QATAR UNIVERSITY

COLLEGE OF ENGINEERING

OPTIMIZING AND EVALUATING THE EFFECTIVENESS OF VIBRATORY SHEAR ENHANCED PROCESS FOR THE SUSTAINABLE MANGEMENT OF COOLING WATER BLOWDOWN

BY

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ABSTRACT

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Title: Optimizing and Evaluating the Effectiveness of Vibratory Shear Enhanced Process for the Sustainable Management of Cooling water Blowdown

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In this work, the implementation of vibratory shear enhanced process (VSEP) as an emerging membrane technology for the treatment of cooling water blowdown (CWBD) was investigated. VSEP offer the advantage of reducing the fouling problem associated with the membrane and give a higher flux over conventional membrane technologies. For this purpose, at the lab scale, the performance of six membranes made of different compositions were tested for best treatment, including four for reverse osmosis (ACM, ORM-31K, ULP, AG) and two for nanofiltration (DK and HFT-150). A membrane selection study was conducted to decide upon the most suitable membrane based on major parameters such as the permeate rate stability and its quality. Additionally, a pressure study was performed to choose the optimum pressure and use it for the concentration study to know the recovery percentage, then conduct a vibration and fouling studies. Key parameter such as pressure, flowrate, pump speed, and vibration speed were monitored or controlled to reach the desired permeate quality. The findings of the study showed that membrane ORM-31K gives a good balance between TDS removal of 99% and permeate flux of 75 $L.m^{-2}.hr^{-1}$ at a lower pressure of 380 psi compared to other membranes. The removal of dissolved ions like sodium, calcium, magnesium, chloride, sulfate, and nitrate were between 81% and 99%, and 92 and 99% for ULP and ORM-31K, respectively. Furthermore, increasing the vibration frequency from 0 to 43 Hz helped in increasing the permeate flux by 45.3% and 57.1% for ACM-

RO and HFT-150-NF, respectively. The cleaning study on ORM-31K, helped in recovering the 75% of the initial flux at an optimum pressure of 380 psi.

Finally, according to the permeate quality it is suggested that this effluent can be used in many applications. Mainly, reusing it back in the district cooling facility as a make-up water or it can be discharged safely to surface water without any damage to marine creatures.

DEDICATION

This research work is dedicated to my parents, brothers and sisters who have been providing me an endless support, and to my academic supervisors, Prof. Fadwa ElJack and Prof. Fares Almomani for their guidance and encouragement to complete my study.

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CHAPTER 1: INTRODUCTION

1.1. Research Overview

Water and energy are considered key resources consumed in large quantities currently due to the dramatic growth of the industries as well as population. According to the rapid and continuous development and advances in technologies, it is expected that by 2050, the demand for water and energy will increase by 55% and 80%, respectively [1]. Consequently, water scarcity will increase, which will boost other water depletion problems. To adapt and overcome these global issues, the reclamation and reuse of wastewater should be maximized; this impacts the operation of many industrial sectors and the community in general. One of the industries that can benefit from its wastewater is district cooling facilities (DC). These systems have an important role in providing cooling needs at higher energy efficiency and they have many advantages over conventional in terms of low cost, energy consumption, and small footprint[2]. Nonetheless, DC face a problem with managing the concentrated effluent wastewater generated from their facilities. The continuous recirculation of cooling water during the cooling and evaporation process increases the concentration of dissolved ions in this process stream. Hence part of the operation is to drain the stream effluent to maintain an acceptable level of constituents[3]. The discharged wastewater is called cooling water blowdown (CWBD). Such stream has various contaminants including heavy metals, dissolved salts, corrosion preservatives, and biocides [4]. The current management of this effluent is mainly discharging it into surface or groundwater, which might cause impacts to the end-point environments [5]. Therefore, applying an end-of-pipe solution would be the best option in managing such wastewater as to deem the stream quality more suitable for discharge or reuse. One of the efficient and commonly used treatment options for wastewater treatment is reverse osmosis (RO)[6]. However, it has many challenges that limit its application or minimize its performance in various industries. The main obstacle is the fouling tendency of these membranes, which reduced the permeate quality and flux and shorten the membrane lifetime[4], [6], [7]. Recently, an emerging technology known as the vibratory sheared enhanced process (VSEP) was developed to overcome or diminish this phenomenon and stands out as a pressure-driven membrane separation technology. Fundamentally, VSEP is featured by the minimal fouling because of the created intense shear waves on the membrane surface by a vibration drive motor[8]. Such waves result in lifting solids and foulant off the membrane surface; ensuring high quality and stable permeate flux as opposed to conventional membrane systems[9]. The VSEP unit is designed as common membrane system to separate the influent (Feed) into two streams as shown in *Figure 1*; permeate (treated water) and concentrate (concentrated or waste stream). Through the membrane, the produced permeate results from the pressurized feed into the porous membrane, which is designed to allow the penetration of only water and rejecting other suspended or dissolved particles with larger molecular sizes.

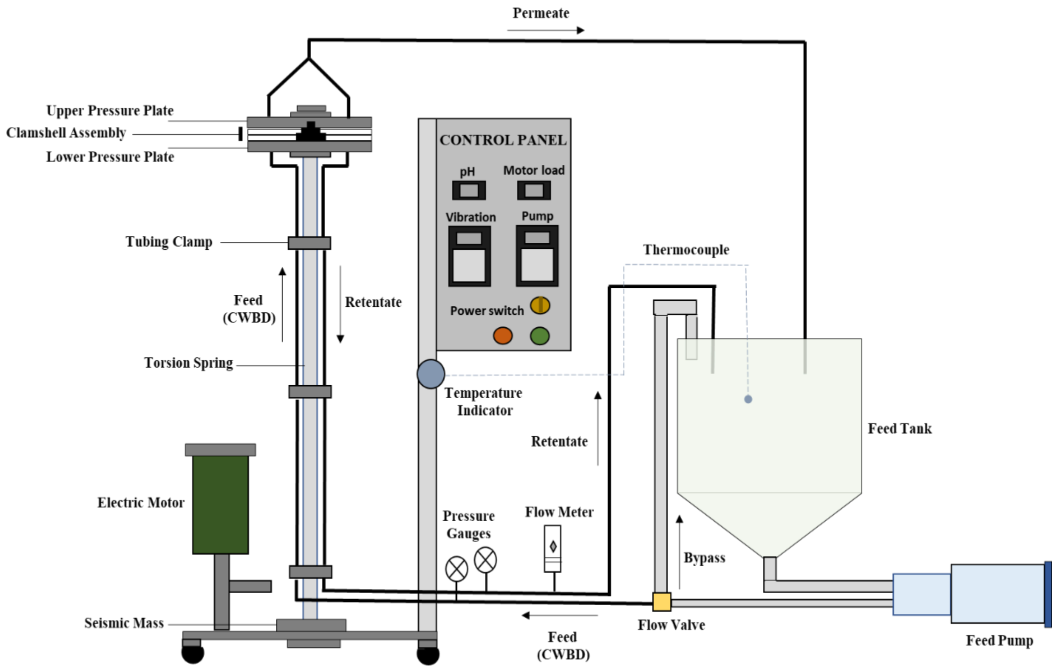


Figure 1:Vibratory Sheared Enhanced Process (VSEP) unit

The research interests in the distinctive VSEP technology are increasing in recent years because of its numerous features and advantages in addition to reducing membrane fouling. For instance, installed membrane is not limited to Reverse Osmosis (RO)[10]; Nanofiltration (NF) [11], Ultrafiltration (UF)[12], and Microfiltration (MF) [13] can be used according to the targeted constituent to be removed and desired permeate quality. Additionally, the system is compact and simple with only two moving parts [14]. Moreover, one can easily access and control various parameters such as pressure, vibration frequency, pump speed, and feed flowrate.

Although the footprint of VSEP is only 1.85 square meters[15], it provides an extremely outstanding product quality and recovery with a low concentrate volume of less than eleven liters[16]. Furthermore, according to the manufacturer company, the application of VSEP unit is not limited to the treatment of wastewater [17], however, it can be used in **Petroleum and Biofuels;** DEA recovery, drilling fluid recycling, and ethanol stillage, **Pulp and Paper;** hardboard squeezing and paper coating recycling, **Chemical Processing;** ammonium nitrate concentration, and polymer diafiltration, **Water, Food, and Beverage;** cheese whey effluent, olive oil filtration, and orange juice clarification, **Manufacturing;** catalytic converter coating recovery and coolant recovery as well as in **Mining industries;** acid mine drainage and nickel mine sulfate removal[17].

With the wide range of VSEP applications, wastewater treatment and recovery of targeted constituents are the focus in the majority of the conducted studies and the number is a substantial increase. Various research studies ensured the high performance of the VSEP in treating complex water and wastewater streams such as dairy wastewater[18]–[20], brackish and RO brine [21], [22], magnetic ion exchange process concentrate[23], NOM removal[24], produced water[25], livestock wastewater[26], landfill leachates[27], coffee products wastewater[28], [29], tannery wastewater [30] and many others[11], [13], [31]–[33].

Despite such features, the unit does not have a feed temperature controller, or an integrated feed mixer. In addition, the high-power consumption is the main drawback of this unit as it requires power for the feed pump and the vibration motor. Nevertheless, VSEP is a robust technology option for CWBD treatment in terms of wastewater volume reduction, and rejection of dissolved constituents and contaminants with a high tolerance for TDS content in the feed ranging between 1000 mg/L[10] up to 91000 mg/L[23]. In terms of power consumption, many parameters affect the required power in VSEP, such as the feed quality, the operating pressure, and vibration frequency, as well as the targeted quality and quantity of the permeate. Therefore, operating the VSEP system in an optimum mode will reduce its power consumption to be in the range of other technologies or even lower.

1.2.Research objectives

The overall target of this research study is to provide an efficient alternative and practical solution for the treatment of CWBD; seeking high-quality and stable permeate that can be recycled, reused, or even discharged safely without negatively impacting the discharge point. This can be achieved by addressing the following objectives:

i. Studying and comparing the VSEP performance in terms of permeate flux and quality (TDS removal), using different membranes (four RO ~~made~~ and two NF) made of different materials.

ii. Evaluating the effect of operating the VSEP in vibrating and nonvibrating modes on permeate flux and quality.

iii. Obtaining the optimum operating pressure for each membrane by conducting a pressure study with a pressure range between 230 psi and 500 psi.

iv. Performing concentration study to get the percentage of water recovery at optimum pressure.

v. Enhancing the performance of fouled membranes by applying a cleaning study.

vi. Studying the effect of other operating conditions such as vibration frequency.

vii. Characterizing the new and used membranes by SEM, and contact angle to check the permeability, morphology, and hydrophilicity of these membranes.

viii. Study the environmental aspect of treating CWBD and water management options.

1.3.Thesis structure

The structure of the presented thesis seeking the treatment of CWBD using VSEP technology is started with a systematic literature review in *Chapter 2*. Through this chapter, an overview of district cooling systems is performed to understand the source of the CWBD stream. It also reviews the quality of CWBD as well as its affecting parameters, and regulations to control the wastewater quality for discharging or reusing in different applications. An overview is presented on CWBD management, and the available and proposed treatment technologies, including membrane, nonmembrane-based technologies, and others. The CWBD water treatment technologies with VSEP are evaluated based on main parameters such as cost, treatment performance, permeate quality, moving parts, and others. More focus is directed toward the general working principle, advantages, disadvantages, and applications of the VSEP system. Above all, the chapter highlights the existing gap in CWBD treatment by the emerging VSEP technology.

Following that, *Chapter 3* describes the VSEP system, including the unit components and required materials, with a focus on water and membrane characterization and analytical methods. A description of the overall methodology used to address the project's previously defined objectives.

In *Chapter 4*, a discussion of the project outcomes is presented. It includes presenting the experimental results for CWBD treatment using VSEP and discussing the environmental impact of the VSEP treatment option for CWBD management.

1.4.Research Contribution

According to the literature, there are many studies that implement different technologies for CWBD treatment. For example, electrocoagulation (EC) [3], [34]–[36], membrane distillation (MD)[37], electrodialysis (ED) [38], electrochemical oxidation[39], [40], ultrafiltration (UF) [41]–[43], nanofiltration (NF) [7], reverse osmosis (RO) [4] and other technologies [44]–[47]. Among these technologies, RO can be considered the most conventional and widely used technology with good performance in terms of water quality and flux However, the high fouling tendency restricts its applications, shortens the membrane life, and increases the operating cost. Therefore, the available studies concentrated on enhancing the performance of RO technology, in respect of finding solutions to the membrane fouling issue through introducing a pretreatment technology prior to the RO system.

For example, applying a coagulation-filtration or ultrafiltration (UF) pretreatment to RO, would increase the membrane performance in terms of permeate flux and extend its lifespan. Hossein et al.[7] studied the CWBD recovery for reuse by applying polyaluminium chloride (PACl) coagulant and UF membrane. Results revealed an improvement in permeate flux by about a 25 and 33% after operating the system for 100 min in an applied pressure of 10 and 15 bar for NF and RO, respectively. Other pretreatment options such as Constructed wetlands, Powdered activated carbon (PAC) adsorption, and Microfiltration (MF) were reviewed by Ahmed et al. [4]. Regardless of the reported improvement in RO performance, these pretreatment technologies can have adverse effects and disadvantages. To illustrate, adding chemicals such as coagulants will contribute not only to the total treatment cost but might affect the quality of the process stream if the treatment targets the removal of dissolved particles. Moreover, if a membrane process is used as a pretreatment method, fouling and cleaning of the membrane should be considered, resulting in higher chemicals requirement and time to clean two membranes. Other disadvantages of applying such pretreatment options are an increase in the treatment technology footprint, and the required maintenance.

Hence, there should be an alternative to operating RO technologies in a conventional mode without the need for pre-treatment of water influent. Fortunately, an emerging technology, known as a vibratory sheared enhanced process (VSEP), was developed to overcome and minimize various problems of traditional RO. The introduction of the vibration mode, in which a shear rate is created on the membrane surface, helps to avoid any settling or accumulation of particles on the surface, resulting in high permeate flux and lower fouling. In the presented work, research studies for the first time, focus on the treatment of CWBD using VSEP technology. Through the study, various experiments are performed to validate the VSEP performance in terms of vibration effect, membrane type, operating condition, and permeate recovery. The results of the study should provide guidance to district cooling facilities, for the management of their CWBD discharge stream in an efficient and effective way. Various options and suggestions will be provided based on regulations and desired objective of the facility for managing the treated effluent. Amongst the recommendations: recycling treated CWBD as makeup water, using it in a wide range of applications; inside or outside the facility, or safely discharging it into natural water environments without causing any adverse effect to the discharge point.

1.5.Thesis outcomes

1. Soliman, M.; Eljack, F.; Kazi, M.-K.; Almomani, F.; Ahmed, E.; El Jack, Z. Treatment Technologies for Cooling Water Blowdown: A Critical Review. *Sustainability* **2022**, *14*, 376. https://doi.org/10.3390/su14010376

CHAPTER 2: LITERATURE REVIEW

2.1.Overview on district cooling systems

Energy consumption for air conditioning purposes is increasing in the world because of the rapid growth in population and industrial activities. In Qatar, 60-80% of electricity is used for air conditioning[48]. Therefore, Qatar and many other countries are continuously shifting paradigms towards the usage of district cooling (DC) plants not only to satisfy the rapidly growing demand, but to reduce both CO_2 emissions and energy consumption[48]. District cooling systems (DCS) have been developed as an essential technology because of their high effectiveness and high-quality cooling[49]. DCS are significant for areas where high density of buildings is available. The thermal energy in a form of chilled water is distributed from the central source DCS to residential, institutional, commercial, and industrial consumers for space cooling and dehumidification[49], [50]. Generally, DCS can provide major advantages over the installed conventional standalone chiller plants in industrial and commercial facilities or individual buildings. For example, DC plants offer low energy requirements than on-site cooling systems because of the high efficiency of the large-scale central water-cooled chiller plants in contrast to the on-site small-capacity air-cooled systems[2]. In addition, DCSs are efficient and provide a flexible capacity use to obey the load variability and diversity[2]. DC plants have a lower unit cost of cooling due to the lower maintenance, construction, and energy costs. Moreover, these plants help in reducing the environmental impact by minimizing the emissions and by making them easily controlled from a remote, centralized chiller plant than individual conventional cooling systems. DC systems also have the advantages of space saving at the end user location [2], [51]as well as being a reliable service because of the longer life span, advanced equipment, and on-going maintenance support and operation. In spite of these advantages, ***district cooling facilities face a problem with managing the wastewater effluent from cooling towers operation***. During the process of cooling water is continuously recirculated in the process, while some water evaporates; this leads to an increase in the concentration of salt and contaminants to high levels. As the number of recirculation cycles increases, the solubility of various solids is reduced, consequently, solids will form a shale shape on the warm surface of the condenser pipes. The formed scales in the cooling tower unit cause a reduction in the heat transfer efficiency as they insulate the metal surface of the tower[3]. With further recirculation of the concentrated water, permanent damage can occur to the cooling system[38]. Therefore, this highly concentrated water stream is discharged out of the system as a cooling water blowdown water (CWBD), which requires good management as it contains various contaminants that might affect the environment they are discharged to.

2.2.CWBD quality and affecting parameters.

As a part of the cooling processes in cooling towers, a portion of the concentrated water is discharged out of the system as CWBD to control the concentration level of different ions and compounds in the cooling tower. The type and the quantity of contaminants available in that effluent vary from one system to another and depend on many factors. Key factors include the source of the inlet and make-up water to the cooling tower as it has a great impact on the presence of various contaminants over others; and the types of chemicals used for treatment purposes, such as inhibitors or even as an anti-corrosion inside the towers, can greatly affect the composition of chemicals found in water. Stratton et al. [52]investigated the water quality parameters of the tower's blowdown and make-up water from eleven cooling systems. The results showed that the chemical composition of the water varied greatly between the cooling towers for the reasons highlighted above.

Table 1 presents the most common contaminants that can be found in CWBD stream from different recent references. Ahmed et al. [4] showed an excellent representation of the CWBD characteristics in terms of the available contaminates and their corresponding concentrations for different streams and references. Common contaminants are found in all or at least in most effluents including calcium ions, magnesium ions, and chloride (see *Table 1*). Sulphate, phosphate, iron and sodium ions, and TDS besides others can be also found in the CWBD. The noted difference in contaminants levels in the effluent streams is expected as the reported studies did not conduct full characterization analysis for all available contaminants in CWBD, and that can be due to the scope of the focus of their studies. The study of Abdel-shafy and his colleagues in their paper[3] for example was focused on the treatment of CWBD contaminents such as calcium, magnesium, and silica ions using magnesium electrodes in electrocoagulation (EC) technology; thus their analysis focus was only on these ions. Hong and other authors in a thesis project[38] focused on reducing the total dissolved solids (TDS) level in CWBD to be equivalent to tap water. Another noted difference in levels of contaminants was attributed to the cyclic concentration; and to increase the evaporation rate in cooling towers [53], [54]. The differences in rates of evaporation depending on the design and the efficiency of the tower. The quality of air passed in the cooling tower also impacts the characterization of CWBD water because air with a high amount of dust will increase the total amount of suspended solids and turbidity of the CWBD stream compared to filtered air[4].

Table 1: Common contaminants available in CWBD water.

Parameter	unit	[3]	[4], [45]	[39]	[38]****
pH		8.2	7.9	6.8±0.2	
Calcium (Ca)	mg/L	392**	1204**	338±7.6	125.9
Magnesium (Mg)	mg/L	280**	259**	58±2.4	12.5
Silica (SiO_2)	mg/L	27***	0.9		
Chloride (Cl^-)	mg/L	162	500	458±10	205.32
Zinc (Zn)	mg/L	1.2			
Phosphate (PO_4^{3-})	mg/L	6.61*	5.9		
Iron (Fe)	mg/L	0.1			0.6343
Sulphate (SO_4^{2-})	mg/L	711		1043±52	469.05
Barium (Ba)	mg/L		0.145		0.1142
Potassium (K)	mg/L			75±1.3	8.1
Sodium (Na)	mg/L			334±2.9	262.8
Strontium (Sr)	mg/L		1.500		1.0853
Bromide (Br-)	mg/L				43.35
Total Suspended Solids (TSS)	mg/L		12		
Total Dissolved Solids (TDS)	mg/L	1297			1329
Total Organic Carbon (TOC)	mg/L			41±1.3	
Chemical Oxygen Demand (COD)	mg/L			107±6.4	
Nitrate (NO3-)	mg/L		86.7	57±1.8	
CWBD water source	Effluent of a urea fertilizer plant	From a cooling tower (CT) next to the Dow premises in Terneuzen (Netherlands)	From (CT) of Dow Benelux BV	From CSULB cooling towers	

*Total phosphate as PO_4 **As $CaCO_3$ ***Silicates as SiO_2 **** Unit changed from µg/l to mg/l

2.2.1. *Contaminants of concern in CWBD and their impacts*

The effluent from the cooling tower contains a wide range and various types of contaminants that can greatly affect the environment and human life. Total dissolved solids (TDS) at high concentrations are considered as one of the major contaminants. In a standard desalination plant, 50,000 to 70,000 ppm are considered as a common range for the effluent TDS in CWBD[38], [55]. Dickerson and Vinyard [56] reported that the elevated concentrations of TDS caused the extinctions of two nonindigenous species of fish in Walker Lake, Nevada. The impact of elevated levels of TDS in water streams can cause scaling and corrosion to pipelines[38], [42], consequently affecting transport efficiency and increase maintenance costs of such systems.

Weber-Scannell et al.[57] discussed the effects of TDS on aquatic organisms and noted that discharging CWBD water with a high amount of phosphate ($PO4^{3-}$) into natural water bodies increases the growth of algae, leading to oxygen depletion in the water[58] , and eventually mortality of aquatic creatures such as fish, flora, and fauna[5].

Groundwater is a freshwater resource that can be highly impacted by high concentration of contaminants such as those found in CWBD. Ions of Sodium (Na^+), magnesium (Mg^{2+}), sulfate (SO_4^{2-}), potassium (K^+), chloride (Cl^-), calcium (Ca^{2+}) and bicarbonate (HCO_3^-) are the main inorganic ions present in natural waters, however, increasing their concentrations can cause health as well as environmental issues. For example, physical inconveniences like diarrhea, skin irritation can be caused when the groundwater is highly concentrated with sulphate[59]. Increasing the level of magnesium and calcium as a result of injecting wastewater streams such as CWBD can cause water hardness. For some developing and arid countries, groundwater is a main or only source of drinking water; thus, the presence of high concentration of these contaminants can threaten their water security. Other contaminants such as arsenic in groundwater with elevated levels can cause cancer[60], loss of limbs, or even in critical cases can lead to death[59], [61]. The drinking of fluoride-concentrated groundwater can have an adverse impact on the growth of children and at extreme concentrations, it can lead to death because of its toxicity[59]. Trace of heavy metals such as zinc, chromium, lead, nickel, silver, aluminum, copper, cadmium, and cobalt also exist naturally in groundwater and their concentrations can be increased with human activities[62], [63] consequently affecting the ecosystem as well as making groundwater unfit for humans' consumption. Zinc is considered a poisoning metal that causes skin irritations, anemia, and other infections[64]. The presence of lead in animal and human bodies impacts the synthesis process of hemoglobin that can lead to anemia and more serious problems[5]. Cadmium is toxic for organisms that live in the aquatic environment and can cause problems to the kidney and liver, while chromium can cause cancer for humans as well as skin irritation[5].

Different types of anti-corrosion chemicals such as chromates, nitrites, molybdates and tungstates [65]and biocides such as Glutaraldehyde, and Isothiazolin[66] are added to cooling towers to inhibit the growth of algae, fungi, and bacteria available in the cooling water. Some of these chemicals and compounds are toxic for all living things and the environment when they are dumped into water bodies[38]. For example, according to material safety data sheet (MSDS) of the DOW chemical company, Glutaraldehyde is moderately toxic to human and aquatic organisms and acute toxic to aquatic invertebrates as well as algae/aquatic plants[67].

By considering the impacts of CWBD contaminants, industries showed be highly aware of these adverse consequences on the environment and obey the regulated discharging limits by treating this concentrated effluent stream in an efficient way. Section 2.2.2 will discuss the regulation used to control the quality of wastewater discharged to various sinks such as the marine environment and wastewater treatment plant.

2.2.2. Regulations to control the wastewater quality for discharging or reusing.

CWBD is considered as a wastewater stream discharged from cooling towers into the marine environment, sewage treatment plants or reused in applications such as irrigation. Each of these discharge points have certain regulations and permissible limits for the water contaminants; the constraints are there to avoid negative and long-term consequences on the environment and society. *Table 2*shows standards that are regulated by the United States Environmental Protection Agency (EPA) and some GCC agencies. Each agency's standards vary depending on the endpoint or application; and there is a noticeable difference in limits between agencies for the application. For example, as shown in *Figure 2* the concentration of the pollutant by EPA for irrigation purposes differ only slightly from the one regulated by Qatar for boron, cadmium, cobalt, manganese, and zinc. However, the concentrations of aluminum, fluoride, iron, and lead are considerably different when both standards are compared. One major reason behind these differences is attributed to the type of soil; in Qatar as in many other GCC countries like UAE, the soil is sandy and that plays a role in trace metal adsorption and translocation in the soil-plant environment. The accumulation of heavy metals such as Zn, Cd, Cu, Cr, Fe, Pb in the soil will be minimal because of the high infiltration of the sandy soil, deep percolation losses as well as high evaporation rate[68]

Figure 2: Comparison of EPA and GCC Regulatory Standards (ppm) of water and wastewater for irrigation

Discharging the treated wastewater into marine environments as compared to irrigation has more stringent levels for some contaminants such as fluoride, TDS, sulphate and COD. This can be because of the negative direct impacts of these contaminants on living creatures such as fishes, flora and fauna[5]. For other contaminants such as: nickel, zinc, BOD, chromium, cobalt, manganese, the standards for irrigation are more stringent than for the marine environment. This can be attributed to the fact the levels are already small and the concentrations of these contaminants will be further diluted in the marine compared to irrigation. Comparing the standards of both UAE and Qatar, one can notice that for some contaminants such as boron, cobalt, nickel, zinc, and BOD, Qatar permits slightly higher concentrations than UAE, and lower concentrations for other contaminants like aluminum, fluoride, and iron. For Oman, almost all regulated contaminants levels are the same as UAE except for cyanide, phosphate, zinc and cadmium. In general, GCC countries have comparable limits on contaminants concentrations. Using diffusers with single or multi ports, and the depth of these diffusers determines the level of dilution for the discharged pollutants [69]. It is also known that discharging using diffusers, in general, dilutes the contaminants more and faster compared to single point discharges [69]. The noted similarities of regulations between GCC countries for discharging to marine life can be mainly attributed to the fact that countries have limited freshwater resources, and protecting marine environment is of higher priority.

Discharging the effluent wastewater from industries into sewage treatment plants is one of the management practices performed by many countries as it can treat various wastewater streams. However, caution should be taken regarding the concentration of the contaminants influent to sewage systems because some are designed for certain types of pollutants and at a specific limited range of concentration, as it may cause various harmful consequences as previously mentioned in section 2.2.1. In *Table 2,* it was noted that the standard concentrations of contaminants influent to sewage treatment plants or sewer systems have higher tolerance compared to irrigation and marine discharging especially in terms of TDS, BOD, and COD. This is expected as treatment plants are designed to handle high concentration of contaminants that cannot be discharged to natural environments. By comparing the regulatory limits by UAE and Qatar for discharge into foul sewage network, one can notice that these limits are determined predominantly by the wastewater treatment plant technologies, hence variations in the regulatory limits are expected between the two countries. Qatar has regulatory limits for wastewater generated by public and for industrially generated wastewater for discharge in WWTP. TDS limits are regulated at 4000 ppm for public or residential wastewater; however, no set limits are found for industrial wastewater, according to Qatar's Law 30 of 2002. One the other hand, UAE has changed their TDS limits to sewage network from 3000 ppm to 6000 ppm in 2012 [70], [71]. They noted that the TDS level increase when using direct TSE in cooling towers vs. polished water. Hence, they found a need to increase the regulatory limit as no harmful impact on WWTP is found.

Regarding the regulation related to CWBD discharge, there is no certain restricted regulation as it can be treated as a type of wastewater, however, EPA regulates the discharges of non-contact cooling water. The EPA water quality standards for non-contact cooling water discharge include pH and Temperature and total residual chlorine [72] Each state in the United States has its own regulatory limits for non-contact cooling water discharge. The definition of non-contact cooling water is "water used to reduce temperature for the purpose of cooling. Such waters do not come into direct contact with any raw material, intermediate product (other than heat) or finished product"[73]. And each state has its own standards. It is noted that by looking at Rhod Island, New Hampshire and South Carolina regulations and specifically discharge to saltwater bodies, it is found that metallic ions have maximum discharge limits in addition to the pH, water Temperature and total residual chlorine [72]–[74]. No limitations are set on TDS. And for chemical additives, only those used for biological treatment are prohibited. Other non-toxic additives such as ant-scaling and anti-corrosive are allowed to be discharge to salt water marine bodies [72]. Some of the findings of the literature search are presented below. Please see the following references for more details [72]–[74]. In terms of the **water treatment additive**s, consider those used to control corrosion or scale formation. If these additives are non-toxic then there is no harm on water systems (marine life). Additives used to control biological growth in such cooling systems are prohibited due to their inherent toxicity to aquatic life. “ permit does not allow for the addition of any chemical for any purpose to the non-contact cooling water **except** for non-toxic neutralization chemicals”[72]

Generally, treatment and management of CWBD are necessary; and the suitable options in terms of treatment depend on desired effluent quality. This quality is dictated by the end point of discharge or treated water application as regulated by standards of the country as has been presented and discussed in this work.

Table 2 Standards and regulations of treated wastewater streams for discharging or reusing.

	Standards of water and wastewater for Irrigation			Standards of discharging into Marine				Standards of discharging liquid waste to public foul sewage networks		
Parameter	EPA Irrigation ppm [75]	Qatar Irrigation ppm [76]	UAE Drip Irrigation(Dubai) ppm [70]	UAE ppm [77]	Qatar Discharges ppm [26], [27]	Oman Ppm [78]	Discharge to Saltwater Aquatic life (max ppm) [73], [74]	Qatar liquid waste for treatment by public sewage work [76]	Qatar Industrial effluent discharged to sewers ppm [76]	UAE (Dubai) wastewater to sewage network[70], [71]
Aluminium	5.0	15	2	20	3			30	-	-
Arsenic	0.10	0.1	0.05	0.05	-	0.05	0.069	5	5	0.5
Beryllium	0.10	-	0.1	0.05	-			5	-	
Boron	0.75	1.5	2	1	1.5			-	-	2
Cadmium	0.01	0.05	0.01	0.05	0.05	0.50	0.033	2	10	0.3
Chromium	0.1	0.01	0.1	0.2	0.2		1.1	5	2	1.0
Cobalt	0.05	0.2	0.1	0.2	2			-	-	-
Copper	0.2	0.2	0.2	0.5	0.5	0.50	0.0058	5	4	1
Fluoride	1	15	1	10	1			-	-	-
Iron	5	1	2	2	1	2.0		25	-	-
Lead	5	0.1	0.5	0.1	0.1	0.10	0.22	5	5	1
Lithium	2.5	-		-	-			-	-	-
Manganese	0.2	0.05	0.2	0.2	0.2			-	-	-
Molybdenum	0.01	-	0.01	-	-			-	-	-
Nickel	0.2	0.2	0.2	0.1	0.5	0.10	0.075	5	-	1
Selenium	0.02	-	0.02	0.02	0.02	0.02	0.29	-	-	-
Zinc	2	0.5	0.5	0.5	2	0.10	0.095	10	4	2
TDS	-	2000	1500	-	1500	-		4000	-	3000 – 6000
Sulphate	-	400	200	-	0.1			1000	1000	500
Phosphate as P (PO43-)	-	30		2	2	0.10		-	-	

2.3.Overview on CWBD management

2.3.1. Recycling or reusing of CWBD in different applications.

As a type of wastewater, various countries are dealing with CWBD as a source of water that can be reused in various applications or recycled back to the cooling system. The recycling of CWBD is highly limited because of it is concentrated with hardness ions that will cause scaling to the cooling facilities, consequently, affect the cooling performance and plants lifetime.

Using wastewater and CWBD as an example for irrigation applications is commonly applied in many countries as it can reduce the water scarcity problem[79]. However, the effect of available contaminates in such streams should be considered since they can contaminate soil and crops with lasting impacts on the whole biological chain[80]. Ingestion of such food can result in accumulated levels of contaminants that lead to many of the above-mentioned diseases[79], [81].

Aside from the direct usage of wastewater, some facilities discharge it to sewers to be treated in sewage treatment plants. The design of the treatment system differs based on the type of the sewage. The availability of grit chambers, screens, sedimentation tanks, and other units will greatly affect the treatment ability of the sewage treatment plants in terms of many aspects[82]. The efficiency, maintenance costs, and the penetration of some contaminants with the effluent water could be some of the impacts of industrial wastewater on the sewage treatment plants that can adversely affect the environment. The Sewage treatment systems are designed based on technologies that can handle certain types and concentrations of contaminants and variations can lead to the formation of undesired products or damage to the system.

Considering the environmental, health, and operational undesirable impacts of CWBD contaminants on different water systems, there is a need to consider water treatment technologies as means of managing CWBD. The following sections of the paper, present reviews of existing technologies and evaluate them based on their technical, environmental, and economic performance.

2.3.2. Treatment of CWBD

The technologies that will be reviewed in this section are extensively implemented for the treatment of wastewater, and CWBD as a type of wastewater. There are many pre-treatment processes used for CWBD water that can screen solids and remove other contaminants to reduce the load on the major treatment technologies, which are used to remove dissolved contaminants, suspended solids, etc., however, the focus here will be on the treatment processes, which were found to be applicable and suitable for CWBD treatment based on conducted studies and literature, the technologies are presented in *Figure 3*. Non-membrane-based technologies include EC and BSF, while membrane-based technologies are MD, ED, RO, and NF. All these technologies and others will be reviewed in this section, then evaluated based on their ability for removal of contaminants, maintenance requirement and other factors.

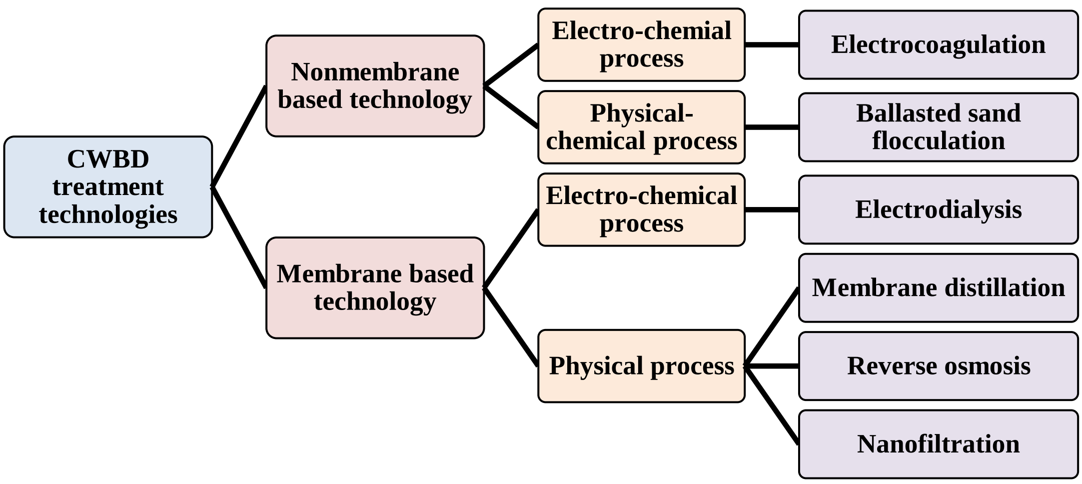


Figure 3:A summary of CWBD treatment technologies.

Membrane based technologies.

Membrane-based technologies are used to separate contaminants out of various streams such as wastewater. These processes do not require the addition of chemicals, have relatively low energy and can be used and operated easily[83]. The principle of membrane processes is mainly based on the semi-permeable membranes that act as a filter that allows water to flow through and catch other contaminants. Substances can penetrate through the membrane under certain conditions such as high pressure and the presence of electric potential[83]. Although the working principle is common between the membrane technologies, several differences make these technologies unique, major differences will be highlighted in the following sections for each process.

Electrodialysis process (ED)

The electrodialysis process for the treatment of Cooling water blowdown is an electrochemical[38] and membrane-based process. Ions in this process are transported and separated selectively by electrical field across several ion-exchange membranes[84]. At the end of the process, the concentration of ions increases in the concentrate compartment and decreases in the dilute compartment[38]. Further information about ED in the food, nutraceutical, beverage industries and other industrial and municipal wastewater industries and designs are covered within these references[84], [85]. Hong et.al[38] reported the usage of ED process for the treatment and removal of TDS and other contaminants from CWBD efficiently. Major outcomes showed the ability of ED in a two chambered cell to reduce TDS by 91.3%, 84.6%, 83.7% and 93.4%, for trial 1, 2, 3, and 4 respectively. Additionally, ED had the ability to reduce the sulfate content in CWBD by 96% for each sample, reduce chloride for all samples by 91.9% and an average removal of sodium and calcium 93.8% and 95.7% respectively.

Membrane or thermal membrane distillation (MD or TMD)

Membrane distillation is another membrane-based separation and physical technology used for the treatment of solutions that contain mainly water such as CWBD. In MD, there is a direct contact between the aqueous solution and the microporous membrane, which is hydrophobic, at least from one side of that membrane[86]. MD is a thermally driven membrane[37], where the temperature difference between the two sides of the membrane induces a partial pressure gradient that leads to mass transfer of molecules through the pores of the membrane[37], [86]. More well represented and reviewed details about this process can be found in the following papers[37], [86]–[89]. For CWBD treatment, MD can utilize the waste heat from cooling towers in the process to create the temperature and pressure gradient as the driving force for the separation[37], [90]. Koeman-Stein et.al [37] studied the potential of MD for desalination of CWBD. Concentrating CWBD by a 4.5 factor, whereas maintaining a flux of approximately 2 l/m^2 *h was achievable with a 78% water recovery for reuse. Additionally, a sever decrease in flux occurred at higher concentration factors because of scaling phenomena. Advantages from that study were the possibility of cooling capacity reduction and a 37% total reduction of make-up water, as well as minimization of greenhouse gas emissions, chemicals demand, and energy. Ma et.al [90] investigated the possibility of reducing fresh water consumption of cooling systems by using thermal membrane distillation (TMD) to treat CWBD, then recycling the permeate back to tower as makeup water. Results show that optimization model can get up to 29.4% cut on freshwater consumption compared to the system without a recovery of wastewater. Moreover, 99% of the salt in the feed can be removed by MD, leading to almost a zero-salt concentration of permeate water.

Reverse Osmosis (RO)

Reverse osmosis (RO) is one of the commonly used membrane-based technologies to treat wastewater streams effluent from different industrial processes as well as other sectors. This technology can be implemented to treat CWBD and usually requires a pre-treatment process to limit and reduce the membrane fouling as reviewed and studied in the literature [45], [91], [92] . RO is a membrane desalination process driven by pressure, where a semipermeable membrane is used to allow only water to penetrate, leaving behind the dissolved ions and salt. Several pre-treatment processes have been reviewed by Ahmed et al.[4]; they include constructed wetlands, coagulation settling and filtration, microfiltration, powdered activated carbon (PAC) adsorption, and ultrafiltration (UF). The result out of the review showed that physico-chemical processes are practical for CWBD pre-treatment. Among the prefiltration processes, ultrafiltration is the most popular option; however, MF can be a better alternative to UF. Löwenberg et al.[45] conducted experiments and investigated the suitability of using PAC adsorption, coagulation and UF as pre-treatment processes before RO for the treatment CWBD. The main output of this study showed that coupling PAC with UF is the best combination as a pre-treatment process to enhance the performance of the RO process. In another study, Hossein et al.[7] investigated the suitability of coagulation-filtration and UF as pre-treatment processes before nanofiltration (NF) and RO to treat CWBD. Results showed that both pre-treatment processes are efficient; however, UF may face fouling, hence it requires a pretreatment to overcome this issue.

Nanofiltration (NF)

It is a membrane-based technology used for the treatment of waters such as desalination of brackish water and seawater. Moreover, it can treat wastewater streams from different applications such as textile, industrial, and pharmaceutical[93]. With a pore size between 1 to 10 nm, small ions, and organic substrates can be selectively removed by NF with low consumption of energy[93]–[95]. Olariu et al.[42] mentioned that the pore size of NF membrane could be between 1 to 10 nm which is capable to remove large organics, monovalent and divalent ions. Further details about the process, the working mechanism of NF technology, and other information were well presented in the following papers[93]–[96]. NF can be implemented in industries where CWBD water requires treatment. Olariu et al. [42]used NF process as a treatment process of CWBD water in a pilot plant with other pre-treatment steps. Results showed that around 97% of salts were rejected. In addition, Hossien et al.[7] experimented as a part of their study on the effect of using RO or NF as a post-treatment process, and the results showed that both were applicable and produced a high-quality water for reuse.

Non-membrane-based technologies

Electrocoagulation process (EC)

Electrocoagulation is a non-membrane based and electrochemical separation process used to remove different types of pollutants by applying chemical and physical mechanisms[97]–[99]. The supplied electricity to the system can destabilize emulsified, dissolved, or suspended pollutants and contaminants in an aqueous medium[99]. This process can be used in many industrial applications to treat the effluents out of the processes such as in manufacturing[100] and petrochemical industries[101]. It is used to remove contaminants such as hardness ions[102], nickel[103], iron[104], chromium[105], fluoride[106], and phosphate[107]. More description of the mechanisms used in the process and the reaction are available in the following references[99], [108]–[110]. Recently, El-khateeb et al [3]studied the possibility of using magnesium rod-electrodes in EC process to treat the effluent stream blowdown from cooling towers and results showed that the system was able to remove hardness ions and silica with efficiencies of 51.80 and 93.70% respectively. Hafez et.al [35] investigated the effect of EC using Iron(Fe), aluminum (Al), and Zinc(Zn) electrodes for removing dissolved silica and hardness ions from CWBD. Results showed that at the optimum operational conditions, the removal efficiency of Al-electrode for scale forming species from CWBD was higher than both Fe and Zn electrodes. Zn, Fe, and Al, electrodes removed 95.62% and 38.63%, 98.93% and 36.99%, as well as 99.54% and 55.36% for the silica ions and total hardness respectively. Answer et.al [34] studied the performance of EC using (Al) electrodes with Monopolar- parallel (MP-P), and bipolar – series (BP-S) arrangement for simultaneous removal of hardness ions (calcium, and magnesium) and dissolved silica from synthetic CWBD. The obtained results evidence that BP-S is the best for both electrodes' configuration with the removal of 60 %, 97% and 98% for calcium, magnesium and silica, respectively through 30 min of treatment at a current density of 1mA/cm^2 and pH=10. Martin et.al [36] carried out a study about the impact of water quality on the removal of dissolved silica using electrocoagulation technology with aluminum electrodes. Results showed that treatment of CWBD resulted in the ratio mgl^{-1} Al^{3+} dosed /mgl^{-1} silica removed of 0.85 ± 0.1. Additionally, the consumed cost of chemicals, energy and electrodes was about US$0.53 m^{-3} for treatment of CWBD. Liao et. al [111] investigated the effectiveness of EC using Al and Fe electrodes for treating CWBD containing Ca^{2+}, Mg^{2+} and dissolved silica ($Si(OH)_4$). For coagulant doses ≤ 3 mM, the removal of silica was a linear function of the coagulant dose, for each mole of Al or Fe, a 0.4 to 0.5 moles of silica are removed. Fe electrodes were only 30% as effective at removing Mg^{2+} and Ca^{2+} as compared to Si. Moreover, outcomes of the study indicated that in the absence of organic additives, there was no clear removal of hardness ions by Al electrodes.

Ballasted sand flocculation process (BSF)

BSF is one of the physical chemical non-membrane-based processes used for the treatment of water and wastewater streams effluent from various sectors. It is capable of removing many contaminants such as total suspended solids TSS, COD, BOD, and a wide range of heavy metals[112]. BSF can be used for the treatment of urban run-off water[113], stormwater runoff[114], CWBD [115] and others. Three main processes followed in BSF technology include injection of micro-sand, coagulant, and polymer to the system, followed by a maturation process, and finally settling of the mixture and separation[112]. Further details and experimental work about BSF can be found in these references[112]–[114], [116], [117].

Other treatment technologies

Other methods were implemented for the treatment of CWBD and showed promising results. Li et.al [118] tested the treating of CWBD for the removal of organics and phosphorous by applying a hypered treatment process of adsorption and electrocatalytic oxidation to deliver an an eco-friendly treatment loop. Results of this work showed the effectiveness of polyaniline- modified TiO_2 (PANI/TiO_2) as an adsorbent for the treatment of CWBD. The removal% of total phosphorous (TP) and COD were around 90 and 55% respectively. The crystallinity and morphology of the adsorbent did not show clear change and the adsorption capacity remained stable even after 30 cycles of regeneration. Additionally, the refractory eluate with pollutants of high concentration was treated using electrocatalytic oxidation, with a COD removal of 50% after 6 h.

Saha et.al [40] studied the Removal of organic compounds from CWBD by electrochemical oxidation and emphasized on the role operational parameters and electrodes on the treatment performance. Results showed with the boron-doped diamond (BDD-anode) the removal of total organic carbon (TOC) and COD were 51 and 85% respectively; on the other hand, for mixed-metal oxide (MMO) the removal were 12 and 50% at neutral pH and a j-value of 8.7 mA cm^{-2}. Additionally, increasing the j-value helped in increasing the TOC and COD removal; however, hydrodynamic conditions, various pHs, and the addition of supporting electrolytes had a negligeable effect on the removal with both types of anodes.

Saha et.al [39]evaluated the usage of electrochemical oxidation (EO) with BDD and MMO anodes combined with a vertical flow constructed wetlands (VFCWs) for the treatment of CWBD. Results showed that specific conditioning chemicals (Ocs) such as benzotriazole were effectively removed from CWBD by VFCW. Nevertheless, the deduction of bulk Ocs in VFCWs was minimum, because of the recalcitrant humic substances available in the Ocs in CWBD. In addition, it was reported that Ocs removal was increased when EO-treatment was applied after VFCW-treatment, especially with BDD-anode.

2.3.3. Evaluation of CWBD Water Treatment Technologies

Implementing one of the previously reviewed technologies for the treatment of CWBD water is highly applicable. However, considering the most suitable, green, sustainable, and highest performance technology is the main objective targeted by industries. Before implementation, screening and evaluating suitable technologies is necessary and requires a clear definition of the performance criteria. In this section, key criteria are used to compare and assess the treatment systems for CWBD; *Table 3 and Table 4* shows a summary of the findings. The criteria considered are the scale of process; maintenance requirements; chemical requirements for the system; energy consumption; permeate (effluent) quality; sludge characteristics; and, most importantly, the ability to remove CWBD contaminants and cost.

Most of the seven technologies presented earlier were implemented in different scales, including laboratory, pilot, and commercial or industrial. However, ED and RO processes are considered one of the most established and well-known processes and are widely used[119]–[122]. NF, VSEP, BSF, and EC can be considered as emerging technologies, and this is due to limitations in their performance and cost, as is highlighted below.

Required maintenance for a system is often a factor that the industry considers. This criterion is impacted by the material used in the system, the number of moving parts, availability of membranes and associated fouling problems, and many others. EC technology requires maintenance mainly related to the periodic replacements of the electrodes used in the system [99]. It is considered a low maintenance system as compared to membrane-based technologies such as RO, ED, and NF. As some require high operating pressure and have issues with fouling. ED process has a longer membrane lifetime, and therefore maintenance will be lower than RO process [123]. Applying a pre-treatment process ahead to these technologies can reduce the fouling problems, consequently reducing the maintenance requirements. MD and VSEP processes require low maintenance; the latter is designed with a vibrating membrane to minimize fouling. The needed maintenance by VSEP is mainly associated with the few moving parts in the system [14].

The use of chemical additives in the process is an inherent part of some water treatment systems. Moreover, often, chemical treatment is required for the regeneration and cleaning of membrane-based processes such as RO and NF. In the studied water treatment systems, BSF technology requires a high quantity of chemical dosages. The optimum values are 5–150 mg/L of alum, 40–190 mg/L of $FeCl3$ (ferric chloride), 0.3–1 mg/L of polymer, and 3–12 mg/L of sand.

Energy requirements and consumption is critical aspect that affects the operational cost of the process directly impacts on the environment in terms of emission. Electricity is the main source of power used in these processes; however, in MD, most of the consumed power in the process is in terms of heat, with a small amount of electricity for running pumps [37]. Both NF(0.3–1 kWh/m^3) [124] and ED processes (depending on the level of TDS) require less energy compared to the RO process (1.5–6 kWhe/m3) [125], [126], mainly due to lower pressure requirement [127], [128]. However, increased energy requirements are observed for ED for influent streams with higher salt content [129]. VSEP requires higher energy than RO process mainly due to the need for intense shear requirements on the membrane; under the same conditions, at TDS of 500 mg/L, motor/pump efficiency of 85%, and feed water recovery of 75%, the energy required by RO is 0.7 kWh/m3. In contrast, VSEP requires 2.1 kWh/m3. In the BSF process, hydro-cyclone is used for the separation and recirculation of micro-sand back to the process, which requires high-pressure input, and consequently higher energy consumption [130]. Finally, for EC, the operation of the process depends mainly on a continuous source of electricity. However, many studies were conducted to reduce the consumption of power by using more effective electrodes or changing their configurations for lower energy, as indicated in *Table 3,and Table 4*. The alternative available for EC is to consider using of a renewable energy source such as a solar system to reduce environmental impacts from energy consumption [131].

The quality and characterization of the permeate stream (treated) and the sludge or concentrated stream (rejected with contaminants) are key factors in selecting a suitable wastewater treatment technology. EC process produces high-quality effluent with low content of TDS and has neither color nor odor. EC system removes hardness and silica ions with different types of electrodes such as Zn, Fe, and Al electrodes with a removal efficiency of 38.63% and 95.62%, 36.99% and 98.93%, and 55.36% and 99.54% for the total hardness and silica ions, respectively. Although the water quality effluent from RO process is high, ED process has a higher recovery rate in comparison. For MD process, low recovery or flux of water is produced as compared to RO process, but the salt concentration in permeate is approximately zero. NF process has stable flowrate and clean permeate as in Table 4; in fact, many industries are using the technology and some are replacing their RO process [93]. BSF is comparable to conventional processes, e.g., RO and ED, and in some cases outperforms others in terms of permeate quality [112]. VSEP is the only technology that produces a permeate stream free of solids in comparison to the studied alternatives.

In terms of sludge or the concentrated stream produced from these technologies, EC has non-toxic and low amounts of sludge with no brine formation compared to the membrane, ion-exchange, and conventional technologies [35]. On the other hand, ED produces a high amount of sludge and RO has a highly saline concentrated stream. The discharged volume and the retentate concentrations of NF process are lower as compared to RO process. For BSF process, the generated flocs can be easily eliminated. VSEP concentrated stream contains a high amount of salts (30–35%) compared to the process influent [132], [133]. Finally, the MD process rejects various types of contaminants with a very high percentage close to 100% to form a concentrated stream of non-volatile compounds, macromolecules, and inorganic ions.

Table 3: Evaluation of the treatment technologies according to the selected criteria.

Criteria	Electrocoagulation (EC)	Electrodialysis (ED)	Membrane Distillation (MD)	Ballasted Sand Flocculation (BSF)	Reverse Osmosis (RO)	Nanofiltration (NF)	Vibratory Sheared Enhanced Membrane Process (VSEP)
Process scale	All levels [110]	Large-scale [122]	Pilot scale, large scale are implemented mostly in desalination process [89]	Pilot and large-scale [112]	Large-scale [91]	Implemented in large scale for coking wastewater treatment [134]; Pilot scale implementation for rubber wastewater	Large-scale VSEP as a recovery system for CWBD water in several facilities such as gas production, coal gas-fired power plant, and biomass plants [135], [136]
Maintenance	Low [137]	Maintenance and the cost of maintenance associated only with the membrane [138]. Low maintenance [139]	Low [140]	High maintenance Required for example for the hydro-cyclone [141], [142]	High maintenance requirement due to fouling [45]; Low maintenance if pre-treatment process is used [143]	Low maintenance if pre-treatment process is used [143]	Low maintenance because system has few moving parts [14]
Chemicals additives to the process	None [35]	None [84], [144]	None [89]	Require high amount of chemicals, e.g., Alum and FeCl3 compared to traditional processes [112]	None [145]; Requires chemicals for membrane cleaning to prevent fouling [146]	None [147] [147][147]	None [14]

Table 4: Evaluation of the treatment technologies according to the selected criteria.

Criteria	Electrocoagulation (EC)	Electrodialysis (ED)	Membrane Distillation (MD)	Ballasted Sand Flocculation (BSF)	Reverse Osmosis (RO)	Nanofiltration (NF)	(VSEP)
Utility and energy requirements	0.18–3.05 kWh/m3 with magnesium electrodes for CWBD treatment [3]; Requires electricity [35]; Al electrode and monopolar-parallel connection, the energy consumption is less compared to bipolar-series [34]	From 1.1 to 2.9 kWh/m3 for the treatment of almond industry wastewater; Requires a source of electricity; Less energy intensive compared to RO and thermal processes [138]; A lot of electricity is consumed in case of high level of salt in the influent stream [129];	Required energy is mainly in form of heat, and with a small amount of electricity for pumps [37]; The process requires high energy [86], [148]	High energy for hydro-cyclone [130]	Relative: energy demand increases as a result of the fouling issue [45]	Less energy compared to RO process [128]	With same conditions, the energy consumption of VSEP process is three times higher than RO process [10]
The quality of permeate (effluent water)	Low content of TDS, odorless, and colorless effluent [34]	Higher water recovery rate than effluent from RO process [148]; Requires post-treatment to remove the remaining sludge [34]	Low water recovery [148] ; Low permeate flux compared to RO process [149]; Low (salt concentration near zero) [90]	Comparable quality to conventional treatment technologies [112]	High quality [150]	Produce clean, high-quality water, and the permeate has a stable flowrate [95], [151]	High quality [84], [152]; Solid-free permeate [14]
The sludge quality (rejection)	Low sludge discharge, stable, and non-toxic [35], [153] ; Sludge contains mainly metallic oxides/hydroxides [34]	High sludge discharge [34]	Non-volatile compounds, macromolecules, and inorganic ions are all highly rejected from the water stream to the sludge with (99–100%) and the separation theoretically can reach 100% [154]–[156]	Flocs easily eliminated by settling [112]; Sludge layer is distinct, clear, and supernatant [116]	A concentrated stream with high salinity [157]	Low discharge sludge [157]; Retentate concentrations lower than RO for low value salts in the influent stream [147]; Rejection efficacy altered when fouling occurs [93]	Concentrated waste stream with 30 to 35% total solids (higher than the feed) [132], [133]

Contaminant removal effectiveness of the technology is a top criterion in selecting the CWBD treatment system. The literature has presented the removal and treatment capability of EC, ED, and MD processes for several contaminates in CWBD stream. It is important to clarify that the conducted experiments by EC and ED processes analyzed the removal or reducing levels of targeted contaminants such as magnesium, calcium, and silica for EC and reducing the level of TDS for ED. Hence, the results presented in *Table 5* reflect the published data on the ability of the technology to remove contaminants and do not reflect the technology's ability to remove all the other contaminants in *Table 1*. As shown in *Table 5*, all three methods (ED, EC, MD) can remove major common contaminants in CWBD streams such as calcium, magnesium, chloride, and sulphate. TDS, which is considered one of the crucial contaminants of concern, can be removed by both EC and ED processes. According to the literature, only EC is reported to remove silica, zinc, and phosphate, and only MD is reported to remove copper and manganese. Additionally, ED can remove bromides and fluorine ions from CWBD water. Moreover, sodium and potassium can be removed using ED and MD, but Fe can be removed only by EC and MD. The removal efficiency differs for each technology, and it depends on the concentration of the feed and the operating conditions as reported by the authors of that literature.

The applicability for the treatment of CWBD streams using BSF, RO, NF, and VSEP technologies has been reported in the literature, even though there is a lack of published experimental data related to the specific contaminants that can be removed by these systems [4], [7], [45], [136]. Reference [115] discussed the fact that the BSF process can be used for the CWBD effluent treatment, and Ahmed et al. [4] studied the potential for CWBD water recovery by reverse osmosis, discussing the fouling parameters as well as implemented various pre-treatment processes ahead of RO. Löwenberg et al. [45] conducted experimental work to evaluate various pre-treatment processes before applying RO as the final treatment step for CWBD. For NF and RO, Hossein et al. [7] also studied reusing CWBD after recovering it by NF or RO processes and investigated various pre-treatment steps to control fouling problems. As an emerging technology, VSEP technology website [136] reported that this process could reduce the volume of CWBD stream for either disposal or recycling it back to the cooling towers on the basis of pilot plant data.

In general, the reviewed technologies can remove a wide range of contaminants from many water and wastewater streams. For example, RO can remove almost all contaminants of concern such as TDS, ammonia (as N), iron, lead, nitrate (as N), sulphate, chloride, phosphate, calcium, magnesium, and others [158], [159]. BSF can remove TP, TSS, iron, lead, zinc, etc. [112]. NF process can remove iron, manganese, calcium, magnesium, fluoride, sulphate, and more [160]. For VSEP technology, TDS, chloride, sulphate, calcium, magnesium, fluoride, nitrate, and others can be removed [10].

Table 5:The contaminants that can be removed by CWBD treatment technologies.

Contaminants	CWBD Treatment Technologies		
	EC [3]	**ED** [138]	**MD** [37]
Total dissolved Solids (TDS)	√	√	
Calcium (Ca^{2+})	√	√	√
Magnesium (Mg^{2+})	√	√	√
Silica (SiO_2)	√		
Chloride (Cl^-)	√	√	√
Zinc (Zn^{2+})	√		
Phosphate (PO_4^{3-})	√		
Iron (Fe^{2+})	√		√
Sulphate (SO_4^{2-})	√	√	√
Aluminium (Al^{3+})			
Barium (Ba^{2+})			
Potassium (K^+)		√	√
Sodium (Na^+)		√	√
Copper (Cu)			√
Strontium (Sr^{2+})			
Bromide (Br^-)		√	
Fluorine (F)		√	
Manganese (Mn^{2+})			√
Nitrate (NO^{3-})			

Conducting a cost analysis is another criterion to evaluate the technologies since the economic aspect should be justified and viable. Table 6 summarizes the operational and capital costs of the treatment technologies on the basis of color-coding. EC and MD technologies have low capital and operating costs, and consequently, lower total costs. The operating cost of EC process is mainly attributed to the fact that the power consumption in the form of electricity is high since it is one of the major requirements for the system to run and remove contaminants. For MD technology, it contains various designs and configurations for that the cost differs. For example, Air Gap membrane distillation (AGMD) is considered an effective method compared to others as it has how operational and maintenance costs. For the capital cost, MD generally has a lower capital cost than reverse osmosis, and such lower costs make the total cost low. Moving to RO and VSEP technologies requires high capital and operating costs, hence relatively high overall total cost. The high operational cost of RO process can be attributed to the fouling problems that shorten the membrane's lifetime and requires replacing it; moreover, the RO process operates at high pressure, which consumes high energy, leading to a higher cost of operation. For the emerging technology VSEP, the high operational cost is because of the high energy requirements to generate shear and vibrating the membrane. Subramani et al. [10] reported out of the conducted study that the consumption of energy by VSEP process is three times (2.1 kWh/m3) higher than RO process (0.7 kWh/m3), reaching more than 10 years, all of which contribute to lowering the operational cost [123]. However, ED has a high capital cost, which makes the total cost at a moderate level. The BSF process has a higher operational cost than conventional or traditional processes, and this can be said to be mainly due to the high dosages of chemicals needed for the process [112]. On the other hand, for the capital cost, BSF requires smaller sedimentation units because it has high settling rates; additionally, the BSF requires less land size, and hence lower capital cost, leading to a moderate total cost. For NF, which is another membrane-based technology, the process operates at low pressure and requires less energy consumption; hence, it has low operational costs. However, for the capital cost, the implementation of NF technology at large scales causes the capital cost to be high, which limits NF applications for treatment purposes in industries and makes the total cost relatively moderate. In the end, the total cost depends on many factors such as the size of the plant, the concentration of the influent stream, and the maintenance and energy requirements. Reducing the total cost can be done by enhancing the treatment technology by using efficient material with low cost, running the system at optimum operating parameters, and unitizing renewable sources of energy instead of a direct source of power.

Table 6:Cost analysis of CWBD treatment technologies.

	EC	**ED**	**MD**	**BSF**	**RO**	**NF**	**VSEP**
Operational cost	Green	Green	Green	Red	Red	Green	Red
Capital cost	Green	Red	Green	Green	Red	Red	Red
Total cost	Green	Yellow	Green	Yellow	Red	Yellow	Red
References	[161]–[163]	[162], [164]	[165], [166]	[112], [167]	[91], [162]	[168], [169]	[170]

Color coding	Meaning
Green	Low
Yellow	Moderate
Red	High

To conclude, in this review, it was noticed that membrane technologies and more specifically, RO and NF systems have high performance in terms of permeate flux and quality, however, fouling restricts their applications and shortens the membrane life.

Although applying pretreatment such as coagulation-filtration[7], constructed wetlands, Powdered activated carbon (PAC) adsorption, and Microfiltration (MF) or ultrafiltration (UF) [4] contributed to extending the membrane lifespan and performance, they also revealed several disadvantages. To illustrate, adding chemicals such as coagulants can contribute not only to the total treatment cost, but might affect the quality of the process stream. Moreover, if membrane processes were used as a pretreatment method, fouling and cleaning of these membranes should be considered, resulting in higher chemicals requirement and time to clean two membranes. Other disadvantages of applying such pretreatment options are increasing the treatment technology footprint and requiring additional maintenance. Therefore, in this study, VSEP technology was selected for the treatment of CWBD to eliminate the need for pretreatment methods, which will result in cost savings and a protected environment.

2.4.Vibratory Sheared Enhanced Membrane Process (VSEP)

In spite of the increasing popularity over the last 20 years, of membrane-based separations for the treatment of various contaminants and dissolved solids [171], this technology still faces challenges of high and rapid fouling tendency[172]. The formation of a boundary layer on the membrane surface is the main reason for the fouling; this causes a long-term loss in the throughput capacity and reduces the design selectivity as well as the flux performance of the membrane. Huertas et al. [173] tested the performance of RO and NF membranes in removing boron from a synthetic wastewater stream. Results revealed a decline in the permeate flux to less than 25% compared to the initial quantity. In order to control and decrease the buildup of the gel or boundary layer, the crossflow velocity along with the membrane module configuration should be manipulated. Therefore, a method known as crossflow filtration or tangential flow was developed by membrane designers. This technique relies on high-velocity fluid flow pumped across the membrane surface, in which, membrane parts are placed in a spiral-wound cartridge, plate-and frame, or tubular assembly, through which the sample is pumped rapidly[172]. However, in crossflow designs, creating a shear force of more than 10, 000 to15, 000 inverse seconds is not an economical choice, thereby restricting the use of cross-flow to fluids with low viscosity. Moreover, a significant pressure drop from the inlet to the outlet might occur in case of elevated cross-flow velocities, resulting in premature fouling of the membrane and reduced permeate flowrate to an unacceptable level [172].

For the past few years, an alternative technique of generating intense shear waves on the membrane surface was developed by the New Logic Research company as a solution to fouling. This method is known as Vibratory Shear Enhanced Processing (VSEP).

2.4.1. VSEP background

VSEP is considered as emerging technology, where the feed slurry remains almost stationary, going in a leisurely, twisting flow between membrane leaf elements[16]. The vigorous vibration of the leaf elements causes the shear cleaning action in a way tangent to membrane faces[16].

Introducing vibration at the exact needed position on the membrane surface helps in reducing the tendency of the formation of undesired layers and in having a consistent flux[15], [16]. This technology can provide effective treatment solutions in many applications if the

appropriate type of material and membrane were selected. In typical VSEP units, the used membranes are arranged in a plate and frame configuration as shown in *Figure 4*.

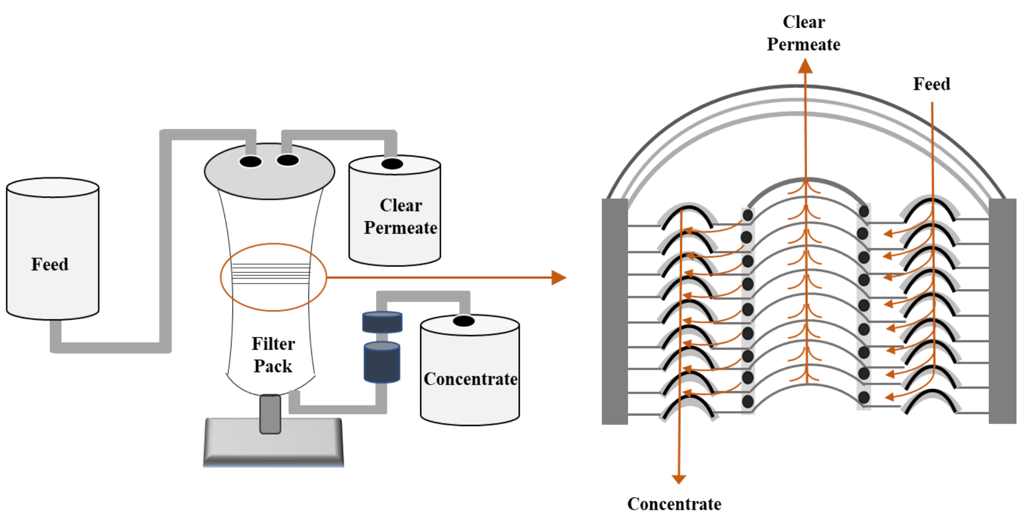


Figure 4: Plate and frame configuration in the filter pack of VSEP.

The VSEP system needs a series of studies or tests such as membrane selection, pressure, and concentration studies to determine the best-suited membrane material and conditions to achieve a very stable flux for the considered feed water quality.

A patented resonating drive system (shown in Figure 5) is the core of the VSEP unit as it attains a high energy efficiency by creating a shear into a thin zone close to the filter surface[16].

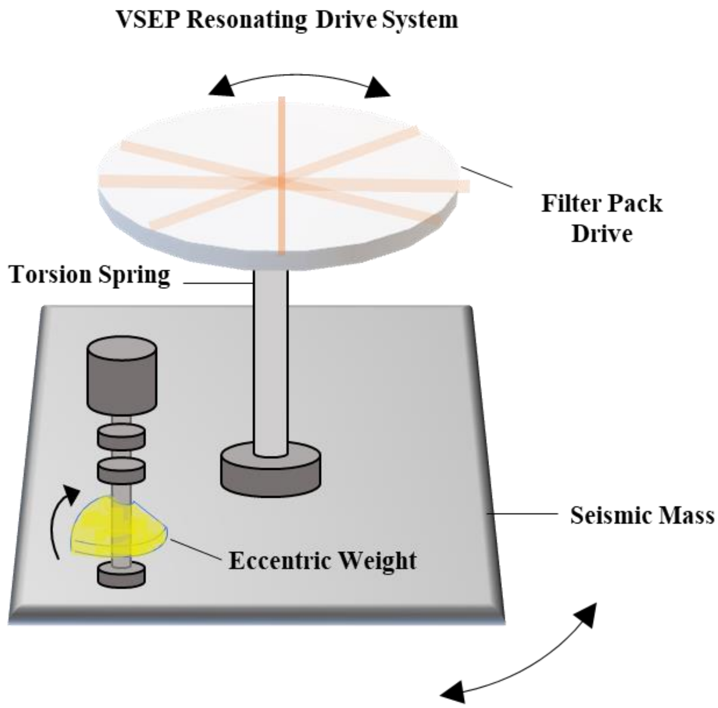


Figure 5: Resonating drive system in VSEP.

The produced shear waves by the vibration of the membrane cause foulant and solids to be lifted off the surface of the membrane [16], [25], [174] as shown in

Figure 6. This behavior is opposite to the conventional membrane systems, where membrane pores get blocked with the accumulated particles that result in shortening membrane life[175], [176]. Because of the independency of VSEP on feed flow-induced shearing forces, the extremely viscous slurry feed can be dewatered easily[15]. The concentrate stream is forced out between the elements of the vibratory disc and leaves the VSEP once it reaches the desired concentration level. Therefore, VSEP can be run in a single pass through the unit, eliminating the demand for associated valving, ancillary equipment, and costly working tanks [16]. VSEP technology uses different types of

membranes and materials, and this makes the technology a great choice for a wide range of water treatment applications as will be discussed in section 2.4.5.

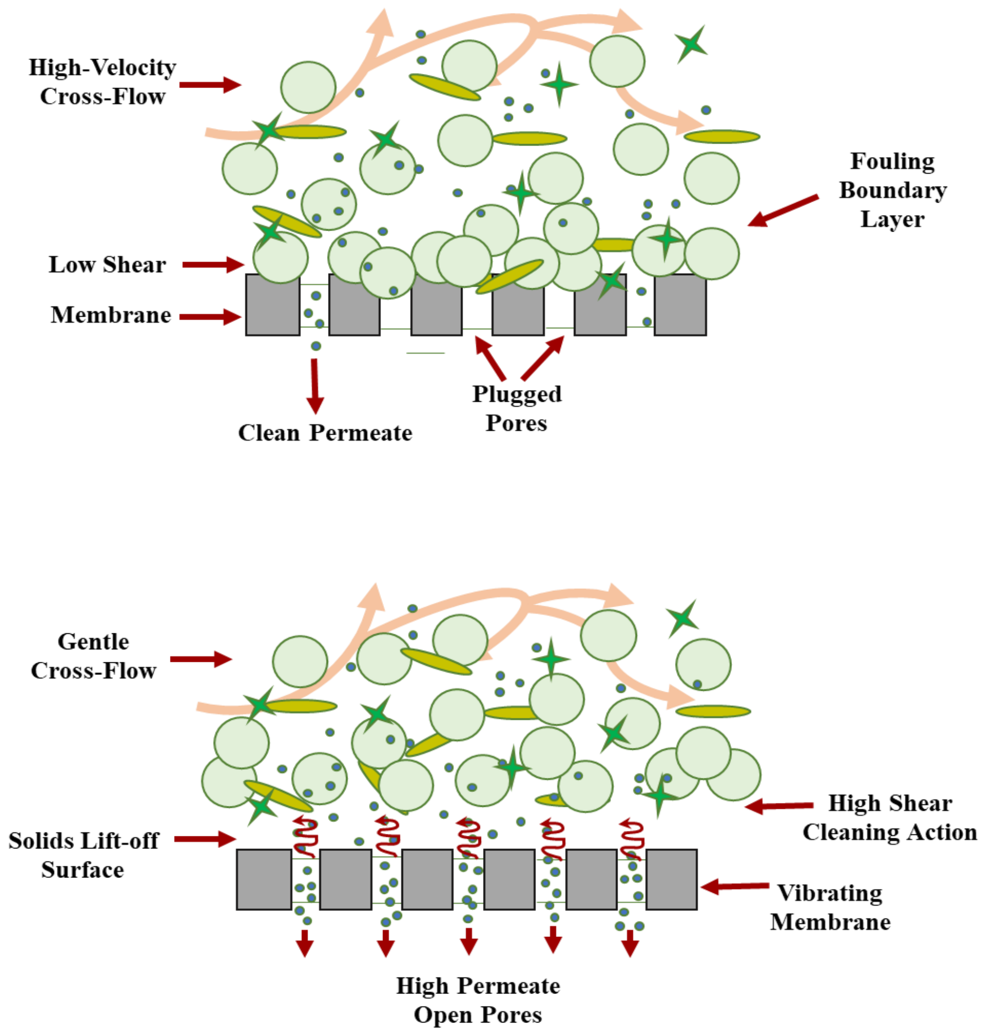


Figure 6: Foulants behavior corresponding to crossflow in a) conventional and b) VSEP systems.

2.4.2. VSEP membrane types

The applied membranes in VSEP technology are manufactured from different types of polymers including, polyamides, polyethersulfone, and other thin film composites[177]. According to the manufacturer company, over 200 various membrane types are employed and used in the VSEP units. Fundamentally, membranes are designed to allow certain constituents to pass through and reject undesirable pollutants[178]. Therefore, any inlet feed stream to the VSEP system will be separated into two streams; the permeate with clean water and a concentrate that can have desired materials in case of product recovery or a concentrated slurry of contaminants as in wastewater treatment processes. The VSEP system can be operated with the four basic categories of membranes as discussed below:

- Microfiltration (MF) (0.1µ - 2.0µ)
- Ultrafiltration (UF) (0.008 µ - 0.1 µ)
- Nanofiltration (0.001µ – 0.01µ)
- Reverse Osmosis (RO) (30 Daltons – 0.001µ)
- Microfiltration (MF) (0.1µ - 2.0µ)

In VSEP units, the majority of the used microfilters are made of PTFE (Teflon) [177]. MF membranes are designed to remove targeted constituents or pollutants such as large colloidal particles, most bacteria, small, suspended solids, and some emulsions[179]. These are not capable of rejecting or holding back any dissolved solids because of the large pore sizes[180]. MF membranes are useful in various applications, mainly in dewatering slurries like calcium carbonate and titanium dioxide[177]. Compared to other membrane types, Teflon MF membranes are considered the most robust as they are chemically inert, can handle an elevated temperature of 130 ℃, and withstand pH levels of 0-14[177]. Usually, MF membranes operate a pressure range between around 2 to 7 bar (30 to 100 psi).

Ultrafiltration (UF) (0.008 µ - 0.1 µ)

This type of membrane has a smaller pore size compared to MF and it is being used in a wide range of VSEP applications to completely hold back 100% of the suspended solids[177]. In VSEPs, UF membranes can be used without chemicals to break emulsions. Such membranes can also remove large organics such as colloids, pyrogens, proteins, and bacteria[181]. The employed UF membranes in VSEP units include regenerated cellulose, PVDF, and polyethersulfone[177]. These membranes can operate at different conditions depending on the application and configuration. They have a pH tolerance range from 1 to 14, work at a pressure between around 2 to 14 bar (30 - 250 psi), and have an upper-temperature level of approximately 90℃[177].

Nanofiltration (0.001µ – 0.01µ)

Nanofiltration (NF) is an emerging and semi-permeable membrane fabricated of different composites such as polyamides, sulfonated sulfone, and other thin film materials[177]. These membranes can be used for the removal of numerous dissolved materials, and organics[182]. NF can be applied as a pretreatment step to RO or RO VSEP and the resulting permeate will be "soft" water[177], [183]. Moreover, many wastewater streams, such as dairy effluent, can be treated using NF membranes to remove biochemical oxygen demand (BOD)[184]. The operating pressure of NF membranes can range between 14 to 41 bar (200 to 600 psi) and can handle a pH range from 1 to 14[177].

Reverse Osmosis (RO) (30 Daltons – 0.001µ)

RO membranes are considered the tightest of all other types that are commonly used in seawater desalination processes. These membranes are constructed to hold back dissolved solids such as sodium chloride[185], [186]. For instance, when RO is applied, around 99.5% of NaCl can be rejected from seawater desalination units[177]. In a single unit operation in VSEP systems, RO is generally applied to remove traces of metals, organics as well as traces of oil[187]–[189]. In some industrial applications, RO membranes have been maligned because of their fouling tendency. VSEP however, mitigates such a problem by introducing the vibration to the system, hence opening the door to various applications, in which the removal of contaminants of low molecular weight is crucial. Recent VSEP' RO membranes are constructed of polyamide, TFC polyamide, or composite polyamide. Such membranes can operate at a pressure of 21 to 69 bar (300 to 1000 psi) and can withstand a pH range between 2 to 12. *Table 7* below summarized the key parameters of the four types of membranes [177].

Table 7: VSEP membranes (According to New Logic Research company)

Membranes	**Pore size MWCO**	**Membrane compositions**	**Clean water pH tolerance**	**Temperature tolerance (ºC)**	**Chlorine tolerance**	**Pressure range (psi)**	**Example of targeted constituents****
Microfiltration (MF)	0.05 µm to 1.73 mm	Polyethersulfone, PTFE on Polypropylene (PP)/ polyester (PE), Teflon on Rigid Polyester, and others	1 to 14*	80 to 200*	No effect	35-80	Large colloidal particles, most bacteria, small, suspended solids, and some emulsions
Ultrafiltration (UF)	1400Da to 150,000Da	Proprietary TFC, Polyethersulfone, Polyethersulfone on PP, Polyethersulfone on PE, and Kynar PVDF	0 to 14*	50 to 90*	20 to 500ppm*	35-150*	Suspended solids, large organics such as colloids, pyrogens, proteins, and bacteria.
Nanofiltration (NF)	150 to 800Da	Proprietary TFC, Polypiperzinamide/PES/Polyester, Composite Polyamide, Thin-film Non-polyamide, Polyethersulfone	1 to 12*	45 to 90*	0 to 500 ppm*	100 to 1000	Various dissolved materials and organics
Reverse Osmosis (RO)	30 to 45Da	Composite Polyamide, Polyamide, and TFC Polyamide	1 to 12	60 to 70	0 to 0.1 ppm*	100 to 1000	Dissolved solids such as sodium chloride

* Varies based on membrane material and pore size from the vendor

** Not limited to these constituents

2.4.3. VSEP Performance and Engineering features

Performance advantages

VSEP unit has numerous features that make it an outstanding technology in wastewater treatment. It maintains the filter or membrane surface clean because of the generated intense shear waves that are about ten times higher than the rates of the crossflow filtration systems (approximately 150,000 inverse seconds), hence increasing the fouling resistance [190]. Importantly, the specific and accurate application of shear leads to very low power consumption and efficient energy conversion. In VSEP, almost all of the energy input to the system (99%) is converted to shear at the surface of the membrane compared to conventional crossflow filtration systems, where only around 10% of the total energy is converted on the membranes as a shear[15], [191] Cost wise, VSEP is considered as one of the lowest cost systems of its types for various reasons including, high efficiency that lowers the operating cost, less fouling, limited cleaning and membrane replacement, compact configuration, savings in space required during installation, and high flux rates; high output capacity per dollar of the invested capital[190].

Engineering advantages

VSEP is a closed, simple, and compact system[190]. This unit will require a similar level of attention as a pump under normal conditions of operation[15]. The separation of this unit is a purely physical process. The only two moving parts in a VSEP system are the bearings that are automatically lubricated; and the torsion spring which is examined to guarantee an infinite life[15]. Moreover, uninterrupted performance is assured by the self-repair patented redundant membrane unit in case of any failure of the membrane elements.

VSEP systems have a footprint of only 1.85 square meters and can accommodate up to 185 square feet of membrane area[192]. This unit is designed in a way that can be easily expanded based on the desired application. This feature is extremely important in district cooling facilities as they can scale the unit according to the available space in the plant. An extremely high product recovery in batch processes can be achieved as the disc pack holdup volume of a unit with 130 square meters of membrane area, is lower than 190 liters. After draining the stack, the amount of the effluent waste stream is lower than eleven liters, achieving almost 95% volume reduction[193]. This is advantageous for cooling facilities as reducing the waste stream will lower the associated cost of storage and transport and the environmental impacts.

2.4.4. Operating Parameters of VSEP

In the VSEP system, multiple parameters can affect the quality of separation such as residence time, temperature, pressure, and vibration amplitude[194]. Aside from these parameters, membrane selection is considered the most significant parameter that can affect the overall system performance. To achieve the desired quality of the permeate, all of these elements are optimized during the testing stage, then introduced to a programmable logic controller (PLC) that monitors the unit. The operating pressure of the VSEP machine is generated by the feed pump and this system can work at a pressure of up to 986 psi (~ 68 bar) [15]. Although the permeate flow rates increase with higher pressures, it would also consume more energy, thus, the used operating pressure should balance between the energy consumption and the flow rates.

Temperature is another parameter that can impact the filtration rate as in most cases, increasing the operating temperature improves this rate and its quality. The applied temperature in the system is dependent on the selected membrane, but generally, it can go up to 90 ℃ in common feed streams and up to 130℃ in other influents[15], [177]. The filtration rate is also affected by the varied vibration amplitude and the equivalent shear rate. The torsion oscillation of the filter stack is the source of the produced shear. In general, the amplitude of the oscillated stack oscillates ranges between 1.9 and 3.2 cm peak-to-peak displacement at the rim of the stack [16].

As the feed material circulates and remains in the machine, the solid level in the feed increases. After the test, a specific cleaning solution is added to the membrane stack and with continuous oscillation, the membrane can be cleaned in a few minutes. This procedure can be automated and only around 190 liters of cleaning solution is consumed, hence minimizing the cleaner disposal problems found in other membrane systems[15].

2.4.5. VSEP Application

VSEP system has been used in a wide range of applications that is not restricted to wastewater [17]. Pulp and paper industries have applied the VSEP unit for the treatment of groundwood mill circulation Water (GMW) to reduce or remove targeted constituents such as COD, TOC, and conductivity[195]. Moreover, the treatment of wastewater streams from the food industry was extensively studied using the VSEP system[196]. Kertész et al.[197] experimented with the unit on dairy wastewater to reduce the lactose, COD, dry matter content, protein, and conductivity. In another study, Kertész et al. [198] compared the vibrated UF and stirred modules to treat cheese whey and results revealed a reduction of

99.83%, 36.29 %, and 73.74% for turbidity, dry matter, and protein respectively.

Petroleum and biofuel industries utilize the VSEP for drilling fluid recycling, DEA recovery, ethanol stillage, and oil separation from water streams. Piemonte et. al [25], [199] studied the water treatment and recovery from produced, water and outcomes showed TDS removal of more than 99%.

Moreover, the treatment of brackish and RO concentrate by the VSEP system was examined in many studies aiming to reduce the concentration of various dissolved ions or TDS in general[200]. A study conducted by Johnson et al. [201], to compare the performance of the VSEP systems to conventional technologies for the treatment of RO reject from brackish well water, found that the VSEP can recover around 98% of the feed water. Furthermore, Yenal et al. [202] conducted an economic study on VSEP units and ion exchange for reverse osmosis concentrate volume reduction. Results revealed savings of approximately six million dollars per year using the VSEP compared to the RO units alone.

The treatment of other wastewater streams such as magnetic ion exchange process concentrates (MIEX) by VSEP was studied for the removal of multivalent ions and dissolved organic carbon (DOC) [23]. In a different study, Leong et al. [9] conducted a techno-economic analysis on the use of VSEP to treat MIEX concentrate. The system was able to remove more than 97% of DOC, recover more than 80% of the waste stream in the form of permeate, and reduce the waste disposal and salt consumption by 23.9%, and 42%, respectively.

Other than the previously mentioned studies, a wide range of studies was conducted to separate constituents or lower the presence of targeted pollutants such as natural organic matter (NOM) [24], humic substances[203], pig manure[31], [204], skimmed milk[32], [205]–[210], livestock wastewater[26], inorganic pigment[211], albumin solutions[212], biological constituents[213], and MBR sludge[214].

Table 8-14 below summarizes the studies performed using the VSEP system in various applications.

Table 8:A Summary of the conducted studies by VSEP with different types of samples.

Sample type	Main targeted constituents	Membrane used	Temperature	Pressure	Vibration frequency and amplitude	Removal%	References
Dairy wastewater	chemical oxygen demand (COD)	UF: **7 kDa** PES5 (polyethersulfone) NF: **240 Da** NF-270 TFC polyamide RO: **50 Da** BW-30 polyamide	50°C.	**TMP** UF: 0.8 MPa NF: 2 MPa RO: 3 MPa	Vibration amplitude: 24.5 mm	**The rejection% of COD After vibration** UF: 40.0% NF: 90.5% RO: 98.6%	[19]
Dairy wastewater	COD, turbidity, salts, DS, and milk components	**NF**: 240Da TFC **UF membranes:** 30 kDa PES UF 10kDa PES UF	NA	**UF**: 0.4, 0.6, 0.8, and 1.0 MPa **NF:** 2.0, 2.5, 3.0, and 3.5 MPa	Vibration amplitude: 0.0125 m and 0.0250 m	**NF:** ~100% for all constituents**30 kDa PES UF:** ~ 65% COD rejection **10kDa PES UF:** ~70% COD rejection	[18]
Dairy wastewater	Turbidity, COD, and TOC	PES-10 SYN **UF membrane** with 10 Da	50˚C	0.8 MPa.	Amplitude: 2.54 cm Frequency: 54.2 Hz	Turbidity: > 98.6% **COD rejection**: changed as a function of pressure, from 72 at TMP of 0.3 MPa to 81% 0.8 MPa. **With vibration:** 77–81%. **TOC rejections With vibration:** 63 to 65%	[12]

Table 9:A Summary of the conducted studies by VSEP with different types of samples.

Sample type	Main targeted constituents	Membrane used	Temperature	Pressure	Vibration frequency and amplitude	Removal%	References
Dairy wastewater	COD, Electrical conductivity (EC), protein, lactose.	Polyethersulfone **UF membranes** with a pore size of 10000, 7000, and 5000Da. **Thin film composite NF** with 240 and 200Da.	50± 1°C	TMP of UF: 0.8 MPa TMP of NF: 3 MPa	Amplitude: 2.54 cm Frequency: 54.1 Hz	**In single stage experiment rejections of TFC 240 Da NF membrane with vibration:** EC: ~80% **Rejections of PES 10 kDa UF membrane with vibration:** EC: ~21%	[20]
Dairy wastewater	COD, conductivity, turbidity.	**Various UF membranes** (US100P, UH050P, and UH030P) **NF270 membrane**	Feed: 35°C Permeate: 25°C	Single NF: 2 MPa UF + NF: 2.5 MPa	Amplitude: 30.2 mm Frequency: 60.75 Hz	**Single NF:** COD: ~99.55%, Conductivity: ~ 54.94% **UF + NF:** COD: ~99.69%, Conductivity: ~ 60.06%	[215]
Dairy wastewater	COD	**NF membranes:** ***Two polyamides with cut-off between 150 and 300 Da ***One Filmtec NF with 200 Da cut-off **RO membranes:** *Desal AG	45±1 °C and reduced to 25°C in some cases.	0.3 up to 4 MPa.	Frequency: 60.75 Hz	COD rejection with **RO membrane:** ~99.93% COD rejection by **NF membranes:** * Filmtec membrane: ~99.74 *Desal 5 DK membrane: ~99.90	[8]
Cheese whey	Protein, dry matter, COD, and turbidity.	RC UF membrane (C-30F) 30 kDa.	25 ± 2°C	0.4 MPa	Frequency: 54.8 Hz Amplitude: 1.9 cm (3/4 inch)	Protein: 73.74% Dry matter: 36.29 % Turbidity: 99.83% COD: 29.45%	[198]

Table 10:A Summary of the conducted studies by VSEP with different types of samples

Sample type	Main targeted constituents	Membrane used	Temperature	Pressure	Vibration frequency and amplitude	Removal%	References
Brackish water reverse osmosis concentrate	Various ions	ESPA RO membrane	25°C	NA	NA	*TDS: 94% *K, Na, Br, Cl, SO_4^2, Ca and Mg: > 92 *F: 84.5, Nitrate: 89.8, and Boron: 44.2%	[10]
Brackish water and brine	Various ions	Two RO membranes: FE and LFC	30 ◦C	140 psi	Frequency: 55 Hz	**Brackish solution:** Mg^{2+}: ~98, Ca^{2+}: ~98, Na^{+}: ~95, SO_4^{2-}: ~98, and Cl^{-}: ~92 **brine solution:** Mg^{2+}: ~99, Ca^{2+}: ~98, Na^{+}: ~90, SO_4^{2-}: ~92, and Cl^{-}: ~92	[21]
Magnetic ion exchange (MIEX)	Dissolved organic carbon (DOC) and multivalent ions	DowTech nanofiltration (NF-270) membrane	45°C	2400 kPa	Amplitude: 12.7 mm	**DOC: >97** **Multivalent solutes (**Mg^{2+}, Ca^{2+}, SO_4^{2-}): ~70-85	[9], [23]
Oil-in-water (O/W) emulsions	COD and oil emulsion	UF membranes Dextran T2000 Dextran T500	NA	Inlet Pressure: 344.8 kPa Outlet pressure: 125 kPa	Amplitude: 2 cm Frequency: 50 Hz	The COD: 36% to 95%. Oil removal: 97% by UF treatment from all samples	[216]
Oil emulsions	Oil	UF membrane polyethersulfone (PES) 50 kDa	~24°C	Varies but reached a plateau at 100kPa	Frequency: ~ 60.75 Hz	Oil: >99.5	[205]

Table 11:A Summary of the conducted studies by VSEP with different types of samples.

Sample type	Main targeted constituents	Membrane used	Temperature	Pressure	Vibration frequency and amplitude	Removal%	References
Cheese whey	TSS, protein, lactose, total N.	C30F UF regenerated cellulose (30 kDa)	25°C.	0.4 MPa	NA	In the concentration study the retention at 240min of: **TSS**:> 40% **Lactose**: >35% **Protein**: 99.7%	[217], [218]
Groundwood Mill Circulation Water (GMW)	TC, sugar, lipophilic, Ca^{2+}, SO_4^{2-}, and conductivity	**UF:** ***** C30G and C30F (30kD) *PES 50H (50kD) *PA 50H, 50kD *Polyimide G50 8kD **Desal-5 NF membranes**	NA	UF: 2.5 bar	NA	Biological process, then UF+NF: *A removal of >90% for the following constituents: TC, sugar, lipophilic, Ca^{2+}, and SO_4^{2-} *Conductivity:>80 %	[219]
Groundwood mill (GWM)	Conductivity, TOC, turbidity, lignin, and total solids	**Ultrafiltration:** *C 30F membrane *PA 50H membrane	50°C	2 bars	Amplitude: 1.6cm	**C 30F, L-Mode:** Turbidity:94% TOC:70% **PA 50H had similar results**	[195]
Paper mill waters	COD	**UF and NF**	20 to about 40°C	7-35 bar	Amplitude**:** 2-3 cm	**COD by UF**: about 30-60% **Dissolved organic and inorganic compounds by NF**: up to 90%	[220]
Brackish water	Dissolved salts	**2 RO membranes**: BW-30 and FE	30°C	965kPa	Amplitude: 1.59 cm	FE membrane at 50% recovery: Mg^{2+}: 99, Ca^{2+}: 97, Na^{+}: 90, Cl^{-}: 92, and SO_4^{2-}: 92	[22]

Table 12:A Summary of the conducted studies by VSEP with different types of samples.

Sample type	Main targeted constituents	Membrane used	Temperature	Pressure	Vibration frequency and amplitude	Removal%	References
Oil emulsions	Oil	**Two UF** PES 20 and 50 kDa membranes	~25 ◦C	30 kPa	Frequency: ~ 60.75 Hz	With 20 kDa membrane, the oil content in the permeate was negligible with almost zero turbidity	[221]
Drinking water	Arsenic	**Two annular type NF membranes** (denoted as NTR-7450 and UTC-70)	20± 2 °C	310kPa	Vibration amplitude: 13mm	**River water** UTC-70 membrane:>95% NTR-7450 membrane: between 80.5 to 84.5% with the increase of retentate As (V).	[11]
Algal slurry	algae	**PES MF membrane**	20.0 ± 1.0 °C	207kPa	Amplitude: 2.54 cm Frequency: 54.60 Hz.	Algae rejection:>95%	[13]
Surface water	Humic acids	Two Teflon **MF**, three regenerated cellulose **UF**, and one polyamide/polysulfone **NF**.	20 ± 3 ◦C	Depends on the used membrane	Depends on the used membrane.	NF: HA molecules: > 99% For other processes: did not exceed 95%.	[174]

Table 13:A Summary of the conducted studies by VSEP with different types of samples.

Sample type	Main targeted constituents	Membrane used	Temperature	Pressure	Vibration frequency and amplitude	Removal%	References
Landfill leachates	COD, suspended solids, conductivity (dissolved solids), N–NH4+ and of HA.	**One MF** (with mean pore diameter 0.1 µm), **two UF** (with molecular cut-off 100 kDa and 10 kDa) and **one NF** (50% rejection of NaCl)	Temperature: varies during the experiment for each membrane.	**Pressure**: varies for each membrane. **MF** (0.1 µm):5 bar **UF** (100 kDa, and 10kDa): 10 and 17 bar **NF** (50% rej. NaCl):20.4 bar	The vibration amplitude: 25.4 mm.	*COD: > exceeded 60% for all cases. *Similar pattern was found for the retention of suspended solids and turbidity. *The rejection of humic substances depends on the type of applied membrane.	[27]
Piggery wastewater	COD, TN, and others	RO and UF (20, 100, 200 Da)	27–34 °C	200–300 psi	Amplitude: 3/4 in Frequency: 49.3 Hz	COD removal by: VSEP-UF: 65.3% VSEP-RO: 95.9% VSEP-UF and VSEP-RO: 99.5%	[222]
liquid fraction of digestates	N and P	Two RO membranes	Permeate temperature: 45°C	NA	Frequency: 90 Hz	**First VSEP:** Nitrogen: 93% Phosphorous: 59% **Second VSEP:** Total nitrogen: 95% Total phosphorous: 69%.	[33], [223]
Coffee wastewater	COD, turbidity, and conductivity	**PES MF:** 0.05 µm **PES UF:** 7000 Da **NF**: 225 Da **TFC polyamide RO:** 30 Da	20 and 25 °C	Pressure (kPa): **MF:** 350, **UF:**1000, **NF:** 2400, **RO:** 2400	Frequencies: between 53.4 and 54.7 Hz.	COD and turbidity for NF and RO: above 97% Conductivity: **NF:** 75%, **RO**: 99%	[28]

Table 14:A Summary of the conducted studies by VSEP with different types of samples.

Sample type	Main targeted constituents	Membrane used	Temperature	Pressure	Vibration frequency and amplitude	Removal%	References
Coffee extracts	Preconcentration of coffee extracts in soluble coffee processing and COD rejection	150-Da TS80 NF membrane	25°C	1.03, 1.79, 2.4, 3.1, and 3.79 MPa	Frequency: between 53.3 and 54.7 Hz.	Real COD rejection efficiencies were above 0.99.	[29]
Coffee extracts	Turbidity, COD, and conductivity	TS80 NF membrane (150 Da)	50 °C.	400 psi	Frequency: 56.7Hz.	Turbidity: >99.9% COD: >98% Conductivity: >80%	[224]
Starch wastewater	Conductivity	**UF:** PVDF AF 5 (2,000 da) and Cellulose C-100F (100,000 da) **NF:** Sulfonated polyethersulfone	42°C.	bar: AF 5: 8.3 C-100F: 12.4 NTR-7410: 13.8 NTR-7450: 15	NA	Conductivity: NTR-7410: 39.65% NTR-7450: 81.21% C-100F and AF-5: <3%	[15]
Tannery Wastewater	tannins, chemical oxygen demand (COD), Ntotal, turbidity and color.	**Three PTFE MF**: 0.1, 0.45, and 1.0µm **Four** regenerated cellulose **UF** **Two RO polyamide/polyester**	NA	MF: 5 bars RO: 20 bars	Frequency: 53.52, 54.30, 54.60, and 54.76Hz.	COD: UF: 80%–87% MF: 65% COD RO: 96%	[30]

3.1.Experimental setup and materials

3.1.1. VSEP system

The VSEP unit illustrated in *Figure 7*, demonstrates how it operates. The inlet sample exits the feed tank and is pumped upward to enter the membrane housing through an inlet hole in the lower stainless-steel plate. The process stream passes through the vibrated filter pack and is then treated. Only high-water quality flows upward and exits the upper plant in the outlet permeate stream hose; it is either collected or returned to the feed tanks to maintain a constant feed concentration as in the pressure study. A very concentrated stream of various pollutants exits through the retentate hose downward and is either returned to the feed tank or collected for further analysis.

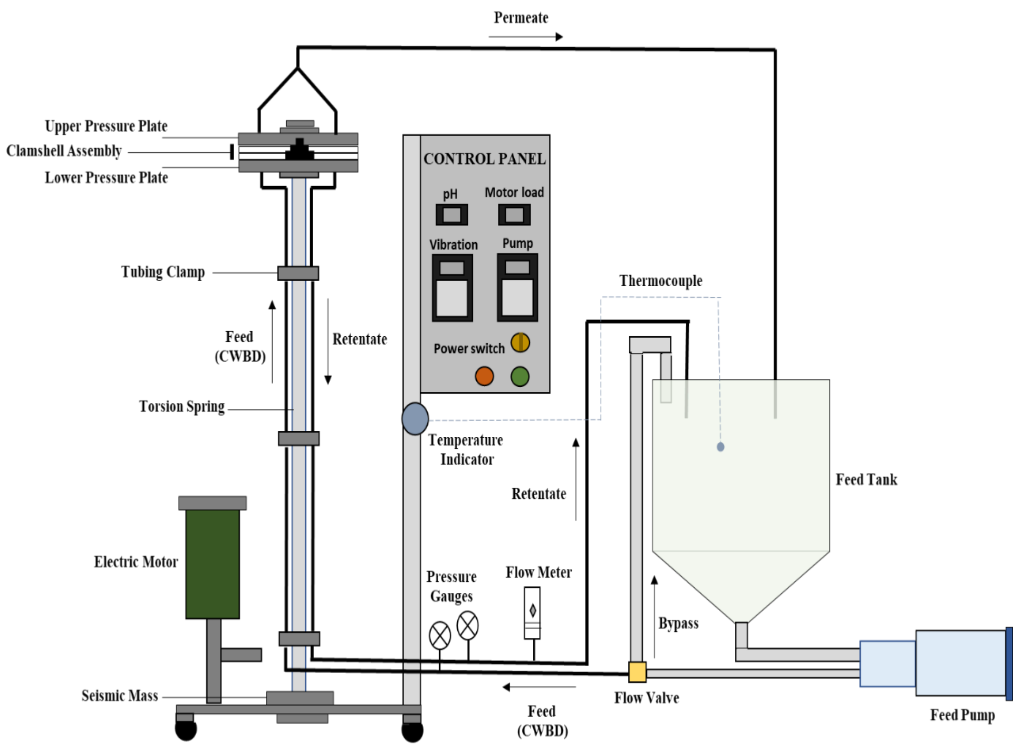


Figure 7: Schematic diagram of VSEP unit

Technically, the VSEP unit consists of a filter pack assembly that has two pressure steel plates as well as the clamshell made of polypropylene, which is the housing containing membrane installation. The unit is manufactured as a series Lab (L) or pilot (P) scale module. The created shaft in the unit is mounted on a seismic mass that acts as a torsion spring, hence transmitting the oscillation generated by the eccentric drive motor upward to the filter pack and the membrane. Consequently, the membrane oscillates with an amplitude in its plane according to the applied frequency of the drive motor. The created shear rate at the membrane is generated by the fluid inertia as in the case of the Stokes layer close to the oscillating plate [32]. The applied frequency of oscillations to the system can be adjusted by an electric controller with an accuracy of 0.01 Hz [27]. The resulting amplitude can be recorded by checking the pattern of the indicator marks located in front of the clamshell previously illustrated in *Figure 7.*

The treated sample by membrane filtration action (permeate) is removed by the permeate tubing placed on the top of the spring at atmospheric pressure. However, the concentrate stream flows in another tube near the lower pressure plate to be placed back to the feed tanks through the ‘process out’ line. Pressure gauges are used in this unit to measure the inlet and outlet pressures and determine the mean of inlet and outlet pressures (transmembrane pressure (TMP)) as the permeate exits the process at atmospheric pressure. For safety reasons, the manufacturer recommended that to start the vibration an outlet pressure of at least 2 bar should be reached. The mode of flow (crossflow or dead-end) and the crossflow velocity can be adjusted by a valve on the exit line of the concentrate. Additionally, the pump speed can be controlled by an electric controller beside the vibration control unit.

3.1.2. *VSEP main components*

Drive System

The VSEP system has a motor with ten to twenty horsepower. It drives an eccentric weight and seismic mass, in which the energy is translated into the Filter Pack through the torsion spring. The motor load is related to the vibration frequency; hence it can be controlled according to the desired level.

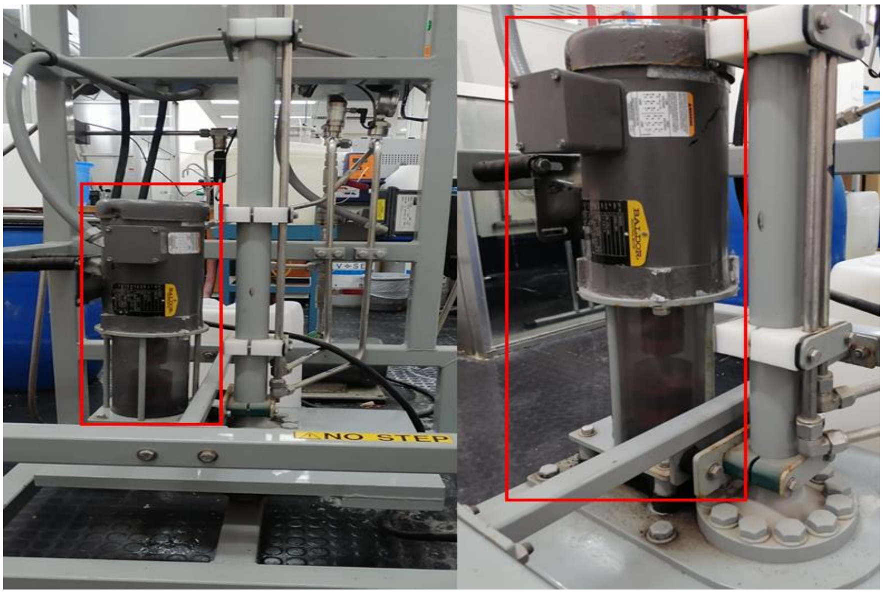


Figure 8: The drive system in VSEP.

Control unit, pressure, flow, pH, and temperature indicators

The VSEP system has a control panel, mainly for the feed pump and the drive motor as shown in *Figure 9*. The panel measures the pH and the motor load; this allows for the continuous monitoring of these parameters. The feed temperature is measured by the thermocouple placed in the feed tank. The feed flowrate can be controlled by the flowmeters to avoid any sudden drop or variation of flowrate. The inlet and outlet pressures of the system can be continuously monitored by the pressure gages.

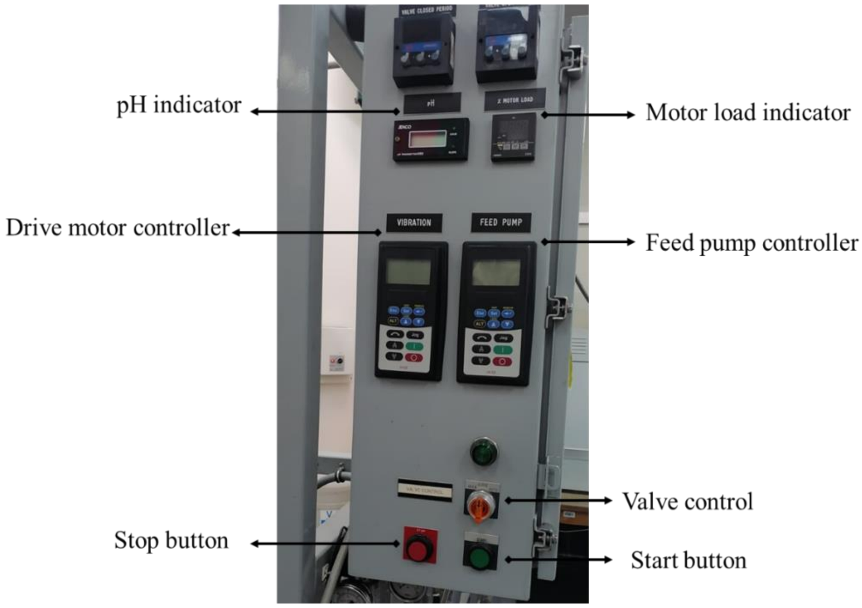


Figure 9:VSEP control panel.

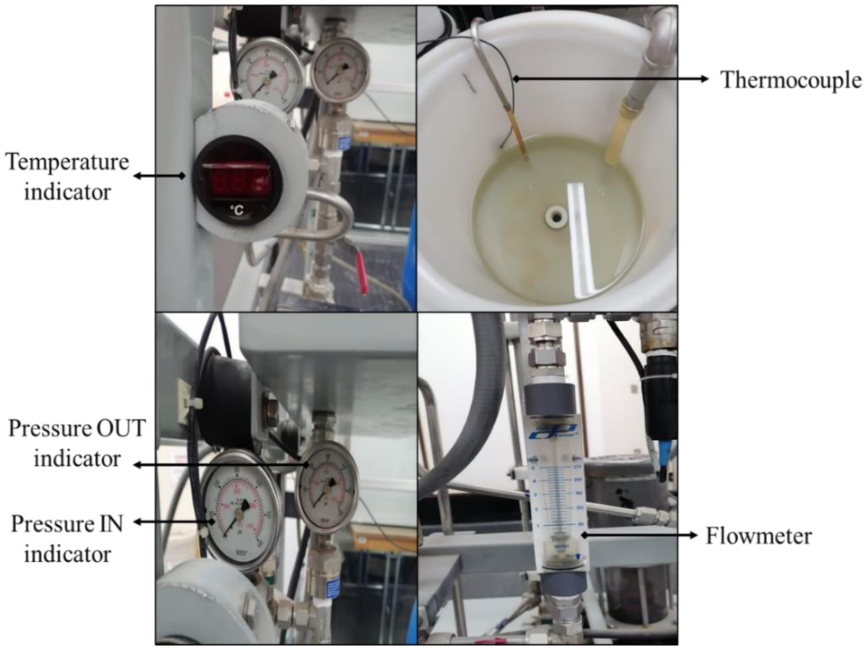


Figure 10:VSEP temperature, pressure and flow indicators

Feed pump

The process stream is fed to the system using the feed pump. In addition, the pump is utilized in the cleaning study to pump cleaning solution from the tank to the VSEP Filter Pack. The speed of the feed pump can be adjusted from the control panel, but the pressure should be monitored as it changes with the pump speed.

Figure 11: The feed pump in VSEP.

Filter pack

VSEP filter packs consist of membrane trays, filament-wound outer housing, polypropylene or Kynar permeate carriers, and stainless-steel end. The membrane trays are made up of a membrane, two stainless steel discs, and drainage cloth, see *Figure 12*. Metal spacers and rubber gaskets exist to separate the trays and to offer a good spacing for the process stream to flow over the trays. To prevent leaking, the assembly is compacted and compressed so that the gaskets form a seal.

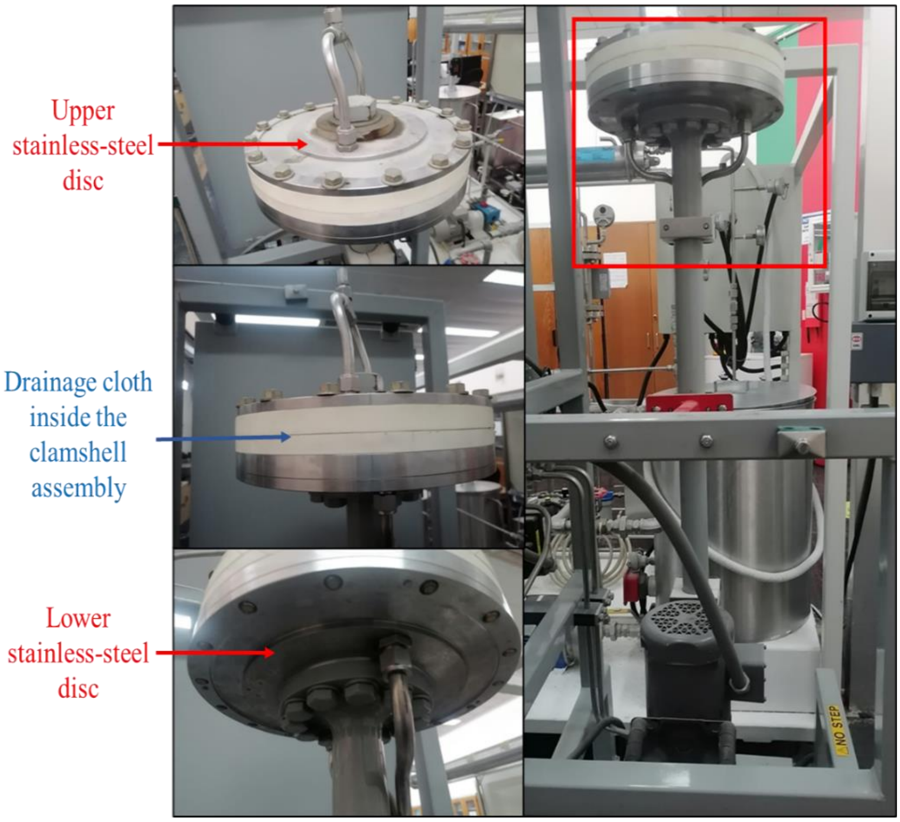


Figure 12: The filter pack in VSEP.

3.1.3. CWBD Analysis Methods and Quality

Characterization of the CWBD is used to determine the quality of water influent samples used in the study. The quantity and the type of pollutants available in cooling tower effluent vary and depend on many factors. For instance, the source of the inlet and make-up water to the cooling tower as well as the cycle of concentration have great impact on the presence of certain contaminating constituents over others. The types of used chemicals during the treatment process as inhibitors or even as an anti-corrosion inside the towers, can significantly affect the composition of chemicals found in collected CWBD. Additionally, the concentration of ions and turbidity of CWBD can increase as a result of an increase in the evaporation rate during the cooling process [12,13], and the quality of influent air with an elevated amount of dust [11].

Herein, the used CWBD in the VSEP system was collected from Qatar District Cooling Company (Q.C.S.C) Plant 1 and 2 located in Qatar. It is worth mentioning that Plants 1 and 2 use treated sewage effluent (TSE) as a source of make-up water for the process; this will contribute to the total amount of constituents in CWBD. There are common contaminants that can be found in most effluents, including, sodium ions magnesium ions, chloride, calcium ions, sulphate, iron and phosphate, total dissolved solids (TDS), Chemical Oxygen Demand (COD), and others. To understand the profile of the applied CWBD in the unit, it was characterized and checked for pH, TDS, as well as the quantity of each dissolved ion using Ionic Chromatography (IC) (850 Professional IC) instrument from Metrohm, using Anion and Cation column.

Table 15 illustrates the type and quantity of constituents in the sampled CWBD before the treatment process.

In this study, the TDS measure will be the main indicator of the purity and quality of the effluent treatment sample as it takes into consideration the removal of dissolved added chemicals and any other dissolved salts.

Table 15: Type and quantity of pollutants in the sampled CWBD (plant 2) before the treatment process

Parameter	unit	Quantity of the influent stream
pH		8
Calcium (Ca^{2+})	mg/L	195
Magnesium (Mg^{2+})	mg/L	46
Chloride (Cl^{-})	mg/L	1030
Sulphate (SO_4^{2-})	mg/L	837
Potassium (K^{+})	mg/L	55
Sodium (Na)	mg/L	724
Bromide (Br^{-})	mg/L	20
Nitrate (NO^{3-})	mg/L	58
Total Dissolved Solids (TDS)	mg/L	4710

Table 16: Chemical used in some of Qatar Cool (QC) plants.

No.	Name of Chemicals	Description	Special hazards arising from the substance or mixture	Description
1	Suez GN 8253	Scale & Corrosion Inhibitor	Hydrogen chloride, oxides of carbon and nitrogen evolved in fire. Oxides of sulphur evolved in fire	Continuous
2	Suez NX1422	No Oxidizing Biocides	Ammonia, hydrogen chloride, oxides of carbon and nitrogen evolved in fire	Every 14 days Basis Shock Dose
3	Suez NX1164	No Oxidizing Biocides	Hydrogen chloride, oxides of carbon and nitrogen evolved in fire. Oxides of sulphur evolved in fire	Every 14 days Basis Shock Dose
4	Sodium HypoChlorite	Oxidizing Biocides	-	Weekly
5	Sulfuric Acid	pH Control	Decomposes on heating, emitting toxic fumes (Sulphur oxides)	Continuous

3.1.4. Studied Membranes

In this study, nanofiltration (NF) and reverse osmosis (RO) membranes are considered alternatives for the treatment of CWBD. The performance of each type of membrane is gauged through the following parameters: permeate flow rate and quality. Six different membranes were examined: four membranes for the RO process; two of them made of composite polyamide, one made of polyamide, and one of thin film composite (TFC) polyamide. While for the NF study, two membranes were tested; one was made of Proprietary TFC, and the other is created out of Polypiperzinamide/PES/Polyester. The operated membranes have a surface area of approximately 593 cm^2 and with flat-disk modules. On the top of the membrane, a drainage cloth and backing screen (spacer) were placed to support the membrane as well as separate it from the upper plate. *Table 17* summarizes the characteristics of the membranes as provided by the New Logic Research company. These new membranes in this study were analyzed by contact angle (DataPhysics contact angle analyzer (OCA 35 Pro, Germany) to test their permeability. Distilled water was dropped on the dry membrane surface and three readings were averaged for each membrane.

In addition, scanning electron microscope (SEM) and energy-dispersive X-ray (EDX) analyses were performed on clean and fouled HFT-150 membrane to understand the morphology and the available atoms at the membrane surface.

Table 17: Specifications of the studied membranes for VSEP (New Logic Research, USA) [177]

Membrane	MWCO Pore size (da)	Membrane composition	pH tolerance		Temperature tolerance (℃)	Chlorine tolerance (ppm)	Best pressure range (psi)
			Cont	Clean			
Reverse Osmosis (RO)							
ORM 31K	30	Composite polyamide	1~10.5	1~12	60	0.1	200-1000
ULP 4	30		1~10.5	1~12	60	<0.1	100-1000
AG	30	Polyamide	1~10.5	1~12	70	<0.1	200-1000
ACM 4	30	TFC Polyamide	1~10.5	1~12	60	<0.1	100-1000
Nanofiltration (NF)							
DK(DS5-DK)	150	Proprietary TFC	1~10.5	1~12	70	<0.1	100-1000
HFT150	150	Polypiperzinamide/PES/Polyester	1~10.5	1~12	70	0	100-1000

3.2.Experimental methodology

This section describes the methods used in the four main studies carried out in this research. The performed experimental work included:

- A membrane selection study to determine the best-performing membranes in terms of permeate flow and quality.
- A pressure study to identify the optimum pressure to maximize permeate flow.
- A vibration study to identify the effect of increasing the vibration frequency on permeate flux and quality.
- A concentration study to determine the permeate recovery and test the effect of feed concentration on the permeate flow and quality.
- A cleaning study to check the performance of the membrane,
- *-16* describes the main conducted experiments and the major changes in the unit.

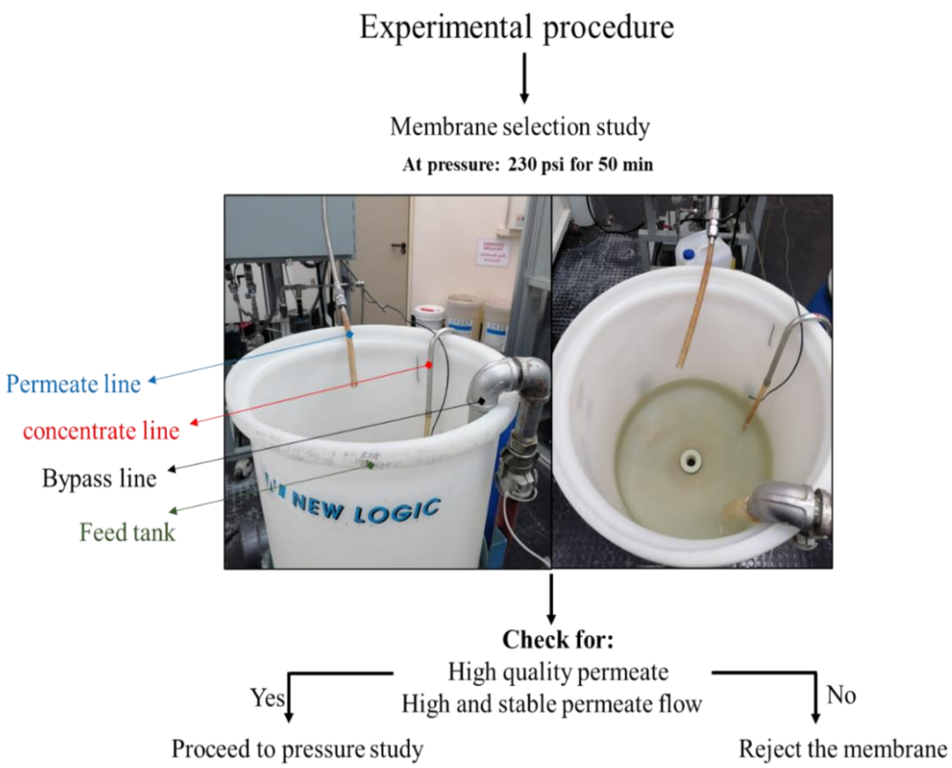


Figure 13: A summary of membrane selection study.

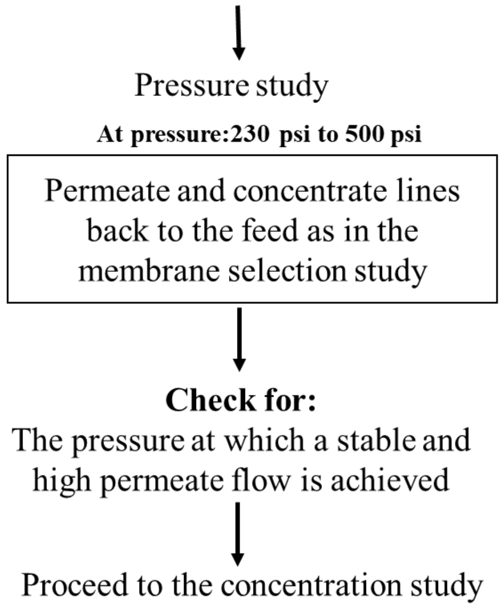


Figure 14: A summary of pressure study.

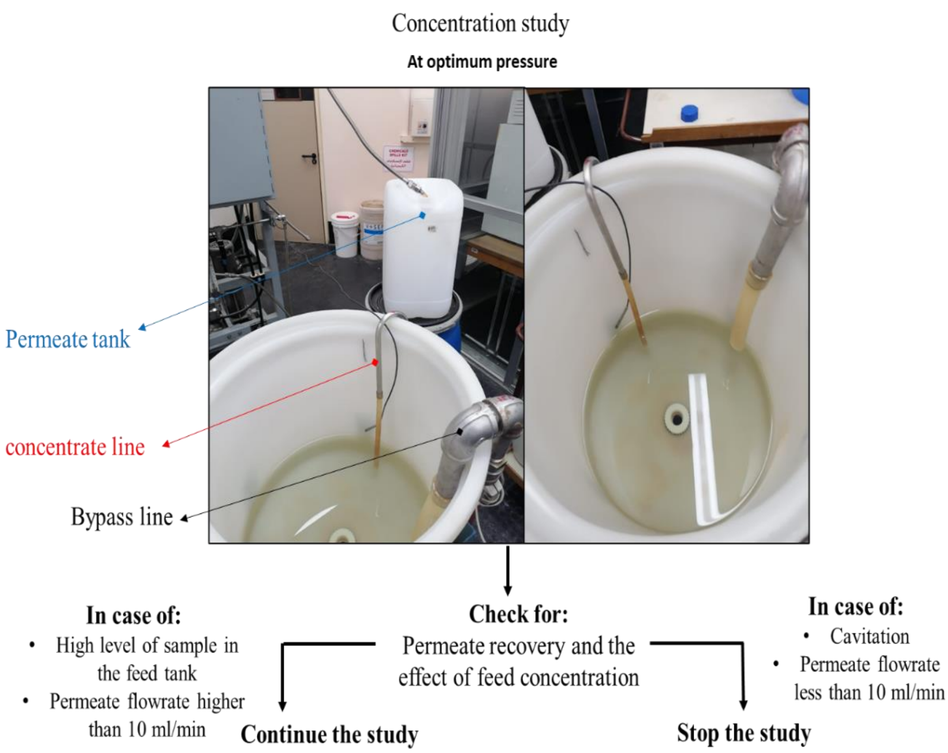


Figure 15: A summary of concentration study.

Cleaning study

Addition of VSEP (404 and 505) solutions
At pressure: 60psi for 45 min

Permeate and concentrate lines back to the feed as in the membrane selection study

↓

Check for:
The membrane treatment performance after cleaning

↓

END of the experimental work

Figure 16: A summary of cleaning study.

3.2.1. Membrane Selection Method

Membrane conditioning

Before starting the membrane selection study, a membrane was installed, and the system was operated to check for leaks for 30 minutes with clean water. After that, the water on the system was drained and around 60L of CWBD was placed in the feed tank to start the test. The system is then turned on as well as the vibration that should be started at a pressure above 30 psi according to the manufacturer company. For each of the studied membrane, the pressure was adjusted to 230 psi. The vibration amplitude was also adjusted to 43Hz using the vibration speed controller and the concentrate flow was nearly 2.6 GPM. The system was allowed to run for about 30min and 1 hour to condition the membrane in two sets of experiments, with both permeate and concentrate lines being returned back to the feed tank to maintain initial concentration.

Data Measurement

The data collection is started by checking the permeate flowrate using a graduated cylinder and stopwatch. Every ten minutes a sample of permeate was collected for one minute to calculate the permeate flux in $L.m^{-2}. hr^{-1}$. Various data were collected, mainly time, as well as inlet and outlet pressures. This procedure was repeated for 1 hour, in which permeate, and the corresponding feed samples were collected to check the quality before and after treatment. In this lineout study, the best membranes were selected according to the permeate flux and quality.

3.2.2. Pressure study

After the best membranes were chosen, a pressure study was conducted by operating the unit at a range of pressure to test and get the optimum pressure. A new membrane was installed, and the system was run at various pressures with 30 psi intervals between

230 psi to 500 psi. The operating pressure in the VSEP unit was adjusted by one or a combination of the following methods:

- Controlling the pump speed using its frequency drive.
- Increasing the pump speed increases the pressure and vice versa.
- Closing the concentrate back pressure valve, will increase the pressure, but reduces the concentrate flow.
- Lastly the pressure can be increased by closing the bypass valve.

3.2.3. Vibration study

In this study, the effect of vibration frequency on the permeate flux and quality in terms of TDS removal. This was examined by increasing the frequency from 0 to 43 Hz by a step change of 8 Hz. At each frequency, the amount of permeate flow per minute was collected to measure the flux and the TDS level.

3.2.4. Concentration study

The concentration study is conducted by operating the system at the optimum pressure determined in the previous study for the corresponding membrane from the previous study. Herein, both permeate and concentrate hoses are returned to the feed tank and the system was operated at optimum pressure for 1 hour and at approximately 2.6 GPM to condition the membrane. After one hour, the permeate hose is directed into a separate tank for collection, thereby increasing the concentration in the feed tank. During this study the following parameters are recorded: the permeate flowrate, pressure, temperature, vibration amplitude, and time intervals between readings to calculate the recovery. The duration of the concentration study was for 2 days with 3 hours per day. The study was stopped in the case of (1) low permeate flow (below 10 ml/min) or (2) if we ran out of the concentrate material in the feed tank, as air will be sucked into the feed pump. Next, both permeate and concentrate samples are collected and weighed to calculate the final recovery rate as shown in the following equation.

The final recovery rate:

$$\%\ Recovery = \frac{(Permeate\ Volume)}{(Permeate\ Volume + Concentrate\ Volume\ )} * 100$$

3.2.5. Fouling study

In this study, the VSEP system and the used membrane are cleaned using two types of chemicals, which are an acidic cleaner (NLR 404), and a basic cleaner (NLR 505). To begin with, a proper amount of 1.4L of the NLR 404 is mixed with 42L of clean water. Once the solution is well mixed, the system is started at low pressure (60psi) and the vibration frequency is adjusted to 43Hz. The outlets of the system (concentrate and permeate) are sent back to the feed tank and the chemical cleaner is circulated in the unit for about 45 minutes. After that, the system is flushed with clean water to remove the residual of any cleaning solution. The same procedure is performed with the basic cleaning chemical NLR 505. This base cleaner is a mixture of surfactants (sodium dodecylbenzene sulfonate (SDBS)) and chelating agents (sodium salt of ethylenediamine-tetra-acetic acid (EDTA))[10].

Afterward, the effectiveness of the cleaning was evaluated by running the unit with CWBD.

3.2.6. Analytical methods

The method used to estimate the permeate flowrate during the experiment uses a volumetric cylinder and a timer. The temperature was monitored throughout the test by placing the thermocouple attached to the VSEP system into the feed tank. The TDS, conductivity as well as pH values of the feed and the permeates are measured using a calibrated waterproof ExStik® II pH/conductivity meter, model EC500. The type and the amount of each dissolved ion in the CWBD are characterized using an Ionic Chromatography (850 Professional IC) from Metrohm, using Anion and Cation columns. The removal efficiency of TDS or any pollutant by membranes is calculated by the equation below. Where, *Cf* represents the initial concentration of the CWBD sample (feed), and *Cp* is the final concentration (Permeate).

$$\%\ \text{Removal} = \frac{Cf - Cp}{(Cf\ )} * 100$$

CHAPTER 4: RESULTS AND DISCUSSION

4.1.Membrane screening study

4.1.1. Conventional Operation without Vibration

Two types of membranes, NF and RO, were studied for the removal of TDS. Both UF and MF membranes were not considered in this study due to their large pore sizes relative to those of dissolved ions in CWBD stream. Therefore, such membranes will result in low TDS rejection and affect the final permeate quality. The results observed by Wisniewski et al.[28] agrees with the stated theory, as UF and MF membranes were capable of reducing the conductivity by only 31% and 27%, respectively in the case of soluble coffee wastewater.

In the membrane screening study, four RO (ACM, AG, ULP, and ORM-31k) and two NF (DK and HFT-150) membranes of different materials are evaluated for CWBD treatment efficiency. This study is performed in the absence and presence of vibration at a constant feed flowrate of 2.6 GPM and operating pressure of 230 psi. The membranes are allowed to condition for 30 min and data is collected for 50 min at 10 min intervals. The screening of membranes is based on the permeate flux and quality.

The results of operating the VSEP system without vibration indicate a minor to a significant increase in the permeate flux with respect to time for all RO and NF membranes as illustrated in Figure 17. The increase during the 50 min test for RO was in the range of 6.67% for ULP to 36.36% for ACM. In terms of RO membranes, ULP membrane showed the highest flux of 65 $L.m^{-2}.hr^{-1}$, while AG membrane has the lowest flux of 35 $L.m^{-2}.hr^{-1}$. Notice that although all the tested RO membranes have the same pore size(30Da), there is a remarkable difference between the obtained permeate fluxes. This can be attributed to material type and compositions used in fabricating these membranes, as they are supplied by various vendors as will be shown shortly by contact angles measurements.

For NF membranes, DK showed a higher permeate rate of 81 $L.m^{-2}.hr^{-1}$ compared to HFT-150 with 54 $L.m^{-2}.hr^{-1}$, which corresponds to a difference of 33.33%. To confirm the theory of the effect of different compositions and materials used in synthesizing the membranes, the contact angle was measured on clean membranes to check the ability of a liquid to wet the membrane surface, hence knowing their permeability. The result of the contact angles is illustrated in Table 18. It is noted that all membranes have contact angles lower than 90^o, hence they are all hydrophilic[18]. DK and ULP membranes have the lowest averaged angles of 38.35^o and 39.16^o, respectively, thus they are highly hydrophilic. The performance of these membranes showed more permeate flow and higher flux compared to other membranes as illustrated in Figure 17. As AG has the highest angle of 53.03^o, this membrane indeed has the lowest permeate flux of 35 $L.m^{-2}.hr^{-1}$as indicated before compared to all other membranes.

Table 18:Contact angles of clean RO and NF membranes

	ACM	AG	ORM-31K	ULP	DK	HFT-150
Contact angle	47.15^o	53.03^o	45.91^o	39.16^o	38.35^o	44.21^o

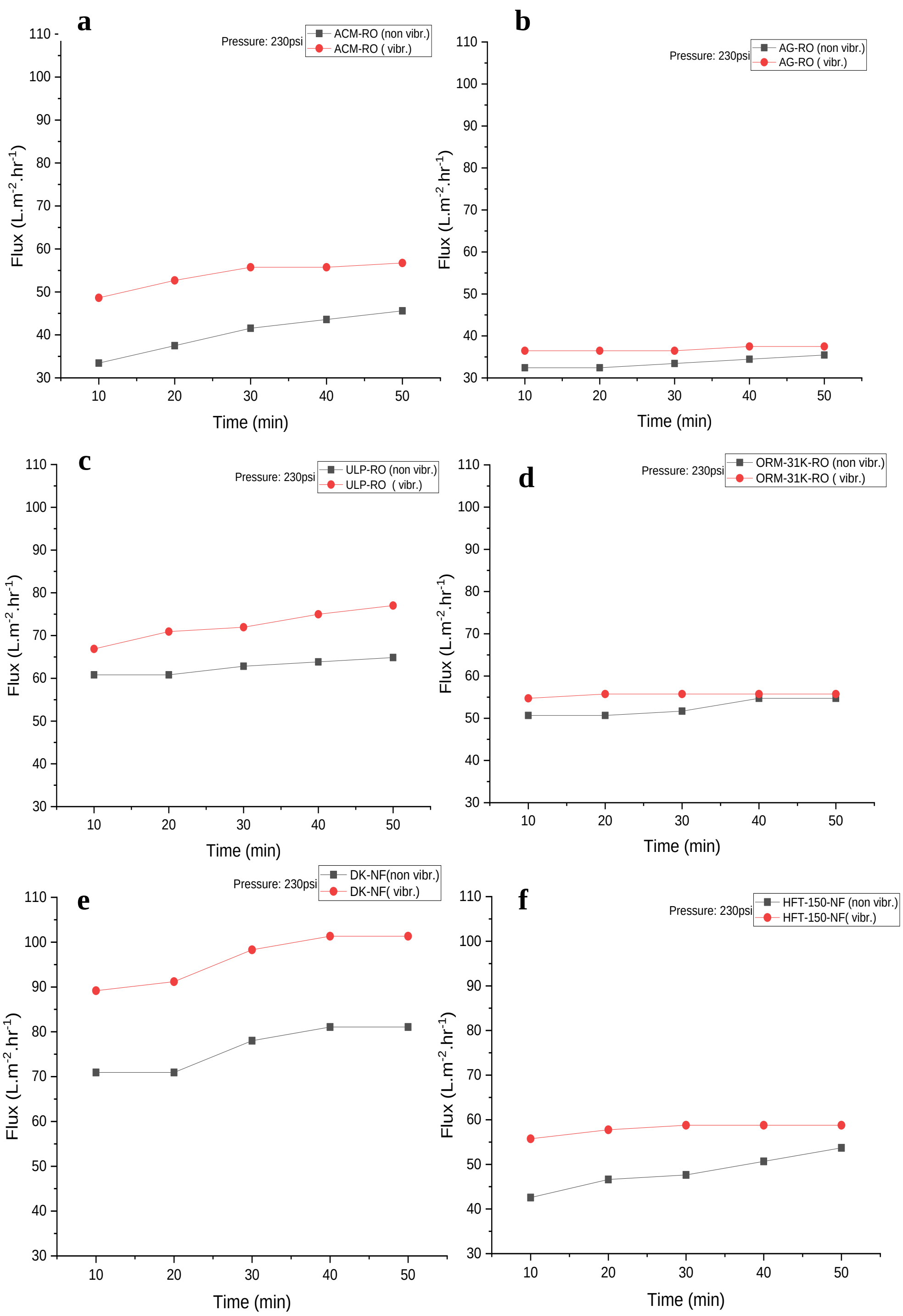


Figure 17:Permeate flux of RO and NF membranes in screening study after 30 min of (pressure:230psi, TDS concentration: ~4500ppm)

To ensure that the membranes are fully conditioned, the conditioning time was increased to 1 hour as performed on other studies [198] to observe its effect on permeate flux and quality. This study was repeated on only two membranes, ULP-RO and DK-NF. The results are shown in Figure 18.

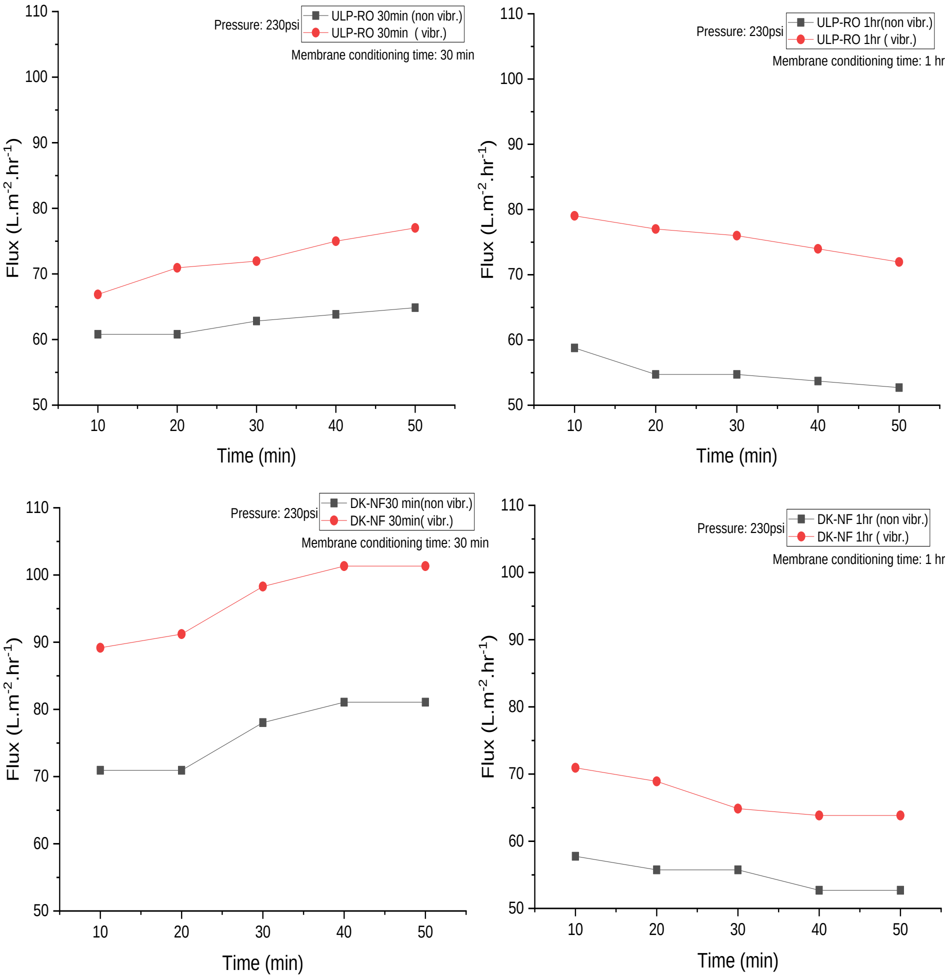


Figure 18: Permeate flux of ULP-RO and DK-NF membranes in screening study after 30 min and 1 hr of conditioning the membrane.

Both membranes showed a decline in flux with time. This indicates that all RO and NF membranes need more time in the conditioning step to ensure the removal of excess preservation chemicals attached to the new membrane surfaces and to allow the opening of pores. According to Kertész et al. [31] the initial drop in the permeate flux is usually caused by the concentration polarization, which is unavoidable in membrane-based technologies. This phenonium occur when the concentration of CWBD constituents increases at the boundary layer near the surface of the membrane because of the selective transport through the membrane. Another reason of the reduction in the flux is the gradual buildup of dissolved particles near the surface of the membrane, resulting in in gel layer formation. This layer will exist in both vibrating and non-vibrating systems, however, the properties and the thickness of this layer will be different, as it will be more significant in non-vibrating mode.

In large-sized pores membranes, solute particles can block the membrane and therefore alter the retention and permeability parameters. The extent of these phenomena differs between the type of membranes. For example, membrane systems without vibration will show a significant reduction in performance compared to vibrating systems as will be discussed later in this section.

The performance of these membranes is also studied in terms of TDS removal from CWBD as a significant parameter in the membrane screening studies. Figure 19 illustrates the TDS reduction resulting from each membrane in the non-vibrating mode. As expected, the performance of RO membranes withstands NF membranes with a remarkable difference, RO TDS removal capacity is over 95% for all studied membranes while NF performance is in the range of 36 – 73.5%. Both AG and ORM 31K RO membranes have almost a constant trend with removal of almost 99%. It is noted that the other two RO membranes, ACM and ULP 4, showed less than a 2% increase in TDS removal during the first 50 min study with a final rejection of almost 97.50% and 96.50%, respectively. This minor increase could be attributed to the 30-minute time used to condition the membrane. This compares positively with applied RO to complex streams with high conductivity (dissolved solids) as in Wisniewski et al. [38] and Coskun et al. [44] studies. They reported a significant conductivity removal between 93 and 99%. According to SUEZ for water technologies and solutions [45], the smallest particles down to ionic size, including small organic and in organic ions as well as aqueous salts can be rejected by RO membranes.

In the case of NF membranes, a lower TDS removal% was observed as compared to RO membranes. HFT-150 showed a removal of 73.50%, which is higher than the removal reported from DK of around 36.70%. The difference in the performance of the NF membranes, 73.5% removal for HFT-150 and 36.70% removal for the DK membrane, could be attributed to the compositions and membrane material used.
. Previous studies showed similar low removal trend for dissolved solids using NF as conducted by Wisniewski et al. [38]. They utilized NF with a pore size of 225 Da to reduce the conductivity of soluble coffee wastewater and found a reduction in the conductivity by only 58%. This percentage is lower than the obtained removal by HFT-150 NF membrane because of the difference in the membranes pore sizes.

The variation between RO and NF membranes is expected as the pore size of the RO membranes is 30 Da, while NF has 150 Da. Smaller pore-sized membranes can prevent almost all the dissolved ions from penetrating through the membrane, resulting in a high-quality permeate. This conclusion is confirmed by SUEZ for water technologies and solutions [45] as they reported that although some ionic removal can be resulted from NF membranes, the rejection occur only for larger ionic species.

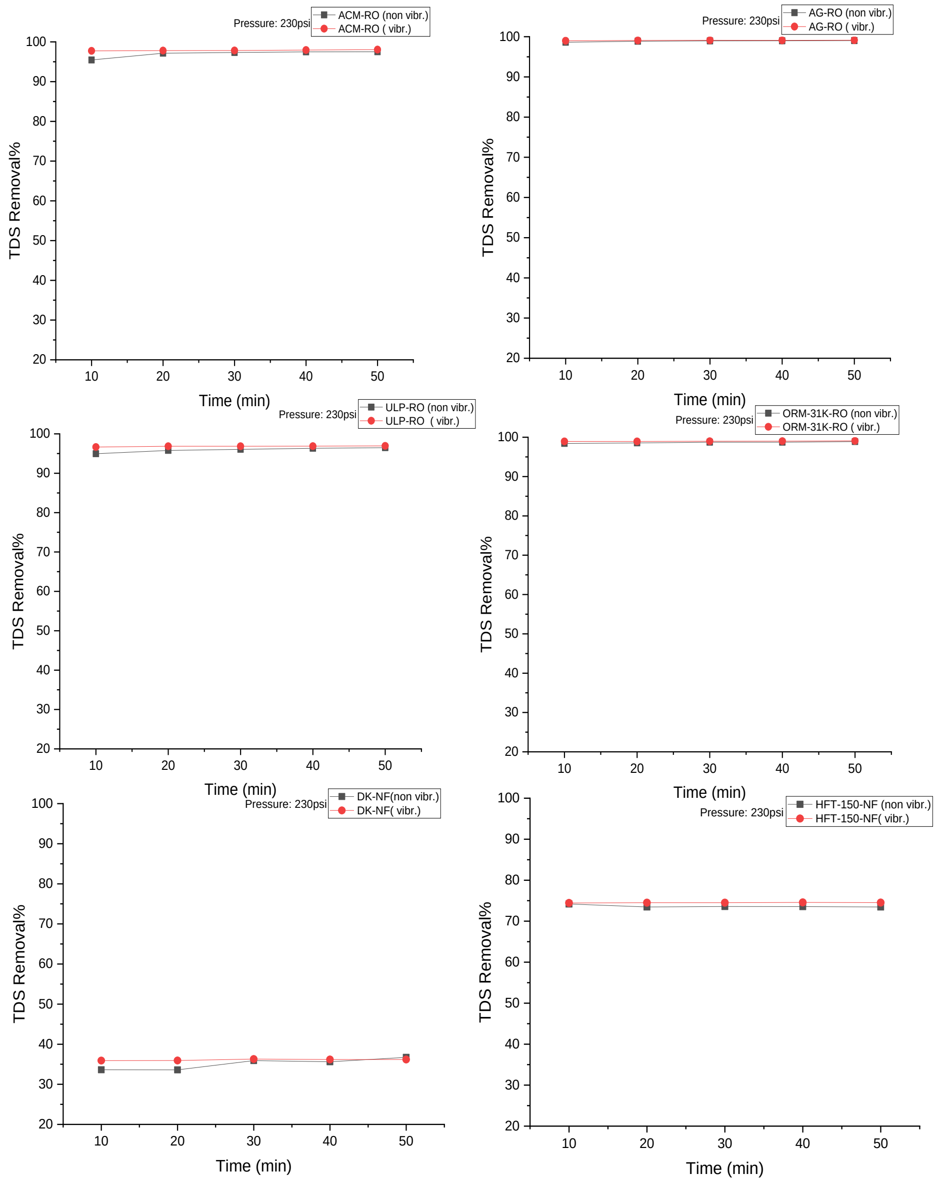


Figure 19: TDS removal of RO and NF membranes in membrane screening study

4.1.2. VSEP operation with vibration

The significance of this study is to introduce the vibration to the membrane system to investigate its effect on the treatment performance. VSEP technology is a vibration-based membrane technology designed to enhance the treatment performance of membranes. Hence, VSEP was functioned under the same operating conditions used in the previous study. The vibration was started at a frequency of 43Hz for 30 min as a conditioning step, then data is collected. As previously presented in Figure 17, the vibration increased the permeate flux in all membranes. This increase can be attributed to the fact that the generated high shear rates with vibrations guarantee a good distribution of the feed material over the membrane and lifting of foulant from the area close to the membrane surface and thereby increasing the flux. The flux increase was clearly evident for the ACM_RO, ULP-RO, and DK-NF membranes with, 24.43, 18.75, and 25.00 %, respectively. Kertész et al.[19] studied the effect of vibration on the flux rate of treated dairy water with time for a 240 Da NF-membrane and 50 Da RO-membrane. They also reported a flux rate increase of 2 times and 3 times for RO and NF membranes, respectively. The higher rate reported by Kertesz as compared to the results here is attributed to the difference between the pore sizes of the membranes. Another reason is the difference in water quality between dairy water and CWBD. These differences are in terms of both constituents and concentrations. In another study, Wisniewski et al. [38] found that the vibration resulted in an increase in the permeate flux by a factor of 1.6 and 4.5 of the conventional cross-flow filtration (CFF). This increase is higher than the obtained in this study because of the difference in the operating conditions, for example they operated at a vibration frequency of 54 Hz, while in this study the frequency was 43Hz. Higher vibrations frequency means more shear on the membrane surface, hence more foulant particles will be lifted of the membrane surface, resulting in higher flux.

In terms of TDS reduction, the vibration did not show any significant change, in fact, less than 1% increase for all membranes as shown previously in Figure 19. These findings are in line with the finding of the study carried out by Kertész et al. [19]. They investigated the impact of vibration on COD removal from dairy wastewater and found that there is no significant effect on rejection for NF and RO membranes.

Through the membrane screening studies, two membranes were eliminated based on their performance in terms of permeate quality and flux. Although RO AG membrane has the highest permeate quality, it is eliminated due to its low permeate flux. It is known that such membranes take a longer time to filter the entire batch of the feed tank, which is not economical.

Other RO membranes showed a good balance between high flux and quality. Despite the high permeate flux of the NF DK membrane, it is excluded due to the permeate quality. Having high-quality permeate is important when it comes to managing and using this treated effluent in various applications such as recycling or even discharging safely without adverse consequences into natural water systems.

After the screening study, the following three RO (ACM, ORM-31K, and ULP) and one NF (HFT-150) are considered in the remaining studies.

4.2.Pressure study

In this study, the pressure was increased from 230psi to 500psi in vibrating and non-vibrating modes. This was performed to study the effect of increasing the pressure on the permeate flux and quality. As illustrated in

Figure 20, for all membranes, increasing the pressure enhances the flux until it reaches a point where the flux becomes independent of pressure increase. This point is noted here as an optimal pressure and will be used in the concentration study. Operating at optimal pressure is significant because higher flux can be obtained, resulting in lower filtration time. It is important to report that in all considered membranes, the vibration has a significant role in enhancing the flux with pressure, which supports the findings in the previous membrane screening study. For example, at 440 psi in ACM membrane, around 32.44% difference increase was noted between the vibrating and non-vibrating membranes.

Similar trend can be found in ORM-31K membrane, however, the ULP membrane showed a major variation in flux between the vibrating and nonvibrating membranes, especially after 410 psi. The flux showed with vibration an increase by around 88% at a pressure of 440 psi (65-123 $L.m^{-2}.hr^{-1}$) compared to 21% (62-76 $L.m^{-2}.hr^{-1}$) in non-vibrating mode. From the previous membrane screening study, it was noticed that ULP membrane has a higher permeability compared to other membranes, which explains in addition to the pressure role the significant increase in the permeate flux. .The results of Wisniewski et al. [38]study using RO membrane is in line with the obtained results here. They found an increase in the permeate flux from 20 to 50 $L.m^{-2}.hr^{-1}$ when the TMP was increased from 1600 to 3050 psi at vibration frequency near 50Hz (d= 2.54cm). It is worth highlighting that the performance of ULP membrane in terms of flux outstands the one tested by Wisniewski because in this study the vibration frequency is only 43Hz. One can also observe that vibration helps in stabilizing the flux with time and results in a minor drop compared to the non-vibrating membrane which has a dramatic decrease in the flux with time, due to the rapid formation of a fouling layer on the membrane surface.

Aside from RO membranes, HFT-150 with vibration shows the increasing permeate flux trend with pressure until 350 psi; after that, the flux became independent of pressure increase and reached a plateau. Moreover, vibrating HFT-150 still has a higher flux compared to the non-vibrating one with an increase of around 72% at 350 psi. Wisniewski et al. [38] reported that applying the vibration in the pressure study using resulted in a significant enhancement in the flux of the NF membrane.

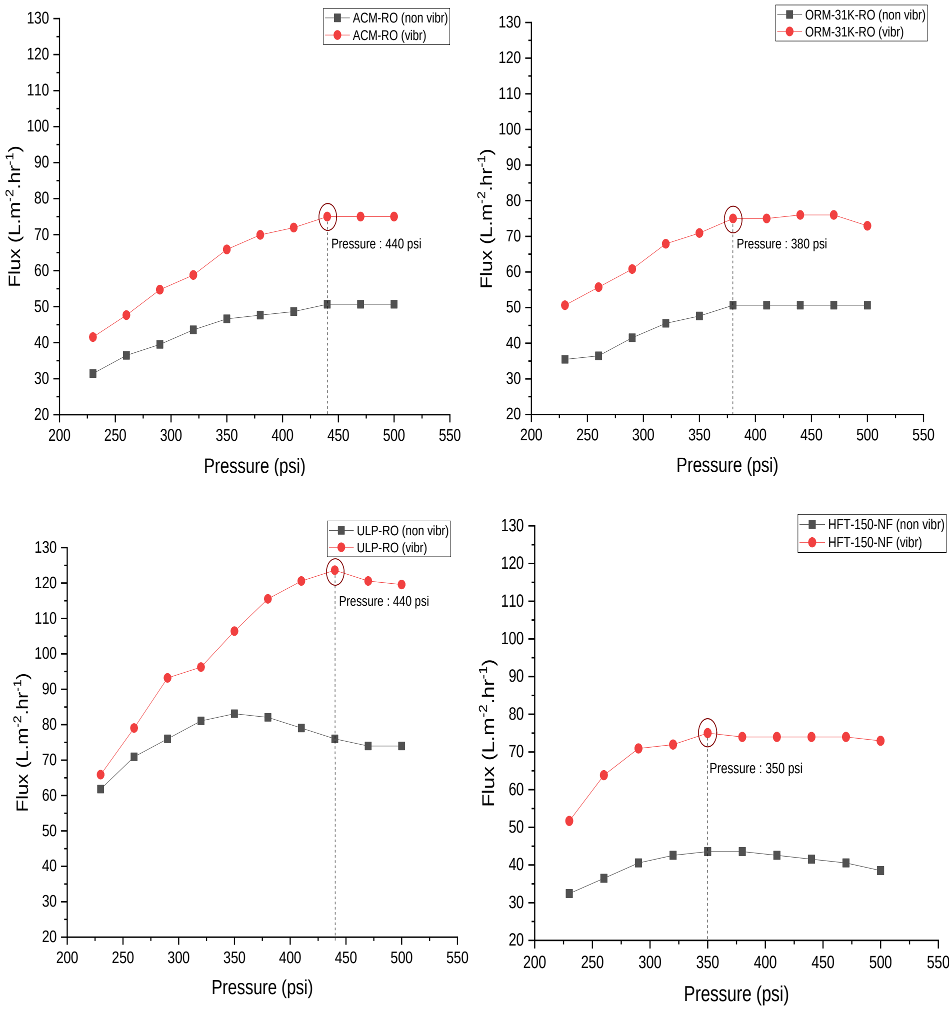


Figure 20: The effect of pressure on permeate flux.

The effect of pressure on the removal of TDS and major ions was insignificant for the RO membranes, as it already showed high rejection of TDS with vibration and maintained a removal above 97% for all membranes during the pressure study as shown in Figure 21. Similar results were noticed in a pressure study conducted by Wisniewski et al. [38], in which the rejection of conductivity in the both vibration and CFF filtration systems maintained a constant trend of about 98%.

On the other hand, the HFT-150 NF membrane showed an increase in the TDS rejection from 74 to 82% and 65.5 to 81% in vibrating and non-vibrating membranes, respectively. One reason that can justify this increase could be due to the increase in permeate flux, hence diluting and lowering the concentration of salts in the permeate. Similar trend was observed by Ahmed et al. [11] for a VSEP study with drinking water that shows increase in the arsenic rejection as applied pressure increases. Frappart et al, [48] noticed a reduction in the permeate conductivity by 50-75% as TMP pressure increases using NF membrane and justified that by the increase in the flux, while the ions diffusive mass transfers through the membrane stayed constant. Another reason for this increase is the reduction in the shielding factor with higher operating pressure, which makes repulsion more effective; hence a better rejection effect[227]. Abdelkader et al. [228] justified the increase in salt rejection in NF in terms of diffusion and convection[229]. In NF membranes, the contribution of convection overcomes diffusion as the pressure increases due to high permeate flux, thus increasing the rejection.

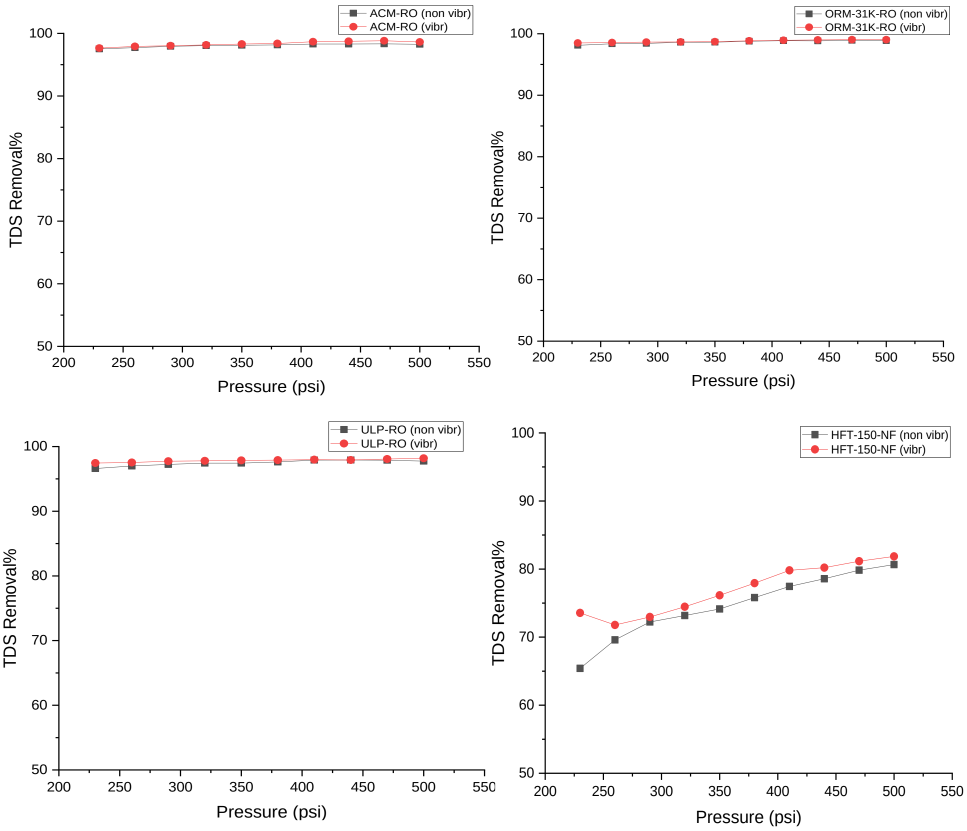


Figure 21: The effect of pressure on TDS removal

To get a better insight into the performance of the VSEP system that usees RO membranes in reducing the concentration of targeted contaminants in CWBD, ionic chromatography (IC) was used to analyze the feed and permeate samples. This is to investigate the effect of increasing the pressure and vibrating mode.

Figure 22 represents the ions that contribute the most to TDS, and they are sodium (Na+), calcium (Ca2+), potassium (K+), magnesium (Mg2+), chloride (Cl-), sulphate (SO42-), nitrate (NO3-), and bromide (Br-). Results revealed that for both ORM-31K and ULP membranes, increasing the pressure has little impact, less than 3% in the rejection of all stated dissolved ions, except nitrate. NO3- showed an increase in its removal by around 5% and 9% at a higher pressure for ORM-31k and ULP membranes, respectively. The general average reductions of Na+, Ca2+, K+, Mg2+, Cl-, SO42-, NO3-, and Br- for ORM and ULP membranes in the pressure study are summarized in Table 19.

Similar removal percentages of the listed constituents in Table 19 were resulted from Shi et al. [35] study as they were treating brine by RO membrane with almost the same characteristics of the applied ones in this work.

Out of these dissolved ions, the concentrations of SO_4^{2-} and Br^- were regulated in the Law 30, 2002 of Qatar as shown in Table 19. It can be concluded that the level of SO_4^{2-} in RO permeate (3-4ppm) is way lower than the regulated levels for irrigations (400ppm), and discharging into sewer network(1000ppm), however, it is slightly higher than the permitted level for discharging into marine environment(0.1ppm). On the other hand, the boron in the collected permeate is almost zero concentrated, thus it complies with all the regulated limits.

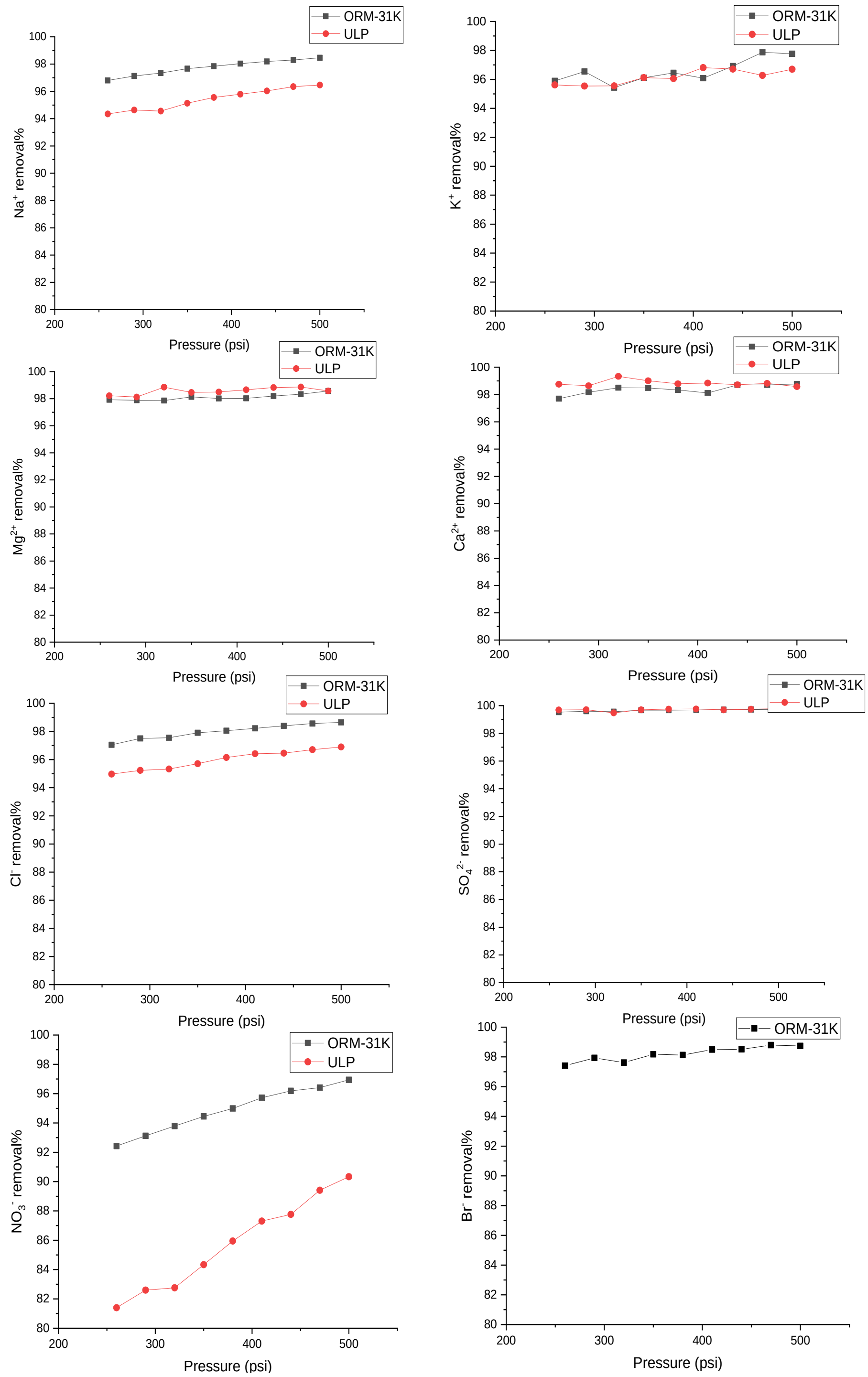


Figure 22: The effect of pressure on the removal of targeted ions

Table 19:Constituents concentration in the feed and permeate and corresponding removal%

	ORM-31K-RO		ULP-RO
Constituents		ppm	
Averaged Na+ in feed (ppm)	736		645
Averaged Na+ in permeate (ppm)	16		29
Na+ removal%	98		95
Averaged Ca2+ in feed (ppm)	197		344
Averaged Ca2+ in permeate (ppm)	3		4
Ca2+ removal%	98		99
Averaged K+ in feed (ppm)	57		52
Averaged K+ in permeate (ppm)	2		2
K+ removal%	96		96
Averaged Mg2+ in feed (ppm)	47		59
Averaged Mg2+ in permeate (ppm)	1		1
Mg2+ removal%	98		99
Averaged Cl- in feed (ppm)	1041		868
Averaged Cl- in permeate (ppm)	21		35
Cl- removal%	98		96
Averaged SO42- in feed (ppm)	852		1215
Averaged SO42- in permeate (ppm)	3		4
SO42- removal%	100		100
Regulated limit for irrigation		400	
Regulated limit for discharge into marine		0.1	
Regulated limit for discharge into public sewer network		1000	
Averaged NO3- in feed (ppm)	59		58
Averaged NO3- in permeate (ppm)	3		8
NO3- removal%	95		86
Averaged Br- in feed (ppm)	20		-
Averaged Br- in permeate (ppm)	0		-
Br- removal%	98		-
Regulated limit for irrigation		1.5	
Regulated limit for discharge into marine		1.5	

4.3.Vibration study

The vibration study was performed on ACM-RO and HFT-150-NF at pressures of 440 and 350 psi, respectively. The effect of increasing the vibration frequency between 0 to 43 Hz on the flux and permeate quality is investigated.

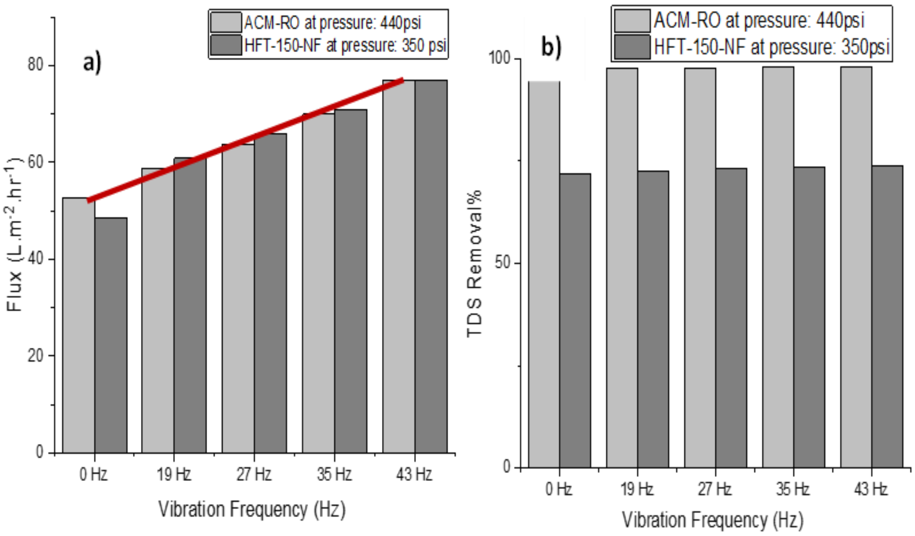


Figure 23:The effect of increasing the vibration frequency on a) permeate flux and b) TDS removal for ACM and HFT membranes.

Figure 23.a illustrates that the permeate flux for both membranes is gradually increasing, as the frequency of vibration increases by a step change of 8 Hz. It is known that both the applied shear rate at the membrane surface and the membrane displacement increase as vibration frequency is intensified. As previously discussed, the created shear by vibration reduces the fouling of membrane surface by reducing the concentration of polluted constituents on the membrane surface. Thus, the mass transfer of such constituents will be restricted through the membrane. In this study, the total increase was more significant when the vibration frequency was increased from 0 Hz to 43 Hz, as resulted in a flux increase of 45.3% and 57.1% for ACM-RO and HFT-150-NF, respectively.

Regarding the effect of increasing the vibration frequency on TDS removal% is shown in Figure 23.b; both membranes revealed a stable trend with no differences. This conclusion is in line with Kertész et al. [46] as they found that there is no significant effect on COD rejection for NF and RO membranes with vibration.

4.4. Concentration study:

In this study, the concentrate stream is circulated back to the feed tank, while the permeate line is separated into a collection tank. Thus, the system is not operating at a steady state condition, due to the increasing concentration of the feed.

The study is conducted to determine the amount of permeate that can be recovered and the effect of higher feed concentration on permeate flux and TDS rejection. The study was carried out over two days for 3-4 hrs per day because of the weak condition of the motor and VFD. The general trend of the permeate flux in all RO and NF membranes is decreasing during the first day of the study as shown in Figure 24.

This is because of the concentration polarization and the starting of foulant accumulation on the membrane surface. Similar trend was noticed in Wisniewski et al.[38] study as the flux was decreasing with the permeate recovery% from coffee wastewater by VSEP. This decrease can also be explained by the fact as more permeate is collected, the higher the membranes exposure to the elevated level of contaminants. Hence, the amount of water molecules decreases compared to other pollutants. The high contaminants concentration in the feed, speeds up the formation of a fouling layer thereby lowering the flux of permeate through the membrane.

On the second day, the permeate flux starts increasing slightly with time until it becomes almost constant. This increase is due to the flow of the process solution over the dry membrane that helps in reopening the pores, hence the permeate flux increases until it reaches almost a constant rate. The drop in permeate flux in the ACM, ORM, ULP, and HFT-150 membranes over the whole study was by 61.04, 66.18, 73.33, and 71.60%, respectively.

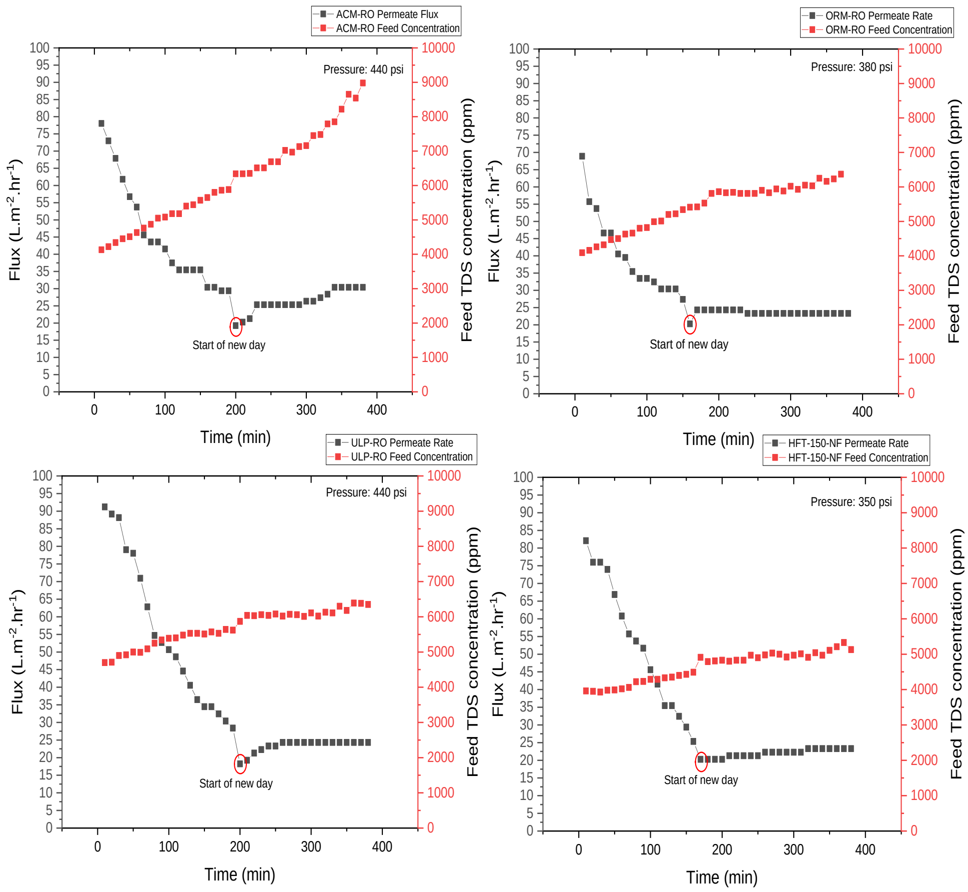


Figure 24: The effect of feed TDS concentration on the permeate flux with time

The treatment performance of the membranes in terms of TDS removal was studied and results are illustrated in Figure 25 and Figure 26. Although the TDS concentration of the feed increased as observed also in Shi et al. [21] study, the permeate quality in terms of TDS removal% showed only a minor reduction of 4% in ACM and ULP-RO membranes, while ORM-31k membrane revealed a constant trend throughout the study, indicating no impact. On the other hand, HFT-150 NF membrane showed a higher reduction in TDS removal by approximately 10%. One reason for this difference is that the pore size in the NF membrane is larger than the ones in RO, hence allowing the penetration of ions with a similar size or smaller than the membrane pore size.

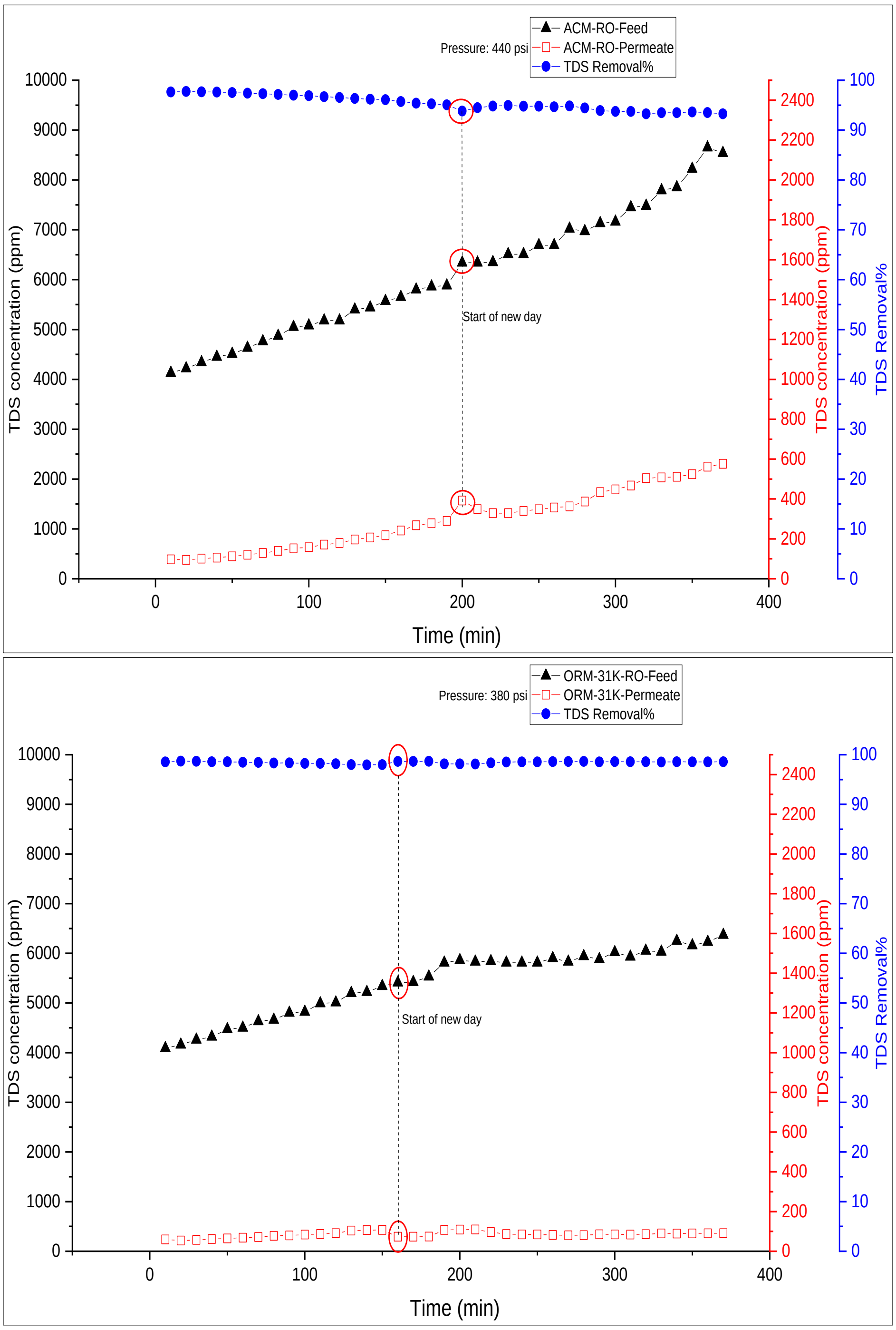
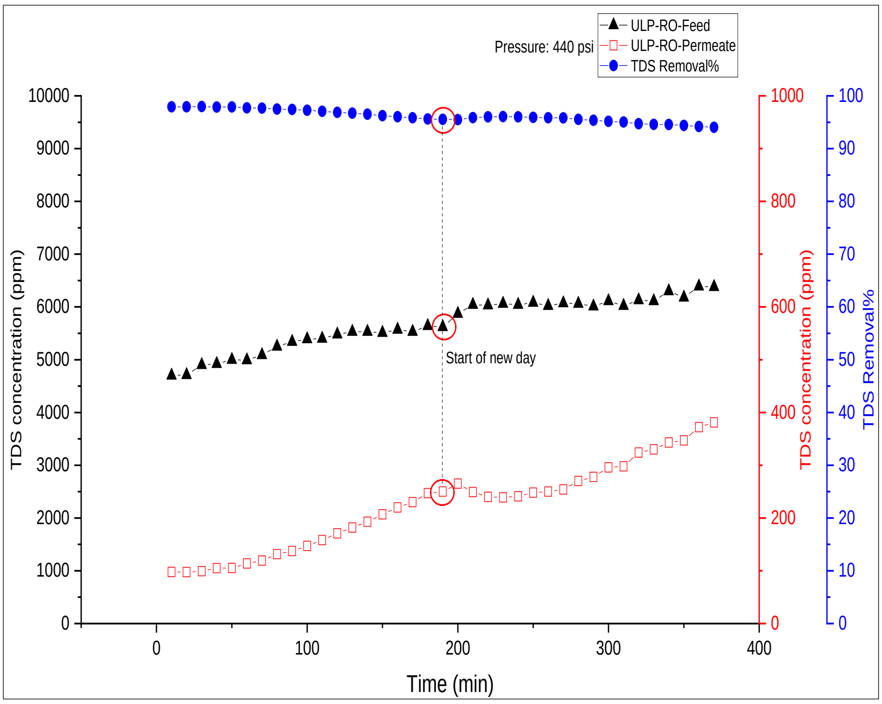


Figure 25: The effect of feed TDS concentration on the TDS removal with time for ACM and ORM-31K membranes.



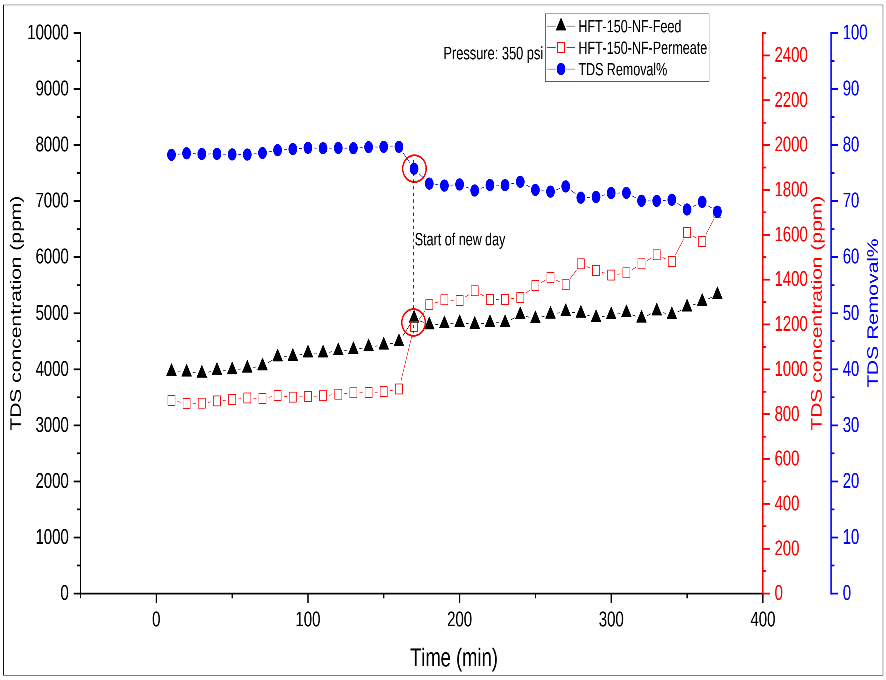


Figure 26: The effect of feed TDS concentration on the TDS removal with time for ULP and HFT membranes.

SEM and EDX analysis were performed on a dry clean and used HFT-150 membranes in the concentration study under vibration, to understand the distribution of the foulants on the membrane surface. As shown in Figure 27.a , the foulant layer does not cover the whole membrane surface, rather it is scattered in different areas, leaving clean parts, that allow the penetration of permeate. This was also observed by Shi et al. [21] in their study of the vibration effect on the type of the formed scale layer on the membrane surface after the treatment of brine solution by the VSEP system. They found that in a non-vibrating system, the scale-covered the membrane uniformly, compared to the vibrating system, in which the distribution of the scale layer becomes more scattered farther from the membrane center.

It was also noticed in our study that the layer on the dried fouled membrane gets removed with a simple movement of the membrane, which means that such fouling is reversible and can be reduced by cleaning.

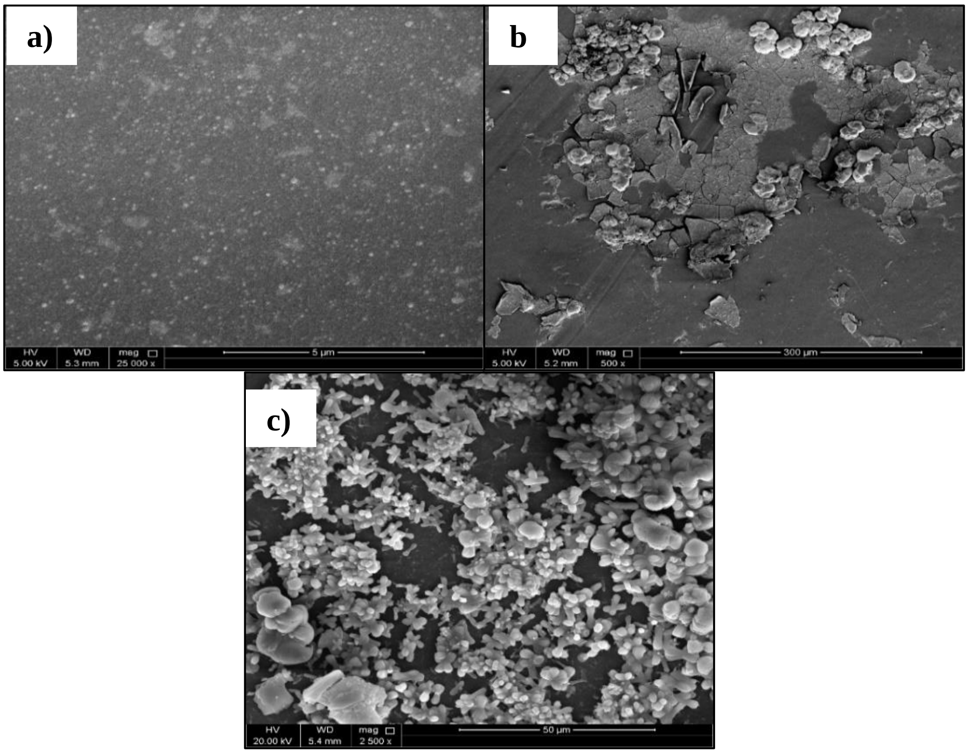


Figure 27: SEM of HFT-150 NF **a)** clean and **b& c)** fouled membrane.

EDX analysis was performed to understand the type of constituents deposited or created on the membrane surface of both clean and fouled membranes. Results shown in Figure 28.a , revealed that only carbon (C), oxygen (O), aluminum (Al), and silica (S) exist at the HFT membrane surface, while the fouled membrane in Figure 28.b has additional sodium (Na^{+}), magnesium (Mg^{2+}), chloride (Cl^{-}) and calcium (Ca^{2+}). Among these atoms, Ca^{2+} showed the highest level on the fouled membrane by around 16 atoms%; and calcium is one of the hardness-causing ions that result in scale layer formation. It was also revealed that the carbon level on the fouled membrane surface decreased by 68.13 % relative to the clean membrane. Similar trends are observed in the NF membranes studied by Kasim et al. [230] for the removal of Mg^{2+} and Fe^{3+} from groundwater. This might be attributed to the fact that during the membrane conditioning, the chemicals or preservative materials on the membrane surface are washed out, resulting in a lower level.

In contrast to carbon, it was observed that the level of oxygen at the fouled membrane increased from 16.29 to 56.38 atom%, which corresponds to an increase by a factor of 3.5. This is expected as water flows through the membrane that has oxygen molecules, hence oxidizing the membrane surface. The absence of Al^{3+} on the surface of the fouled membrane could be attributed to the masking of the Al3+ peak by a peak associated with Na^{+} or Mg^{2+}. This was also observed by Shi et al. [22], in which the S peak was masked by Pt peaks.

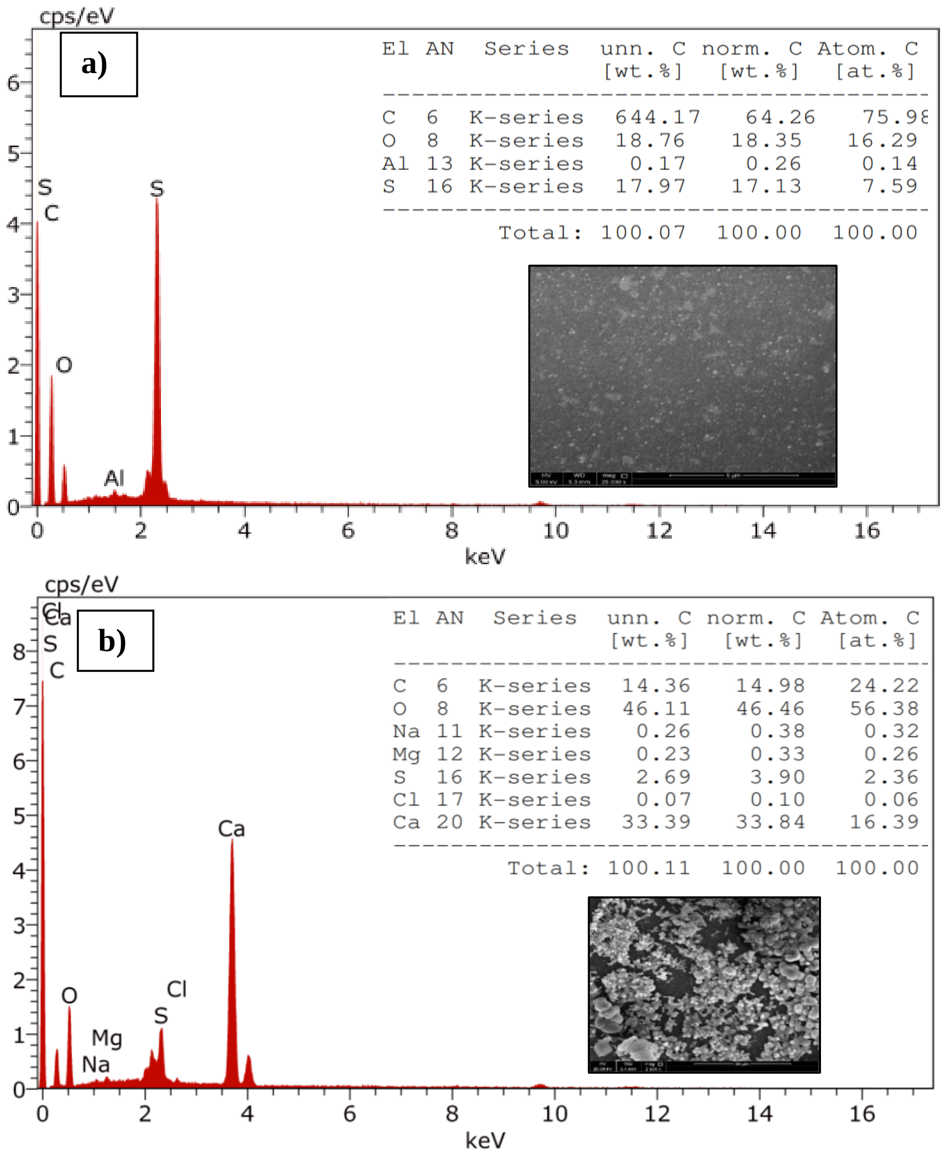


Figure 28: EDX of HFT-150 NF a) clean and b) fouled membrane

Although the membranes are presenting acceptable permeate fluxes between 23 and 30 L.m^{-2}.hr^{-1}, the concentration study is terminated due to cavitation. The amount of collected permeate and remaining feed (concentrate) were used to estimate the % recovery for each membrane as presented in Table 20. The recovery of permeate for all membranes is similar with minor % difference of ± 5%. These insignificant variations show that one can obtain high recovery using HFT-150-NF and ORM-31K membranes, while operating at a lower pressure of 350 and 380 psi, respectively. This is a major advantage when compared to recovery rates at a higher operating pressure of 440 psi, which results in higher operational costs. However, the permeate quality still should be considered based on the targeted usage of the treated stream as is discussed in section 4.6.

Table 20:Recovery study outcomes for RO and NF membranes

Membranes	Total Feed volume (L)	Permeate volume (L)	Remaining Feed volume (L)	Recovery%
ACM-RO	19.95	14.05	5.90	70.42
ORM-31K-RO	19.94	13.40	6.30	69.75
ULP-RO	20.05	15.05	5.00	75.06
HFT-150-NF	19.93	14.33	5.60	71.90

4.5. Cleaning study

This cleaning study is performed on ORM-RO to study the effect of acidic and basic cleaning on the membrane's performance in terms of flux and quality.

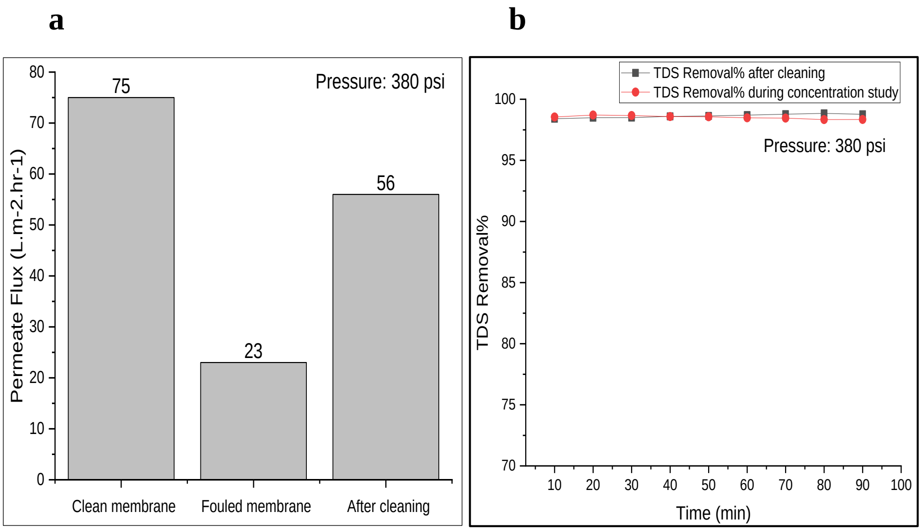


Figure 29:The effect of cleaning on **a)** permeate flux and **b)** TDS removal %.

The permeate flux at the optimal pressure is 75 L.m^{-2}.hr^{-1}with clean membranes and it dropped to 23 L. m^{-2}.hr^{-1} in the concentration study. It is worth mentioning that according to the manufacturing company, the membrane can be considered fouled when the flux is less than 10 L. m^{-2}.hr^{-1}. However, for the sake of this study, 23 L. m^{-2}.hr^{-1}will be considered as a fouled membrane because of the significant observed decline. Results revealed as illustrated in Figure 29.a that ORM-RO membrane reached a flux of 56 L. m^{-2}.hr^{-1}, after both acidic and basic cleaning, which corresponds to around 75% of the initial flux. This increase is due to the removal of the fouling layer on the membrane surface, which allows the flow of water molecules to pass across the membrane. Subramani et al. [31] was able to recover the initial flux by applying the same cleaning solutions to the RO membrane, however unlike this study, they operated at a higher temperature of 40 °C. It is well known increasing the temperature help in reducing the water viscosity, hence it increases flow through the membrane pores.

Regarding the permeate quality for TDS removal, Figure 29.b shows that the performance of the membranes before and after the cleaning was almost the same with a negligible difference.

4.6. Permeate management.

The main contribution of the presented study is discussing the possible alternatives to manage the treated CWBD. An outstanding permeate quality was determined for both NF and RO membranes. The generated water quality for VSEP, makes it suitable for reuse or discharge to wastewater treatment plants or surface water (sea). District cooling facilities (DC) can consider all three alternatives as options in the management of this CWBD. Herein, the quality of the permeate in terms of TDS will be compared to various applications or endpoints. *Figure 30* summarizes the management options of the treated CWBD.

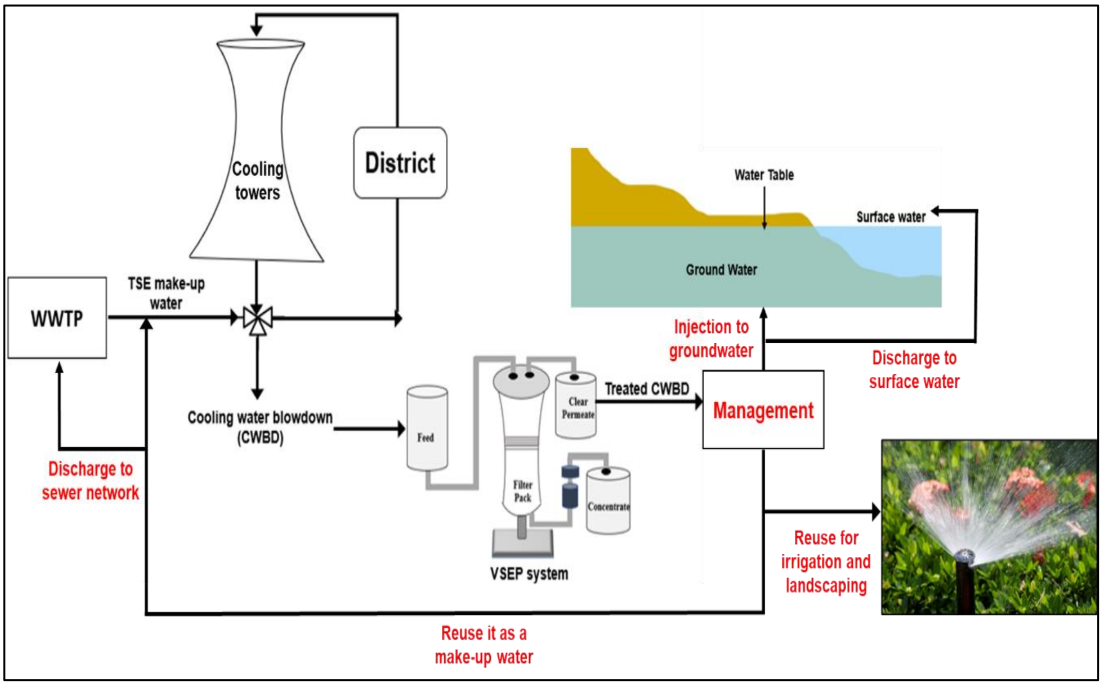


Figure 30:CWBD management options

Reusing Treated CWBD using VSEP in district cooling facilities

As part of the district cooling operation, an equivalent amount of the drained CWBD is sent to the cooling towers as make-up water to compensate for such loss in addition to the evaporation loss. In Qatar, the source of the makeup water to compensate for these losses is TSE with an average TDS of 1500 ppm [6]. However, due to the interruptions that might occur in the TSE flow and quality, desalinated potable water is used as an influent make-up water in the cooling tower. It is important to note that the quality of the drained CWBD depends on the feed quality and this also impacts the cycle of concentration (COC) of the process. COC is the amount of times water can be recirculated within the cooling system before blowdown to avoid scale formation within the process equipment.

Therefore, one of the possible options in managing the treated CWBD is sending it back to the cooling tower as makeup water. This is beneficial economically and environmentally. To elaborate more, the resulting permeate out of the VSEP-RO membranes has a TDS quality of a minimum of 50 and a maximum of 600 ppm during the concentration study. The direct usage of this high-quality stream or mixing it with TSE will help in having a better influent quality as it dilutes the TSE, resulting in increasing the COC and limiting or preventing the usage of potable water, hence protecting the environment.

If this option is selected to manage the treated CWBD, all RO membranes considered in this study will be suitable. However, ORM-31K membrane offers a good balance between the permeate flux and stable high quality, while operating at a lower pressure of 380 psi, compared to other RO membranes as shown in Figure 31, resulting in less operating cost.

For the HFT-150-NF membrane, although the permeate has an acceptable flux at an operating pressure of 350 psi, the TDS level shows a significant increase between 800 and 1800 ppm during the concentration study, which is quite similar to or slightly higher than the TSE quality. This will slightly limit the application the NF effluent as a cooling water, but it can be used in other applications inside the cooling facility such as in cleaning, rinsing, or other maintenance operations. Such conclusion was also considered by Wisniewski et al. [38] and they further suggest that it can be used as cooling water but after diluting the NF permeate.

Despite the suitability of using HFT-150-NF in treating CWBD, district cooling facilities will have to consider the trade-off between having an outstanding permeate quality with a slight increase in the operating cost with ORM-31K membrane (Pressure: 380 psi) or permeate quality similar to TSE at advantage of lower operating cost (pressure: 350 psi) with HFT-150-NF membrane.

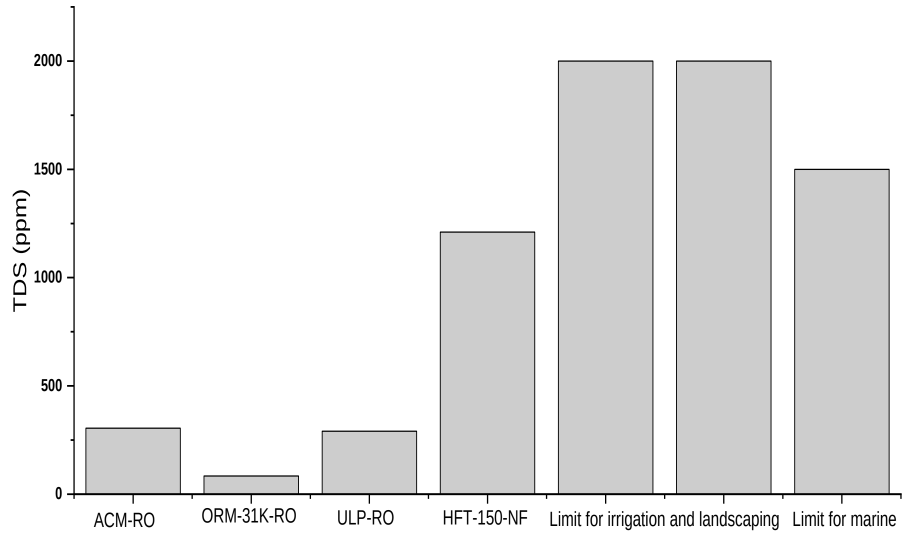


Figure 31:Permeate quality compares to regulated limits of irrigation, landscaping and marine in Qatar.

Reusing Treated CWBD using VSEP for landscaping and irrigation purposes

Part of managing the treated CWBD, is considering utilizing it in landscaping and irrigation. In cooling towers, all the added chemicals to the influent are soluble in water, which means that the recorded TDS accounts for these chemicals. Therefore, the TDS as a major constituent was compared to the regulations of Qatar by Law 30, 2002 for irrigation and landscaping with the averaged permeate quality of all membranes during the concentration study as shown in *Figure 31*. All membranes resulted in a permeate with a TDS level below the restricted limits. This assures that there will be no harm to the environment, the food chain, and human health.

Discharging Treated CWBD to Different End Points

Another option for managing treated CWBD is by discharging it into wastewater treatment plants (WWTPs). Generally, the influent to the WWTP has a TDS concentration above 1500 ppm, and is regulated to 4000 ppm from residential sources, according to Qatari law. Hence, discharging the high-quality permeate resulting from all tested membranes to WWTP will be suitable. In fact, it might dilute the WWTP effluent stream.

Surface water and groundwater can also be used as another discharge points. According to the regulations of Qatar indicated by Law 30, 2002 as shown in *Figure 31*, it permits the discharge of wastewater streams with a TDS level of 1500 ppm, which is higher than the average TDS level of permeate from RO and NF membranes. The TDS quality of treated CWBD is below the permitted limits set by lay for discharge into the marine environment.

In general, the discharging option to natural environments should be the last alternative, especially with such an outstanding permeate quality. The reuse of the treated CWBD in DC facilities as make-up water or even as tap water after disinfection should be highly considered. This will ensure cost savings because of the lower transportation cost, compared to other management options. It is important to highlight that the treatment cost should be taken into consideration, while taking the management decision to achieve the maximum benefits of the treated CWBD.

4.7. Limitations of the study

Before discussing the results, several limitations were faced during this research work and will be highlighted here. The VSEP unit at Qatar University was left without maintenance since the early 2000s and it was not working at the beginning. The system needed a lot of maintenance, but still some parts in the unit were highly affected such as the case of a vibration drive motor. Although the unit has the option of increasing the vibration frequency to 60Hz, it was limited to 43 Hz in this study as increasing it further causes damage to the motor and the Variable Frequency Drive (VFD) of the unit. The system also has other restrictions in terms of controlling the feed temperature and mixing of the feed. The temperature increases and varies in the studies according to the lab condition, in addition to the pump role in increasing the feed temperature. Unlike the performed studies that showed a minor increase in the temperature of only 3℃ during their studies[174], it was noticed in this study that the temperature might show an increasing trend between 20℃ to around 64℃. This can be attributed to the aged pump that does not have internal cooling. The effect of temperature change was not considered in this study as the obtained results did not show any unexpected trends. However, it is well known that increasing the temperature increases the permeate flux and lowers the rejection of pollutants as studied by Akoum et al. [8].

It is important to report that the system in general was weak and cannot withstand more than 4 hours of continuous work. It stops and the VFD gets burnt out if operated for more hours.

Despite these limitations, results were optimistic and the VSEP showed an outstanding performance in treating CWBD as illustrated before in the previous sections.

CHAPTER 5: OVERALL CONCLUSIONS AND FUTURE PERSPECTIVES

Vibratory sheared enhanced process (VSEP) system was evaluated for the treatment of CWBD. The performance of four RO (ACM, ORM-31K, ULP, AG) and two NF (DK and HFT-150) membranes were investigated. AG and DK membranes were eliminated in the membrane screening study because AG presented a low flux rate and DK low permeates quality. Introducing the vibration showed a noticeable effect in increasing permeate flux by 24.4, 5.7, 18.8, 1.9, 25.0 and 9.4% for ACM, AG, ULP, ORM 31K, DK, and HFT-150 relative to the non-vibrating system. In addition, optimum pressure at vibrating mode was determined to be 440, 440, 380, and 350 psi for ULP, ACM, ORM 31K, and HFT-150, respectively. The respective percentage recovery for ACM-RO, ORM-31K-RO, ULP-RO, and HFT-150-NF membranes were 70.4, 69.8, 75.1, and 71.9%. Cleaning the fouled ORM-31K membrane helped in recovering the permeate flux from 23 (fouled) to 56 $L.m^{-2}.hr^{-1}$ (clean).

A significant part of the study was to manage the CWBD treated effluent by suggesting various options such as reusing it as makeup water, which will help in enhancing the quality of the influent and increase the COC. Other alternatives presented include reusing in landscaping, irrigation, or discharging it to ground or surface water.

It is recommended that for future work to study the effect of other parameters together such pH, temperature, flowrate, and membrane pore size on the permeate flux and TDS removal% from CWBD. This is needed to give DC facilities a full picture of the performance of the VSEP unit. Part of expanding this work will be repeating the experiments at least three times to ensure the accuracy of the results and get an estimation of the error%. Performing more characterizations on the membranes will help deepen the analysis of the results and open future ideas on enhancing these membranes. Synthesizing membranes with certain features to enhance the flux and permeate quality, then applying them in the VSEP system would be an excellent addition to this research area.

As this research work was performed on a lab scale, considering scaling up the VSEP system to a pilot scale for the treatment of CWBD will give a clearer insight into the expected results at the industrial scale. Another important aspect that should be considered is the economics of the VSEP system. Performing an economical study on this unit and comparing it to other technologies will help in directing industrial people toward the most suitable method for CWBD treatment.

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