency, cost effectiveness and protection of compounds susceptible to thermal degradation [62]. For instance, conventional extraction and isolation method (such as solid-liquid extraction) of active constituents from the spices and aromatic herbs typically converted the extracts into powder form through evaporation, which could be detrimental to the active constituents as thermal degradation would lead to the loss of desired antioxidant activity [63]. To address this challenge, OSN could be adopted to isolate the active compounds while maintaining the antioxidant property. One example was the extraction of rosmarinic acid (extracts of rosemary) via OSN [64]. The rosmarinic extracts concentrated in NF retentate may be applied directly as preservative and functional ingredient in the foods, cosmetics, nutraceuticals, and medicines since the antioxidant property was preserved after OSN process.

Apart from protecting the valuable compounds, the recovery of solvent via OSN could also be achieved. OSN can be integrated with active pharmaceutical ingredients (API) production process to purify API and recover organic solvent for reuse. Sereewatthanawut et al. demonstrated OSN could remove more than 99% of the impurities from API, producing high-purity API while at the same time reducing the fresh solvent consumption due to the reuse of recovered solvent from OSN [65]. In another industry, ExxonMobil's Beaumont (Texas) refinery process reported promising findings from its large-scale industrial OSN plant for the recovery of dewaxing solvents from lube oil filtrates [66–68]. The OSN process managed to recover solvent mixture (toluene and MEK) with high purity (99%), which could be recycled directly to the chilled feed stream. The installation of OSN also brought many economic benefits, including the reduction of energy consumption per product unit by 20%, increment of the average base oil production by 25 vol.%, reduction of the volatile organic compounds' emissions, and cutdown in the use of cooling water. This proved the potential of NF process in helping the industry to progress toward sustainable development by improving the efficiency of resource consumption (solvent, cooling water, and energy), reducing greenhouse gases emission and saving cost.

The introduction of OSN enables the adoption of more sustainable practices in the industry. Bio-derived solvents such as terpenes are good replacement over conventional solvent (n-hexane) for vegetable oil extraction industry. However, the conventional solvent recovery technology would be quite costly to recover the bio-solvent since high operation temperature is required due to the high boiling points and heat of vaporization of terpenes. Operating the solvent recovery process at high temperature also deteriorates the quality (antioxidant property) of the oil [69,70]. In this context,

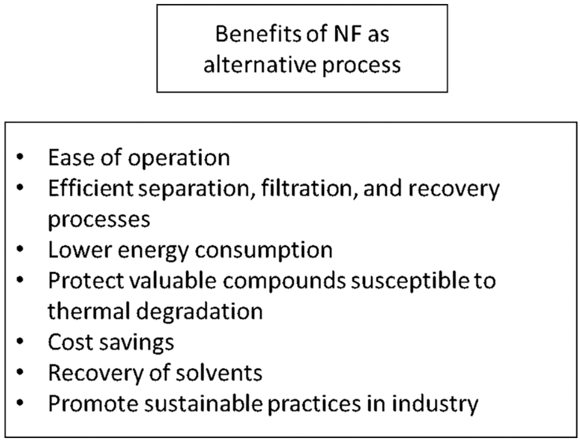

FIGURE 1.2 Benefits of NF as an alternative process.

OSN process that operates at low temperature could be an alternative process for the recovery of terpenes solvent, as shown by Abdellah et al. in canola oil extraction [71]. OSN also offers a more cost-effective process for the recovery of catalyst from organic solvents in hydroformylation and hydrogenation reactions. Conventional distillation method is costly and could degrade the catalytic activity during the recovery stage [72]. The adoption of OSN enabled the recovery of catalysts in retentate, and technological evaluation simulation revealed that recovery using OSN could potentially cut down the energy and costs by 85% and 75%, respectively, as compared to conventional distillation method [73].

NF process has also been used as an alternative technology to produce clean drinking water. The drinking water treatment plant with NF installed as tertiary process could enhance the overall treatment efficiency by removing organic matter and pesticides that conventional treatment processes failed to remove [74]. It was reported that the operational cost of having NF as tertiary treatment process was lower than a traditional plant with refining using ozone and carbon. Similar observation has also been reported by García-Vaquero et al. where compared to conventional treatment system (coagulation, flocculation, sedimentation, filtration, and filtration), NF process possessed greater treatment capability with better removal efficiency toward micropollutants in water [75]. Additional benefits such as the removal of hardness and color could also be acquired with the use of NF process for groundwater treatment as compared to conventional aeration and filtration processes [76,77]. The NF process could replace the softening and carbon filtration and deliver similar treatment efficiency in a single process. Hence, adoption of NF over conventional processes could lead to a more sustainable operation in water industry.

Figure 1.2 depicts the benefits of NF as alternative process. Despite the technical feasibility of NF process in resource recovery and reuse and as an alternative process for more sustainable operation in various industries, more study is required to understand its performance in real field and the associated overall cost. This information will further validate the feasibility of NF or integrated NF process in assisting the industry to attain sustainable development.

1.3 SUSTAINABILITY ASSESSMENT

Knowing the extent of NF process in improving the sustainability of industries, be it in resource recovery and reuse or operation process, would definitely help to convince the decision makers or stakeholders to adopt the NF in their operation for attaining better sustainability status. However, such information is scarce, and the sustainability claims of NF process are normally made solely based on technical or economic feasibility without support by quantitative data. It is to be clarified that sustainability is a complex concept that does not only focus on technical feasibility but also include other issues associated with the process itself, such as greenhouse gas emissions, energy consumption, land use, costs, removal of pollutants, public acceptance, reliability, and many more factors [78]. Past study has demonstrated that the typical cost-oriented selection approach did not necessarily give the best choice of wastewater treatment processes, as one has to balance between the treatment efficiency while meeting the sustainable criteria (e.g., reduce greenhouse gas emissions and energy consumption) [79]. Typically, the treatment process that enables resource recovery (such as biogas valorization and water recovery) would achieve higher ranking in the selection process due to the additional boost to sustainability from the perspective of sustainable resource recovery and consumption [80]. Other factors such as chemical consumption, energy consumption, and environmental emissions associated with the particular process could also affect the environmental and economic impacts caused by the adopted process. Therefore, the sustainability of NF process in various industries is also a complicated case, and the sustainable development brought by the adoption of NF process has to be properly evaluated before conclusion can be drawn on the sustainability status of the whole industry. Systematic assessment criteria will have to be developed and a comprehensive evaluation should be conducted to address this challenge.

The development of sustainability criteria is an arduous task as the criteria might vary between different processes or industries, small and large-scale processes, well-developed and developing or underdeveloped countries, and established or emerging new technologies [79,81,82]. Thus, the sustainability criteria have to be contextualized according to different scenarios since the NF can be adopted in the industries in different ways, either as enabler for resource recovery and reuse, enabler for the adoption of more sustainable practices in the operation, or as alternative technology over existing conventional processes, as discussed in the previous section. A few sustainability categories and indicators used in the sustainability assessment of wastewater treatment plants can be used as a guide to determine the sustainability of NF process in various industries [81–84]. These include technical category (treatment efficiency, compatibility with other processes, ease of implementation, process stability, reliability, complexity of construction and operation and maintenance, health and safety risks), environmental category (waste generation, energy use, global warming potential, land area, quality of effluent, potential recycling, release of chemical substances, CO_2 emission, water reuse potential, resource recovery, climate change, and human toxicity), economic category (investments, operating costs, capital costs, affordability, and cost effectiveness), and social category (odor impact, noise and visual impacts, public acceptance, employee satisfaction, expertise, local employment, safe and healthy conditions, and training). Life cycle assessment, coupled with the inputs from stakeholders, could provide the required information for the sustainability assessment. Hence, the contribution of NF process toward sustainable development in the industries could be measured by first developing the sustainability criteria for different scenarios followed by assessment through data collection. The finding would then be valuable to promote and convince the industry operators to adopt NF process in their operation for attaining sustainable development.

1.4 CONCLUSION

As demonstrated in the past studies, NF process could play a significant role in promoting resource recovery and reuse practices in various industries. These include the recovery of water and other resources such as minerals and acids that could be reused in the processing stages. The adoption of NF process also enables the recovery of valuable compounds as high-value raw materials in other industries. Furthermore, NF process could be an alternative option for existing conventional processes which are less environmentally friendly. All these indicate that the adoption of NF process could promote sustainable development in the industries. However, it is challenging to verify the extent of sustainability contribution from NF process. Sustainability criteria and assessment related to NF process in the industries should be developed such that solid evidence could be obtained and used to convince the industry operators to adopt NF process for a more sustainable operation.

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Recovery of Xylose from Oil Palm Frond (OPF) Bagasse Hydrolysate Using Commercial Spiral-Wound Nanofiltration Membrane

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