

**NOVEL CONFIGURATION OF INTEGRATED FORWARD
OSMOSIS-REVERSE OSMOSIS SYSTEM**

BY

MOHAMMED HASAN AHMED AL-BAITI

A Thesis Presented to the
DEANSHIP OF GRADUATE STUDIES

KING FAHD UNIVERSITY OF PETROLEUM & MINERALS

DHAHRAN, SAUDI ARABIA

In Partial Fulfillment of the
Requirements for the Degree of

MASTER OF SCIENCE

In

MECHANICAL ENGINEERING

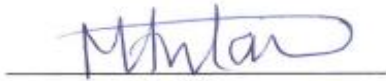
DECEMBER 2023

KING FAHD UNIVERSITY OF PETROLEUM & MINERALS

DHAHRAN- 31261, SAUDI ARABIA

DEANSHIP OF GRADUATE STUDIES

This thesis, written by MOHAMMED HASAN AHMED AL-BAITI under the direction of his thesis advisor and approved by his thesis committee, has been presented and accepted by the Dean of Graduate Studies, in partial fulfilment of the requirements for the degree of **MASTER OF SCIENCE IN MECHANICAL ENGINEERING**.



Dr. Mohammed Antar
Department Chairman



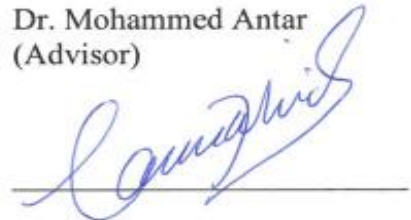
Dr. Suliman Al-Homidan
Dean of Graduate Studies

28 Dec 2023

Date



Dr. Mohammed Antar
(Advisor)



Dr. Umer Zahid
(Member)



Dr. Bilal Qureshi
(Member)



Dr. Ali Al-Shehri
(Member)



Dr. Dahiru Lawal
(Member)

© MOHAMMED HASAN AHMED AL-BAITI

2023

"To my beloved family"

ACKNOWLEDGMENTS

I would like to express my deepest gratitude to all those who have contributed to the successful completion of my MS degree. This journey has been made possible through the support, guidance directly or indirectly, and encouragement of numerous individuals, and I am honoured to acknowledge their contributions.

First and foremost, I would like to thank my thesis advisor, Dr. Mohammed Abdelkarim Antar for his invaluable mentorship and expertise. His guidance, patience, and continuous support have been instrumental in shaping my research and academic growth. I am truly grateful for his dedication and for believing in my potential.

I would also like to extend my appreciation to the members of my thesis committee, Dr. Umer Zahid, Dr. Bilal Qureshi, Dr. Ali Al-Shehri and Dr. Dahiru Lawal, for their valuable insights, constructive feedback, and expert evaluation of my work. Their expertise and diverse perspectives have enriched my research and contributed significantly to the quality of my thesis.

I am indebted to the King Fahd University of Petroleum & Minerals for providing me with the opportunity to pursue and successfully complete my Master of Science degree and Bachelor of Science degree previously. The support and resources offered by the university have played a pivotal role in my academic journey.

My heartfelt thanks go out to my family, who have stood by me throughout this demanding journey. Their unwavering love, encouragement, and understanding have been my constant

source of strength. I am grateful for their belief in me and for the sacrifices they have made to support my aspirations.

To all those mentioned above and the countless others who have played a part in my journey, I offer my heartfelt thanks. Your contributions have left an indelible mark on my educational pursuit, and I am grateful for the impact you have had on my life.

Thank you, one and all.

TABLE OF CONTENTS

ACKNOWLEDGMENTS	i
TABLE OF CONTENTS	iii
LIST OF TABLES	vi
LIST OF FIGURES	vii
NOMENCLATURE.....	xiv
ABSTRACT.....	xviii
ملخص الرسالة	xx
CHAPTER 1 INTRODUCTION	1
1.1 Thermal Based Water Desalination Technologies	2
1.2 Membrane Based Water Desalination Technologies	3
1.2.1 Osmosis process.	4
CHAPTER 2 LITERATURE REVIEW	10
2.1 Forward Osmosis as A Standalone Unit.	10
2.2 Forward Osmosis as Integrated Unit with Other Desalination Technologies.	
.....	11
CHAPTER 3 METHODOLOGY PROCEDURE	16
3.1 Mathematical Modelling.....	16
3.1.1 FO system model	16

3.1.2	RO system model	22
3.1.3	Specific energy consumption.	26
3.1.4	Economic analysis model	28
3.2	Engineering Equation Solver (EES) Software.....	32
3.3	Membrane selection	33
3.3.1	FO membrane.....	34
3.3.2	RO membrane.....	36
CHAPTER 4 RESULTS AND DISCUSSION.....		38
4.1	Forward Osmosis Units Integrated with A Single Reverse Osmosis Unit Located at The End.....	39
4.1.1	The effect of draw solution flow rates on water productivity with respect to the number of forward osmosis units.....	42
4.1.2	The effect of draw solution flow rate on recovery rate with respect to the number of forward osmosis units.....	45
4.1.3	The effect of draw solution flow rate on specific energy consumption with respect to the number of forward osmosis units.....	46
4.1.4	The effect of draw solution flow rate on economic feasibility with respect to the number of forward osmosis units.....	49
4.1.5	Hydraulic pressure effect on FO-RO system performance.	55
4.2	Six Forward Osmosis Units Integrated with A Single Reverse Osmosis Unit Located After First FO Unit.	60

4.2.1	Effect of FO-RO configurations on water productivity.....	64
4.2.2	Effect of FO-RO configurations on recovery rate.....	70
4.2.3	Effect of FO-RO configurations on specific energy consumption.	73
4.2.4	Economic feasibility assessment of FO-RO system.....	76
4.2.5	Hydraulic pressure effect on FO-RO system for different scenarios. ..	79
4.3	Six Forward Osmosis Units Integrated with A Single Reverse Osmosis Unit Located Prior to last FO Unit.	85
4.3.1	Effect of FO-RO configurations on water productivity.....	87
4.3.2	Effect of FO-RO configurations on recovery rate.....	91
4.3.3	Effect of FO-RO configurations on specific energy consumption.	94
4.3.4	Economic feasibility assessment of FO-RO system.....	98
4.3.5	Hydraulic pressure effect on FO-RO system for different scenarios.	101
CHAPTER 5 CONCLUSION.....		107
REFERENCES.....		109
VITAE.....		123

LIST OF TABLES

Table 3.1: Comparison of water flux between the developed model and experimental work results.	21
Table 3.2: CAPEX and OPEX calculations values.....	29
Table 3.3: FO membrane characterization.....	35
Table 3.4: RO membrane characterization.	37
Table 4.1: Operating conditions of FO-RO system.	40

LIST OF FIGURES

Figure 1.1: Schematic of osmosis phases a) osmosis, b) osmotic equilibrium, c) RO	5
Figure 1.2: Schematic of FO membrane layers, AL-FS mode	6
Figure 1.3: Schematic of RO unit	8
Figure 2.1: Integrated FO-RO system.....	12
Figure 3.1: Comparison of water flux between developed model and experimental work results.....	22
Figure 3.2: Comparison of flow rate between current model and validation work results.	26
Figure 4.1: FO-RO configuration connected in series.	41
Figure 4.2: Draw solution flow rate effect on water productivity for FO units No. connected with RO.	43
Figure 4.3: Water flux for each FO unit & RO units for different draw solution flow rates.	44
Figure 4.4: Effect of FO units No. connected with RO on the recovery rate.	46
Figure 4.5: Effect of FO units No. connected with RO on the SEC with & without ERD at draw flow rate $0.416 \text{ m}^3/\text{h}$ and $P = 31 \text{ bar}$	48

Figure 4.6: Effect of FO units No. connected with RO on the SEC with & without ERD for various DS flow rates.....	48
Figure 4.7: Effect of FO units No. connected with RO on the SWC with & without ERD for various DS flow rates.	51
Figure 4.8: Capital Cost of four FO units with RO unit.	52
Figure 4.9: Operational Cost of four FO units with RO unit.	53
Figure 4.10: Total Annualized expenses with respect to FO units.	54
Figure 4.11: Pressure effect on FO-RO system water productivity at different draw flow rates: 31 bar for $Q_d = 0.416 \text{ m}^3/\text{h}$, 34.5 bar for $Q_d = 0.520 \text{ m}^3/\text{h}$, and 38 bar for $Q_d = 0.625 \text{ m}^3/\text{h}$	56
Figure 4.12: Pressure effect on FO-RO system's SEC with & without ERD at different draw flow rates: 31 bar for $Q_d = 0.416 \text{ m}^3/\text{h}$, 34.5 bar for $Q_d = 0.520 \text{ m}^3/\text{h}$, and 38 bar for $Q_d = 0.625 \text{ m}^3/\text{h}$	58
Figure 4.13: Recovery rate of FO-RO system at different draw flow rates: 31 bar for $Q_d = 0.416 \text{ m}^3/\text{h}$, 34.5 bar for $Q_d = 0.520 \text{ m}^3/\text{h}$, and 38 bar for $Q_d = 0.625 \text{ m}^3/\text{h}$	59
Figure 4.14: Pressure effect on FO-RO system SEC with & without ERD at different draw flow rates: 31 bar for $Q_d = 0.416 \text{ m}^3/\text{h}$, 34.5 bar for $Q_d = 0.520 \text{ m}^3/\text{h}$, and 38 bar for $Q_d = 0.625 \text{ m}^3/\text{h}$	60
Figure 4.15: Six FO units connected with RO unit.....	61

Figure 4.16: Six different configuration of recirculating FO-RO system.....	63
Figure 4.17: Water productivity for six configurations at $Q_d = 0.416 \text{ m}^3/\text{h}$, $P = 34 \text{ bar}$...	66
Figure 4.18: Water productivity for six configurations at $Q_d = 0.520 \text{ m}^3/\text{h}$, $P = 34 \text{ bar}$...	68
Figure 4.19: Water productivity for six configurations at $Q_d = 0.625 \text{ m}^3/\text{h}$, $P = 34 \text{ bar}$..	69
Figure 4.20: Water productivity comparison for six configurations at $Q_d = 0.416, 0.520$ and $0.625 \text{ m}^3/\text{h}$	69
Figure 4.21: Recovery rate for six configurations at $Q_d = 0.416 \text{ m}^3/\text{h}$, $P = 34 \text{ bar}$	71
Figure 4.22: Recovery rate for six configurations at $Q_d = 0.520 \text{ m}^3/\text{h}$, $P = 34 \text{ bar}$	71
Figure 4.23: Recovery rate for six configurations at $Q_d = 0.625 \text{ m}^3/\text{h}$	72
Figure 4.24: Recovery rate comparison for six configurations at $Q_d = 0.416, 0.520$ and $0.625 \text{ m}^3/\text{h}$	72
Figure 4.25: Specific energy consumption for six configurations with & without ERD at $Q_d = 0.416 \text{ m}^3/\text{h}$, $P = 34 \text{ bar}$	73
Figure 4.26: Specific energy consumption for six configurations with & without ERD at $Q_d = 0.520 \text{ m}^3/\text{h}$, $P = 34 \text{ bar}$	74
Figure 4.27: Specific energy consumption for six configurations with & without ERD at $Q_d = 0.625 \text{ m}^3/\text{h}$, $P = 34 \text{ bar}$	75

Figure 4.28: Specific energy consumption comparison for six configurations with & without ERD at $Q_d = 0.416, 0.520$ and $0.625 \text{ m}^3/\text{h}$, $P = 34 \text{ bar}$	75
Figure 4.29: Specific water cost comparison for six configurations with & without ERD at $Q_d = 0.416, 0.520$ and $0.625 \text{ m}^3/\text{h}$, $P = 34 \text{ bar}$	77
Figure 4.30: Specific water cost for six configurations considering energy consumption with & without ERD at $Q_d = 0.416 \text{ m}^3/\text{h}$, $P = 34 \text{ bar}$	78
Figure 4.31: Specific water cost for six configurations considering energy consumption with & without ERD at $Q_d = 0.520 \text{ m}^3/\text{h}$, $P = 34 \text{ bar}$	78
Figure 4.32: Specific water cost for six configurations considering energy consumption with & without ERD at $Q_d = 0.625 \text{ m}^3/\text{h}$, $P = 34 \text{ bar}$	79
Figure 4.33: Pressure effect on water productivity of FO-RO system for six configurations at different draw flow rates: 34 bar for $Q_d = 0.416 \text{ m}^3/\text{h}$, 37 bar for $Q_d = 0.520 \text{ m}^3/\text{h}$, and 40 bar for $Q_d = 0.625 \text{ m}^3/\text{h}$	80
Figure 4.34: Water productivity FO-RO system for six configurations at draw flow rates of $Q_d = 0.416 \text{ m}^3/\text{h}$, $P = 34 \text{ bar}$	81
Figure 4.35: Water productivity FO-RO system for six configurations at draw flow rates of $Q_d = 0.520 \text{ m}^3/\text{h}$, $P = 37 \text{ bar}$	81
Figure 4.36: Water productivity FO-RO system for six configurations at draw flow rates of $Q_d = 0.625 \text{ m}^3/\text{h}$, and pressure of 40 bar.	82

Figure 4.37: Pressure effect on SEC of FO-RO system with & without ERD for six configurations at different draw flow rates: 34 bar for $Q_d = 0.416 \text{ m}^3/\text{h}$, 37 bar for $Q_d = 0.520 \text{ m}^3/\text{h}$, and 40 bar for $Q_d = 0.625 \text{ m}^3/\text{h}$	83
Figure 4.38: Pressure effect on SWC of FO-RO system with & without ERD for six configurations at different draw flow rates: 34 bar for $Q_d = 0.416 \text{ m}^3/\text{h}$, 37 bar for $Q_d = 0.520 \text{ m}^3/\text{h}$, and 40 bar for $Q_d = 0.625 \text{ m}^3/\text{h}$	84
Figure 4.39: Six FO units connected with RO unit located prior to last FO unit.	85
Figure 4.40: Six different configurations of recirculating FO-RO system.	87
Figure 4.41: Water productivity for six configurations at $Q_d = 0.416 \text{ m}^3/\text{h}$, $P = 31 \text{ bar}$...	88
Figure 4.42: Water productivity for six configurations at $Q_d = 0.520 \text{ m}^3/\text{h}$, $P = 31 \text{ bar}$..	89
Figure 4.43: Water productivity for six configurations at $Q_d = 0.625 \text{ m}^3/\text{h}$, $P = 31 \text{ bar}$...	89
Figure 4.44: Water productivity comparison for six configurations at $Q_d = 0.416, 0.520$ and $0.625 \text{ m}^3/\text{h}$	90
Figure 4.45: Recovery rate for six configurations at $Q_d = 0.416 \text{ m}^3/\text{h}$, $P = 31 \text{ bar}$	92
Figure 4.46: Recovery rate for six configurations at $Q_d = 0.520 \text{ m}^3/\text{h}$, $P = 31 \text{ bar}$	92
Figure 4.47: Recovery rate for six configurations at $Q_d = 0.0.625 \text{ m}^3/\text{h}$, $P = 31 \text{ bar}$	93
Figure 4.48: Recovery rate comparison for six configurations at $Q_d = 0.416, 0.520$ and $0.625 \text{ m}^3/\text{h}$, $P = 31 \text{ bar}$	94

Figure 4.49: Specific energy consumption for six configurations with & without ERD at $Q_d = 0.416 \text{ m}^3/\text{h}$, $P = 31 \text{ bar}$	95
Figure 4.50: Specific energy consumption for six configurations with & without ERD at $Q_d = 0.520 \text{ m}^3/\text{h}$, $P = 31 \text{ bar}$	96
Figure 4.51: Specific energy consumption for six configurations with & without ERD at $Q_d = 0.625 \text{ m}^3/\text{h}$, $P = 31 \text{ bar}$	97
Figure 4.52: Specific energy consumption comparison for six configurations with & without ERD at $Q_d = 0.416, 0.520 \text{ and } 0.625 \text{ m}^3/\text{h}$, $P = 31 \text{ bar}$	98
Figure 4.53: Specific water cost comparison for six configurations with & without ERD at $Q_d = 0.416, 0.520 \text{ and } 0.625 \text{ m}^3/\text{h}$, $P = 31 \text{ bar}$	99
Figure 4.54: Specific water cost for six configurations considering energy consumption with & without ERD at $Q_d = 0.416 \text{ m}^3/\text{h}$, $P = 31 \text{ bar}$	100
Figure 4.55: Specific water cost for six configurations considering energy consumption with & without ERD at $Q_d = 0.520 \text{ m}^3/\text{h}$, $P = 31 \text{ bar}$	100
Figure 4.56: Specific water cost for six configurations considering energy consumption with & without ERD at $Q_d = 0.416 \text{ m}^3/\text{h}$, $P = 31 \text{ bar}$	101
Figure 4.57: Pressure effect on water productivity of FO-RO system for six configurations at different draw flow rates: 31 bar for $Q_d = 0.416 \text{ m}^3/\text{h}$, 35 bar for $Q_d = 0.520 \text{ m}^3/\text{h}$, and 38 bar for $Q_d = 0.625 \text{ m}^3/\text{h}$	102

Figure 4.58: Water productivity FO-RO system for six configurations at draw flow rates of $Q_d = 0.416 \text{ m}^3/\text{h}$, $P = 31 \text{ bar}$	103
Figure 4.59: Water productivity FO-RO system for six configurations at draw flow rates of $Q_d = 0.520 \text{ m}^3/\text{h}$, $P = 35 \text{ bar}$	103
Figure 4.60: Water productivity FO-RO system for six configurations at draw flow rates of $Q_d = 0.625 \text{ m}^3/\text{h}$, $P = 38 \text{ bar}$	104
Figure 4.61: Pressure effect on SEC of FO-RO system with & without ERD for six configurations at different draw flow rates: 31 bar for $Q_d = 0.416 \text{ m}^3/\text{h}$, 35 bar for $Q_d = 0.520 \text{ m}^3/\text{h}$, and 38 bar for $Q_d = 0.625 \text{ m}^3/\text{h}$	105
Figure 4.62: Pressure effect on SWC of FO-RO system with & without ERD for six configurations at different draw flow rates: 31 bar for $Q_d = 0.416 \text{ m}^3/\text{h}$, 35 bar for $Q_d = 0.520 \text{ m}^3/\text{h}$, and 38 bar for $Q_d = 0.625 \text{ m}^3/\text{h}$	106

NOMENCLATURE

Acronyms

BWRO	brackish water RO
DS	draw solution
ECP	external concentration polarization
ED	electrodialysis
FO	forward osmosis
FS	feed solution
ICP	internal concentration polarization
LPRO	low-pressure reverse osmosis
MD	membrane distillation
MED	multi-effect distillation
MRF	membrane replacement factor
MSF	multi-stage flash
NF	nanofiltration
RO	reverse osmosis
SEC	specific energy consumption
SEEC	specific electric energy consumption
STEC	specific thermal energy consumption
SWC	specific water cost
SWRO	sea water RO
TAC	total annualized cost
TACC	total annualized capital cost

TAOC	total annualized operational cost
TCC	total capital cost
TDS	total dissolved solid
TFC	thin-film composite
UF	ultrafiltration
VCD	vapor compression distillation
WHO	World Health Organization

Roman Symbols

A	cross sectional area, m^2
A_m	effective membrane area, m^2
A_w	water permeability coefficient, $m/s \cdot Pa$
B_s	solute permeability coefficient, m/s
C	concentration, mg/l
CP	concentration polarization factor
D	solute diffusion coefficient, m^2/s
d_H	channel hydrodynamic parameter, m
H	channel height, m
J_s	salt flux rate, mol/m^2s
J_w	water flux rate, m/s
K_{ICP}	solute diffusion resistance coefficient, s/m
k	mass transfer coefficient, m/s
L_f	load factor
M_s	solute transport across the membrane, mol/s

P	pressure, <i>bar</i>
Q	flow rate, m^3/s
Re	Reynolds number
R_g	universal gas constant, $J/mol \cdot K$
R_j	salt rejection rate
RR	recovery rate
Sc	Schmidt number
Sh	Sherwood number
T	temperature, °C
U	velocity, m/s
W	width of channel, m

Greek Symbols

β	van't hoff coefficient
Δ	difference
η	efficiency, %
μ	water viscosity, $kg/m \cdot s$
π	osmotic pressure, bar
ρ	water density, kg/m^3
ϕ	spacer porosity

Subscripts

c	feed concentrate
d	draw side

<i>dd</i>	diluted draw
<i>eff</i>	effective
<i>elec</i>	electricity
<i>f</i>	feed side
FO	forward osmosis
<i>P</i>	permeate
RO	reverse osmosis
<i>swip</i>	seawater intake pre-treatment

ABSTRACT

Full Name : Mohammed Hasan Ahmed Al-Baiti.

Thesis Title : Novel Configuration of Integrated Forward Osmosis-Reverse Osmosis System

Major Field : Mechanical Engineering

Date of Degree : December 2023

Nowadays, the demand of the clean water is rapidly increasing due to population growth, industrial activities, human activities, etc. The desalination processes are globally being operating for decades to occupy the demand of clean water especially in regions with scarcity of clean water. Recently a FO technology has gained more attention for its high effective performance in term of energy consumption. FO can be operated as a standalone system which shows high energy consumption effectiveness, since it does not require high pressure input to run the system. However, FO requires a regeneration system to conduct the goal of desalination such as RO. In this research study, FO system is integrated with RO system to examine a proposed FO-RO configuration system. This new configuration system is proposed so that couple of FO units with one RO unit are integrated. A computational model is developed using an EES (Engineering Equation Solver) program for FO and RO systems and such that the model is verified against previous work done for both systems. The importance of this research is to explore the utilization of multi-FO units with RO unit and assess the effectiveness of water flux performance and specific energy consumption along with economic feasibility.

Six different scenarios are examined at various draw flow rates. The concentration of draw solution and feed solution are considered as Arabian gulf sea of 42,000 ppm and brackish water of 10,000 ppm, respectively. An energy recovery device was incorporated to minimize the SEC by utilizing the high pressure outputted RO unit and recharges with feed flow rate resulted from FO unit and enters RO unit. Systems showed a potential performance in terms of water productivity and specific energy consumption, in addition to an economic feasibility.

ملخص الرسالة

الاسم الكامل: محمد حسن أحمد البيتي.

عنوان الرسالة: "نظام مبتكر لعملية التحلية المتكاملة بتقنية التناضح الأمامي وتقنية التناضح العكسي".

التخصص: الهندسة الميكانيكية.

تاريخ الدرجة العلمية: جمادى الثاني ١٤٤٥.

في الوقت الحالي، يتزايد الطلب على المياه النظيفة بوتيرة سريعة نتيجة للنمو السكاني والأنشطة الصناعية والبشرية. تعمل تقنيات تحلية المياه على مستوى عالمي منذ عقود لتلبية الطلب على المياه النظيفة خاصة في المناطق التي تعاني من نقص المياه. في الآونة الأخيرة، أصبحت تكنولوجيا التناضح الأمامي تحظى بمزيد من الاهتمام بسبب أدائها الفعال فيما يتعلق باستهلاك الطاقة. حيث يمكن أن يعمل هذا النظام كوحدة مستقلة، مما يظهر فعالية عالية في استهلاك الطاقة، إذ إنه لا يتطلب ضغط هيدروليكي عالي لتشغيله. ومع ذلك، يتطلب نظام التناضح الأمامي نظام تجديد آخر لتحقيق هدف تحلية المياه مثل عملية التناضح العكسي. في هذه الدراسة البحثية، تم دمج نظام التناضح الأمامي مع نظام التناضح العكسي لتكوين نظام متكامل. تم اقتراح هذا النظام الجديد بحيث يتم دمج عدة وحدات من عملية التناضح الأمامي مع وحدة تناضح عكسي واحدة. حيث تم تطوير نموذج حسابي باستخدام برنامج تحليل المعادلات الهندسية (EES) للنظام كاملاً. وتم التحقق من صحة وكفاءة النموذج بالمقارنة مع الأبحاث السابقة المنجزة لكل من النظامين. تكمن أهمية هذه الدراسة البحثية في استكشاف استخدام وحدات متعددة من تقنية التناضح الأمامي مع تقنية واحدة من التناضح العكسي وتقييم فعالية أداء تدفق المياه واستهلاك الطاقة بالإضافة إلى الجدوى الاقتصادية.

كُونت ستة أنظمة مختلفة وأختبرت كفاءتها عند معدلات تدفق مختلفة. وأستخدمت تراكيز محلول السحب ومحلول التغذية بما يعادل ٤٢٠٠٠ جزء في المليون و ١٠٠٠٠ جزء في المليون، على التوالي. وتم إضافة جهاز استرداد الطاقة لتقليل استهلاك الطاقة الخاص بالنظام باستخدام الضغط العالي الناتج من وحدة التناضح العكسي وإعادة ربطة مع معدل تدفق المغذي الناتج من وحدة التناضح الأمامي وإدخاله إلى وحدة التناضح العكسي. أظهرت الأنظمة أداءً جيداً من حيث إنتاج المياه واستهلاك الطاقة، بالإضافة إلى الجدوى الاقتصادية.

CHAPTER 1

INTRODUCTION

Water is a crucial resource for humanity and developing nations, yet now, a fifth of the world's population has only very limited access to it, and a further quarter has access but no means of making it drinkable [1], [2], [3]. Knowing that water on earth distributed to portions such that 97% is salty, with the remaining 3% being made up of glaciers, groundwater, and surface fresh water [4]. In 2005, WHO published a report on statistics for the year 2002 stating that 1.1 billion people had lack access to fresh water where two thirds are located are in Asia. In sub-Sahara Africa, more than two fifth of population still have no freshwater access (WHO, 2005). In addition to global population growth, it is expected the water scarcity would extend from aforementioned regions to include Asia-Pacific regions, the Middle East and Central and South America by 2025 [5]. There are few factors can be identified as contributing to the growing water crisis such as growth of population, climate change, urbanization, and the depletion of scarce fresh water supplies. Researchers have invested a lot of time and energy into finding a solution to the freshwater shortage by investigating revolutionary desalination and wastewater treatment technologies that are cost effective and much more efficient.

In Saudi Arabia, water abundance is limited since there is no permanent source of water like rivers, lakes, as well as a lack of rainfall. The sources of water that supply region's needs are ground water, surface water and desalinated technologies. Globally Saudi Arabia

has one of the largest desalinated plants. A hybrid plant of 8 MSF stages and 17 RO units in Ras Al-khair is considered globally as the largest desalination plant [6]. However, this type of plant consumes a massive energy, as a heat to evaporate saline water for MSF, and so for the RO plant a high pressure is required.

The well-known desalination technologies categories into two major groups: thermal based technologies and membrane-based technologies. The former one operates essentially by thermal mean in form of vapor and an electrical mean as a side source of energy for operation process such as MSF, MED, and VCD. These technologies are tremendously energy consumption built in dependence on thermal energy from fuel combustion. The latter one is a separation process which involves a membrane and a pressurizing process operated by electrical energy such as FO, RO, MD, ED, etc [4], [7] [8]. These membrane processes are classified under the corresponding membrane structures and driving forces.

1.1 Thermal Based Water Desalination Technologies

Thermal desalination methods, particularly through techniques like MSF and MED, were the predominant choices in the early stages of desalination development. This was primarily because they closely imitate the natural water cycle and contributed significantly to the global desalination capacity until the 1980s when membrane desalination technologies saw significant advancements [9]. Thermal processes are characterized by their high energy consumption, relying on thermal energy for water evaporation, which involves both sensible and latent heat, as well as electrical energy for various process utilities such as pumps. Consequently, thermal desalination is typically favoured in regions

where energy costs are low or subsidized. Additionally, it's employed when dealing with high feedwater salinity, the need for high recoveries, and elevated feedwater temperatures [10].

Thermal desalination techniques are characterized by their substantial energy demands, relying on the utilization of two distinct forms of energy. The first is thermal energy, which plays a crucial role in supplying the essential sensible and latent heat required for the process of vaporization. This process involves heating the water to transform it into vapor. The second form of energy is electrical energy, which is essential for operating various plant facilities and equipment that support the thermal desalination process. This dual-energy requirement underscores the complex and resource-intensive nature of thermal desalination technologies. These methods are particularly effective in regions where a surplus of both thermal and electrical energy resources is available, making them a practical choice for meeting the water needs of certain areas [11].

1.2 Membrane Based Water Desalination Technologies

The process of desalination by membranes is globally in the concern for decades. This rapid growth and innovations came from the growing demand for fresh water and a new technology is needed to overcome obstacles associated with conventional thermal technologies, not exclusive, like the energy consumption, scaling up and down. These technologies are mainly a pressure driving force. However, a thermal evaporation energy can be combined with a pressure force such as MD. In order to select a practical separation process two essential criteria are taken into consideration: 1) technical feasibility, and 2)

economic feasibility. In this research, membrane technologies will be investigated and classified as pressure driving force.

1.2.1 Osmosis process.

Osmosis is a fundamental natural phenomenon that occurs when a semi-permeable membrane separates two solutions with varying concentrations. In this process, the movement of water molecules takes place from an area of lower solute concentration to an area of higher solute concentration. This movement occurs without any external energy input, driven by the natural tendency of water molecules to balance the solute concentrations on both sides of the membrane see Figure 1.1a. This phenomenon inspired scientists to invent technologies run in the same way to detach water molecules from impurities. The most common technology based on this phenomenon is RO, which operates in opposite manner of osmosis phenomenon, in which water is pressurized from solution with high concentration to solution with low concentration through membrane where salts are nearly completely retained. The other technology is FO, which has arisen as one of the potential energy efficient membrane technologies producing clean water and utilizing on a wastewater treatment and reclamation processes as integrated with other desalination system.

1.2.1.1 Forward osmosis process.

FO technology occurs by the difference of osmotic pressure generated through the membrane to voluntarily induce water transporting while the semipermeable membrane

rejects most of solutes, in which water permeates from the solution with low concentration named FS, which has low osmotic pressure, to the solution with high concentration named DS, which has high osmotic pressure, see Figure 1.2. In other word, this process utilizes osmotic pressure to separate water from dissolved solutes [12], [13], [14].

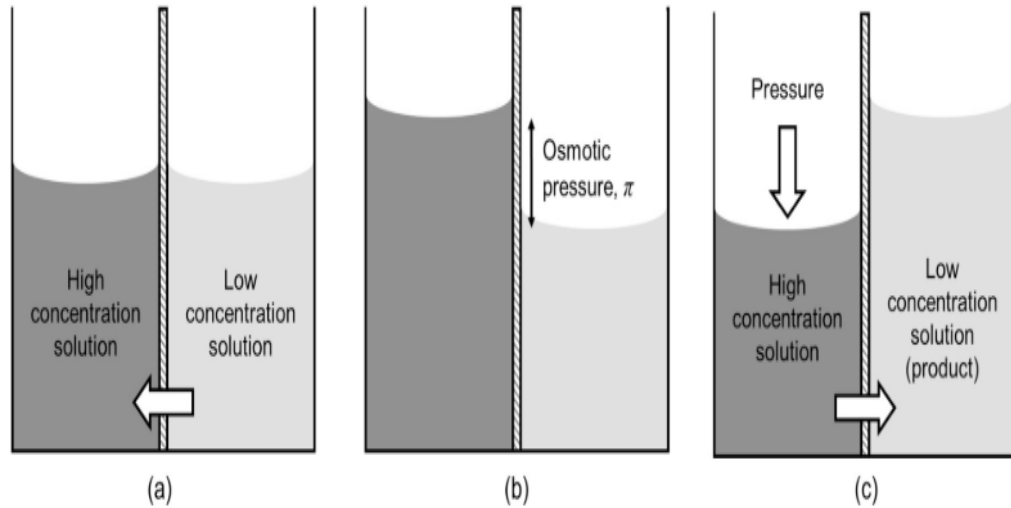


Figure 1.1: Schematic of osmosis phases a) osmosis, b) osmotic equilibrium, c) RO (Adopted from [15])

FO technique is considered as a two-step process where an osmosis step requires a recovery step, in which as the DS receives permeated water, it becomes diluted, which requiring another separation step to separate distilled water and regenerate the DS. Once the draw solute in the DS is retrieved, it is recycled for FO reuse again [16], [17]. The potentially of FO technology that it can be operated as a standalone unit without regeneration process and as an integrated unit with regeneration process [18], [19].

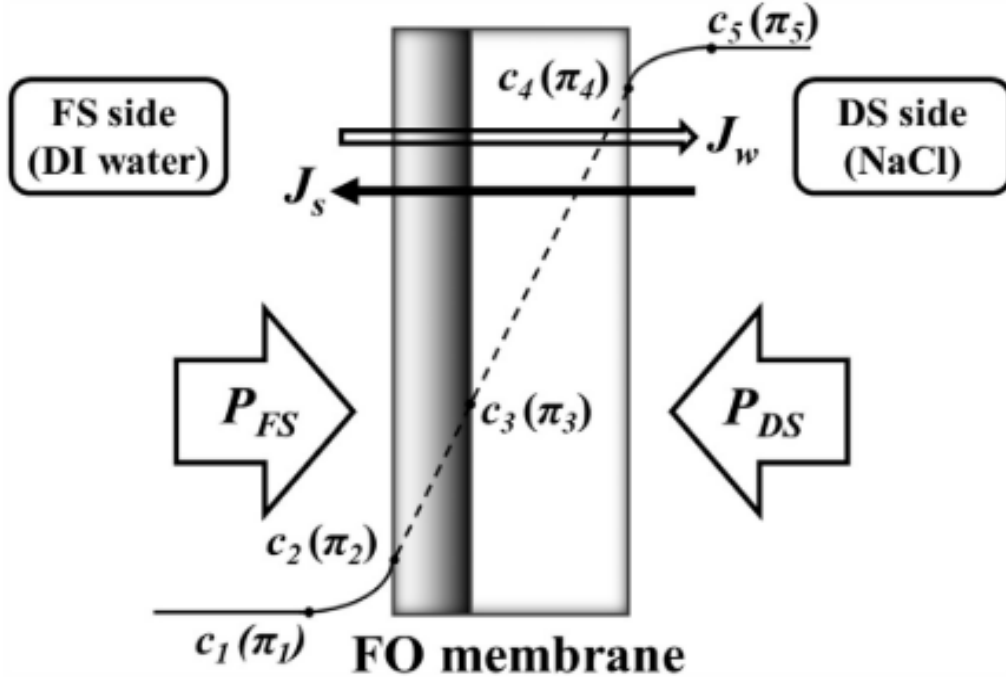


Figure 1.2: Schematic of FO membrane layers, AL-FS mode (Adopted from [20]).

In order to employ FO for long-term water reclamation and desalination of seawater, the system has to provide: 1) membranes with high-performance, 2) effective draw solutes, and 3) simple regeneration system to recover draw solutes and achieve clean water [21]. Generally, FO is considered as low-energy desalination technology compared to other desalination technologies. Since the permeation of water from feed solution with low concentration to draw solution with high concentration is a low-energy process occurred by osmotic flow, then the energy consumption of the overall process is only defined by the DS recovery stage. FO has the potential to operate at higher feed concentration than conventional membrane technologies such RO with low energy consumption and less cost as a result [22], [23]. Also, unlike other membrane technologies, fouling effect in FO process was found to be reversible, dispersed, and uncompressed, since there is a low hydraulic pressure involved. Moreover, it can be easily cleaned by physical washing [24],

[25]. On the other side, FO technology is impeded by numerous of factors, lack of appropriate membrane, an applicable draw solution, and DS regeneration technique with high performance [26].

Aforementioned, it is stated that FO needs a regeneration unit so clean water is achieved from diluted draw solution and in this case the system is known as integrated system. This integrate desalination system can be two or more desalination technologies to improve performance and minimize cost. Integrated systems employ a synergistic approach to overcome constraints of standalone processes and enhance overall system performance. Wherefore, FO can also be combined with other technologies for improving and enhancing the performance of FO. These integrated systems are categorized into five groups: thermally driven systems, pressure driven filtration, precipitation-based, electrolytic recovery, and magnetic recovery systems [4]. FO technology can be integrated with other technologies either as pre-treatment step before other desalination technologies or as post-treatment process after desalination technologies for achieving zero liquid discharge [14].

1.2.1.2 Reverse Osmosis Process.

RO technology is the most effective technology for sea and brackish water desalination, and it is considered as an alternative technique for producing fresh water with minimum cost compared to traditional technologies that use heat energy [27], [28], [29]. Based on the intake water salinity the RO is classified into two groups BWRO plants and SWRO plants. The first group salinity ranges from 500-10,000 mg/L and the second one is around

30,000 mg/L, respectively. Due to the capability of RO to handle these values of salinities, 50% of the global water desalination is done by it [29].

As seen in Figure 1.3, unlike FO unit, there is one inlet stream called water feed stream which divides into two streams one as a brine stream with high salinity than the feed stream and the other is the desalinated water (product) with almost free salts [15].

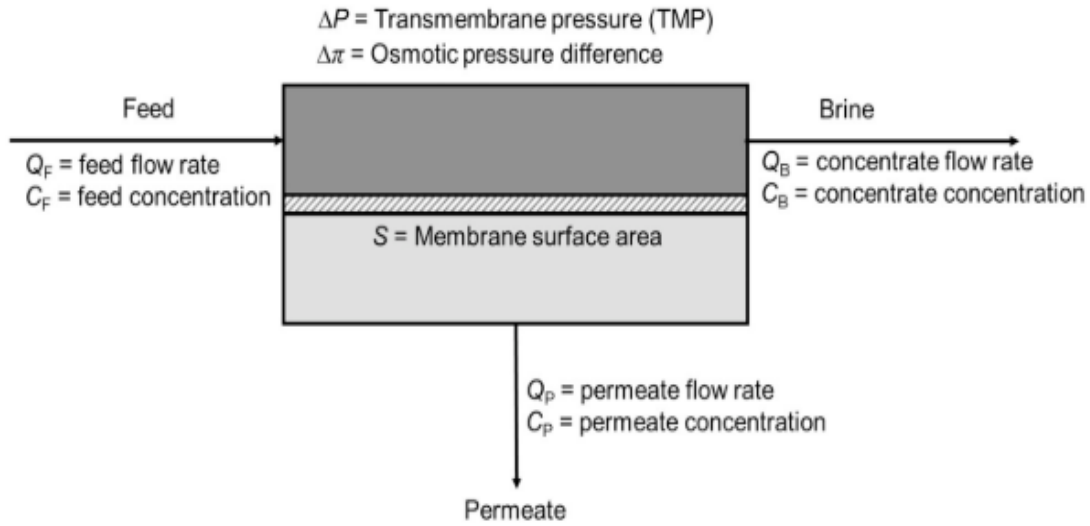


Figure 1.3: Schematic of RO unit (Adapted from [8]).

The main objective of this study is to employ a new effective FO-RO configuration in term of production performance of clean water including energy consumption of the whole system as well. The aim is to explore the potential of this innovative setup in desalination. The proposed system consists of couple FO units operated with single RO unit to achieve as maximum as possible of water flux with a less amount of energy consumption. The innovative FO-RO configuration has the potential to enhance water treatment efficiency, reduce energy consumption, and improve the overall quality of treated water. By employing a carefully selected draw solution in the FO stage, it is possible to concentrate

the feed solution while maintaining a low fouling potential. This concentrated feed solution is then further purified through the RO stage, where smaller molecules, ions, and remaining contaminants are selectively removed.

In conclusion, the main objective of this study is to employ a new effective FO-RO configuration for sea water desalination applications, by combining the benefits of both FO and RO processes. The study aims to provide valuable insights into the performance, optimization, and practical implementation of the FO-RO configuration.

CHAPTER 2

LITERATURE REVIEW

The purpose of the literature review is to provide a comprehensive overview of the existing research and knowledge on a particular topic. It aims to provide an overview of the current state of knowledge and identify any gaps or areas for further research. In this review, we aim to identify the key themes, and gaps in the literature, and to synthesize the findings from various studies. In this review, we will examine the current state of knowledge on FO desalination technology specifically on the energy consumption related to water productivity in case of integrated with other existing desalination technologies and identify the research needs and opportunities for further investigation. The review will critically evaluate the strengths and limitations of the research and identify any gaps or inconsistencies in the literature. Finally, the review will conclude by highlighting the key contributions of the literature and outlining the directions for future research.

2.1 Forward Osmosis as A Standalone Unit.

FO is a promising technology for desalinated and reclaimed water. Despite the need of FO for regeneration technology to reach the desired purpose of clean water, it showed a great potential on energy consumption as a standalone unit. Many studies have been conducted for FO as a standalone system. It was found theoretically that FO must reach a flux of 30 LMH to retain a sustainable life cycle. However, the existing FO recorded less values than

this water flux [30]. In perspective of SEC, FO as a standalone system consumes approximately between 0.10-0.55 kWh/m³ for only low-pressure pump [31].

2.2 Forward Osmosis as Integrated Unit with Other Desalination Technologies.

Hybridization FO with other desalination technologies for draw solute recovery the SEC is between 3-8 kWh/m³ [31]. FO integrated systems give many advantages over standalone FO or any other standalone membrane systems. These systems can get benefit of low FO fouling tendency, this point is controversial as higher fluxes might cause fouling, to pre-treat the feed before it is treated by membrane filtration systems such RO, NF, UF or MD. One more advantage of these integrated systems is that they deliver a multiple barrier to the feed (in terms of contaminants, microorganisms etc.) and consequently a high quality of water is produced [32]. One of the most well-known integrated systems is the FO unit with RO unit (FO-RO). FO stage acts as a preconcentration step, reducing the load on the RO membrane. This results in decreased fouling potential and increased longevity of the RO membrane, leading to improved operational reliability and reduced maintenance costs.

Combining FO and RO in a dual-stage configuration offers several advantages over using standalone FO or RO systems independently. When FO is employed as the initial stage, it serves the purpose of efficiently concentrating the feed solution and pre-treating the water. This pre-treatment step reduces fouling and enhances the overall performance of the subsequent RO stage. The FO process excels at removing larger molecules, colloids, and particles, which are typical culprits for fouling issues in RO membranes.

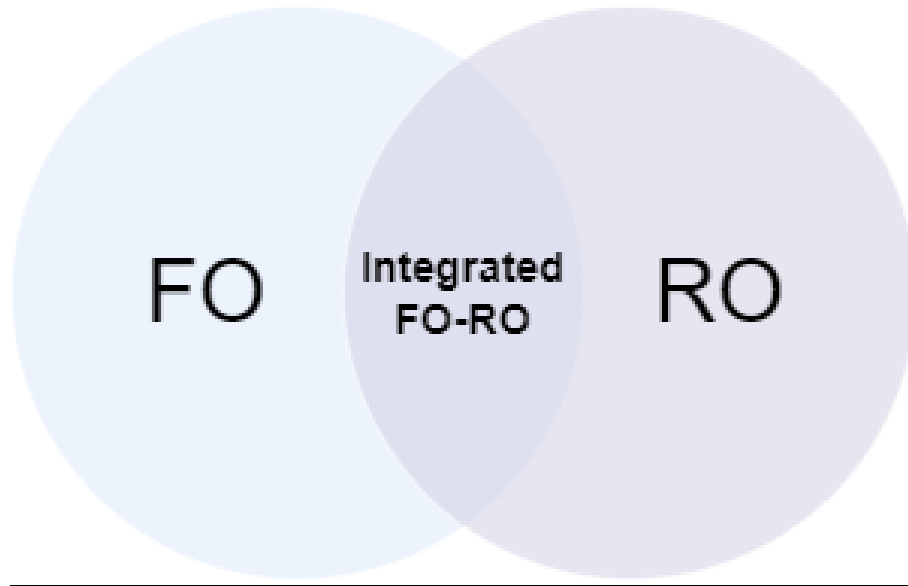


Figure 2.1: Integrated FO-RO system.

It is found that the integration of FO with RO is not energetically efficient for seawater desalination, since the recovery step to regenerate DS, in which the osmotic pressure of DS is higher than the feed solution, i.e., seawater, requires higher energy consumption for RO compared to standalone RO for seawater desalination. However, hybridization of FO integrated with low-pressure RO can be efficient to treat wastewater with a draw solution of seawater, which in osmosis step the wastewater is treated and the seawater is diluted, so the energy consumption for operating pressure in the recovery step to purify seawater is lower [33], [34]. A study showed that FO-RO system is better applicable in case used for feed waters of high fouling tendency [35]. In literature, SEC of a standalone RO of 35 g/L is 2 kWh/m³ and up to 4 kWh/m³ with a pre-treatment process [36].

R. Saeed et al. [2] investigated the practicability of integrated FO-RO system compared to a standalone RO system. The study revealed that FO-RO system exhibited a high energy saving compared to a standalone RO ranged from 87.57% to 87.81%. The integrated FO-

RO SEC was in the range of 0.88-0.93 kWh/m³ for the lower applied hydraulic pressure of RO unit ranged from 0.519-0.545 bar, where a SEC of a standalone RO ranged from 7.157-7.625 kWh/m³ with the corresponding applied hydraulic pressure of 4.186-4.476 bar.

Yangali-Quintanilla et al. [37] conducted an experiment for integrated system of FO and LPRO for indirect desalination. A secondary wastewater effluent is used as a FS and Red Sea with 40,500 mg/L as DS in FO step with average water flux of 3 LMH, in which Red Sea TDS is reduced to 15,000 mg/L. This diluted seawater will have low osmotic pressure which purified by LPRO and results in huge reduction of SEC from 2.5-4 kWh/m³ for a high-pressure standalone RO process to 1.5 kWh/m³ for FO-LPRO integrated system. In literature, total SEC associated with FO-LPRO was found from 1.3-1.5 kWh/m³ [38].

Choi et al. [39] utilized a secondary effluent wastewater with TDS of 2,430 mg/L from the coal-fired power plant as FS in integrated pilot-scale of FO-RO process to dilute seawater. The study showed that the SEC for desalinating diluted seawater and reclamation of wastewater is less by nearly 15% with 2.85 kWh/m³ for FO-RO integrated system compared to a standalone RO unit with 3.34 kWh/m³. Seo et al. [3] developed FO-RO integrated numerical model. The model examined the operation pressure impact on FO-RO integrated system. Considering only SEC of RO at lower applied hydraulic pressure on RO, SEC is 2.68 kWh/m³ lower than standalone RO at 30 bar. Also, at 30.5 bar FO-RO showed lowest SEC of 1.37 kWh/m³ compared to a standalone RO of 1.82 kWh/m³ at 41.4 bar. The recovery rate of RO is found 28% higher than the standalone RO as well. Another study for integrated FO-RO reduced SEC of RO process to 1.5 kWh/m³ and increased distilled water product volume by almost two times [40], [41]. Furthermore, by managing

the recovery rate, concentration of discharged brine is lowered from 60,000 mg/L to 35,000 mg/L, that reducing environmental risks of brine discharge into oceans [42]. Zhao et al. [43] examined an integrated FO-RO system to desalinate seawater feed solution and gained water flux of 4 LMH. The average specific energy consumption for a hybrid FO-RO system were 4.32, 4.89, and 5.8 kWh/m³ for 35, 40, and 45 g/L seawater salinities. However, for a standalone RO SEC is 5.22, 6.13, and 6.97 kWh/m³ for same values of salinities 35, 40, and 45 g/L [36]. For FO-RO hybrid system, it was found that draw solution of FO and the applied hydraulic pressure of RO are the most prime factors for controlling FO-RO process. However, membrane parameters like structure parameter, water permeability, and solute permeability are less significant compared to controlling parameters such as applied hydraulic pressure and flow velocities in minimization energy consumption of RO [3].

For instance, specific energy consumption for DS recovery of integrated FO-NF increased to 2.4 kWh/m³, in comparison with RO, FO-NF is higher than RO by 0.1 kWh/m³ with SEC of 2.3 kWh/m³ for FO-RO [31]. Moreover, these three processes can be integrated together to form a hybrid system. A study of this hybrid system is organized as follows FO-NF-RO. The performance of this system is evaluated using Na₂SO₄, Mg(CH₃COO)₂, and MgSO₄ as draw solutes. FS in the FO process is made up of synthetic and natural saltwater. After that, the diluted DS is regenerated via the NF process. The RO process is used to extract freshwater since the FO and NF processes had minimal NaCl rejection. To analyse the overall performance of the hybrid FO-NF-RO process for seawater desalination, the performance and energy consumption of the FO, NF, and RO processes were thoroughly studied. It is found that the water recovery is 42%, the SEC is 3.16, 3.1, 2.99 kWh/m³ for Na₂SO₄, Mg(CH₃COO)₂, and MgSO₄ as draw solutes, respectively [44].

The integration of FO and RO in a dual-stage setup presents numerous benefits compared to using standalone FO or RO systems alone. By employing FO as the initial stage, it enables effective concentration of the feed solution and pre-treatment of the water, resulting in decreased fouling and enhanced performance of the subsequent RO stage. The FO process is adept at eliminating larger molecules, colloids, and particulate matter, which are commonly responsible for fouling in RO membranes.

CHAPTER 3

METHODOLOGY PROCEDURE

3.1 Mathematical Modelling.

Modelling is the process of creating a representation of a system or process in order to understand, analyse, and predict its behaviour. Also, it plays a crucial role in understanding and optimizing the performance of processes.

The current research focuses on two processes of desalination, namely FO and RO. Although these processes are quite similar in that they involve the separation of water through a semi-permeable membrane, there are still some fundamental differences between them. These differences are reflected in the model parameters, which are demonstrated below.

3.1.1 FO system model

FO system is being analysed by build a model system to investigate the performance. It provides a mathematical representation of the physical and chemical processes that occur during FO and can be used to predict the flux of water and solutes across the membrane, as well as the concentration profiles of the feed and draw solutions. In the current research, FO mathematical models take into account factors such as concentration polarization,

membrane fouling, and the effects of temperature and pressure. The current model mainly obtained from [20]

The mass balance for the FO system is occurred between feed channel side and draw channel side. The water flux transmits from solution side with low concentration (feed side) to solution side with high concentration (draw side), and the salt transfers vies versa. The mass balance of water and salt in FS and DS are as following [20]:

$$Q_{f,FO} - J_{w,FO}A_{m,FO} = Q_{c,FO} \quad 3.1$$

$$Q_{d,FO} + J_{w,FO}A_{m,FO} = Q_{dd,FO} \quad 3.2$$

$$C_{f,FO}Q_{f,FO} + J_{s,FO}A_{m,FO} = C_{c,FO}Q_{c,FO} \quad 3.3$$

$$C_{d,FO}Q_{d,FO} - J_{s,FO}A_{m,FO} = C_{dd,FO}Q_{dd,FO} \quad 3.4$$

Where $J_{w,FO}$ is water flux rate, $J_{s,FO}$ is salt flux rate, $A_{m,FO}$ is effective membrane area, Q_{FO} is flow rate, C_{FO} is concentration and subscripts f, c, d, dd are feed side, feed concentrate, draw side, diluted draw, respectively.

$$c_1 = \frac{C_f + C_c}{2} \quad 3.5$$

$$c_5 = \frac{C_d + C_{dd}}{2} \quad 3.6$$

c_1 & c_5 are the average concentrations for inlet and outlet streams of feed solution and draw solution, respectively, as seen in Figure 1.2.

$$U_{FS} = \frac{Q_{FS}}{A_{FS}} = \frac{(Q_f + Q_c)/2}{\phi_f w H_f} \quad 3.7$$

$$U_{DS} = \frac{Q_{DS}}{A_{DS}} = \frac{(Q_d + Q_{dd})/2}{\phi_d (l/2) H_d} \quad 3.8$$

Where U , A , ϕ and H are cross-flow velocity, cross sectional area, spacer porosity and channel height, respectively.

The water flux is calculated from difference of osmotic pressure between feed side and draw side and transmembrane pressures as well, as shown [45], [46].

$$J_w = A_w (\Delta\pi_{eff} - \Delta p) \quad 3.9$$

$$\Delta\pi_{eff} = \pi_3 - \pi_2 \quad 3.10$$

Where J_w is water permeability. The effective osmotic pressure $\Delta\pi_{eff}$ is the concentration difference at active layer surfaces and Δp is the pressure difference across FS and DS.

$$\pi_1 = \beta R_g T C_1 \quad 3.11$$

$$\pi_2 = \beta R_g T C_2 \quad 3.12$$

$$\pi_3 = \beta R_g T C_3 \quad 3.13$$

$$\pi_4 = \beta R_g T C_4 \quad 3.14$$

$$\pi_5 = \beta R_g T C_5 \quad 3.15$$

Where β is the van't Hoff coefficient, R_g is universal gas constant and T is the absolute temperature. The osmotic pressure for each position in the membrane is expressed by the concentration level at the same position. As shown in Figure 1.2, five locations are taking

in consideration. These locations from 1-5 are feed bulk, active layer membrane surface, interface active-support layer, support layer membrane surface and draw bulk, respectively.

The reverse solute flux is described as the rate of transfer of solutes across a given surface area, and can be expressed as:

$$J_s = B_s(C_3 - C_2) \quad 3.16$$

Where J_s is reverse salt flux., B_s is the salt permeability. C_3 and C_2 are concentrations at active layer's surfaces of membrane inner side to feed side.

The IC plays a significant role in FO process. Since FO membrane is oriented in a way that the active layer heading to the feed side. The water permeates to DS though porous support layer. This induces salt to diffuse back to internal surface of the membrane, in consequence the water permeation is reduced. The following expression describes this dilutive internal concentration polarization [47]:

$$K_{ICP} = \frac{1}{J_w} \ln \frac{B_s + A_w \pi_4}{B_s + J_w + A \pi_2} \quad 3.17$$

Where K_{ICP} is the solute diffusion resistance coefficient. Unlike ICP, the impact of ECP in FO processes is generally considered to be inconsequential, however, it is still a factor that should not be ignored. The following equations demonstrate the effect of ECP on water flux:

- ECP in the feed side:

$$J_w = k_f \ln \frac{C_2}{C_1} \quad 3.18$$

- ECP in the draw side:

$$J_w = -k_d \ln \frac{C_4}{C_5} \quad 3.19$$

Where k is the mass transfer coefficient and it can be calculated by:

$$k = \frac{D \cdot Sh}{d_H} \quad 3.20$$

- For laminar flow < 2000 :

$$Sh = 1.85 \left(Re \cdot Sc \cdot \frac{d_h}{L} \right)^{0.33} \quad 3.21$$

- For turbulent flow > 2000 :

$$Sh = 0.04 \cdot Re^{0.75} \cdot Sc^{0.33} \quad 3.22$$

Where D is the solute diffusion coefficient, d_H is the channel hydrodynamic parameter with W and H are width and height of channel, Sh is Sherwood number, Re is Reynolds number, Sc is Schmidt number, ρ is water density and μ is water viscosity.

3.1.1.1 FO model validation.

FO model is built based on the work of Jeon J. et al. [20]. The obtained results from current model were validated with the results from the same work. The comparison is done for 12

sets of experiments with results of model from the same work. Current model validation has been carried out and results are shown in Table 3.1. It shows results of the initial and final values of experiment sets. The results obtained from the present model demonstrate that the water flux closely aligns with the experimental results for over 65% of the data sets. This indicates that present model is considerably more feasible and reliable compared to the model utilized in the previous work. The close agreement between the modelled water flux and experimental data highlights the accuracy and effectiveness of present proposed approach.

Table 3.1:

Comparison of water flux between the developed model and experimental work results.

Set No.	J_w , current model	J_w , experimental	J_w , model
1	27.69	24.31	15.17
	8.035	7.84	4.85
2	29.52	26.93	18.82
	15.3	14.9	10.29
3	30.06	22.48	20.50
	4.37	5.88	2.89
4	27.69	21.31	15.41
	8.92	5.69	5.51
5	29.31	28.63	18.53
	13.45	15.42	8.71
6	28.40	24.58	17.45
	4.72	6.14	2.91
7	24.59	20.92	14.15
	1.3	0.65	0.73
8	27.79	31.37	15.6
	9.23	10.98	5.6
9	27.98	28.62	15.70
	9.42	13.07	5.91
10	30.03	21.44	20.89
	6.51	7.45	4.17

11	25.76	18.43	14.16
	5.98	4.58	3.06
12	29.53	19.61	18.93
	6.89	4.31	4.47

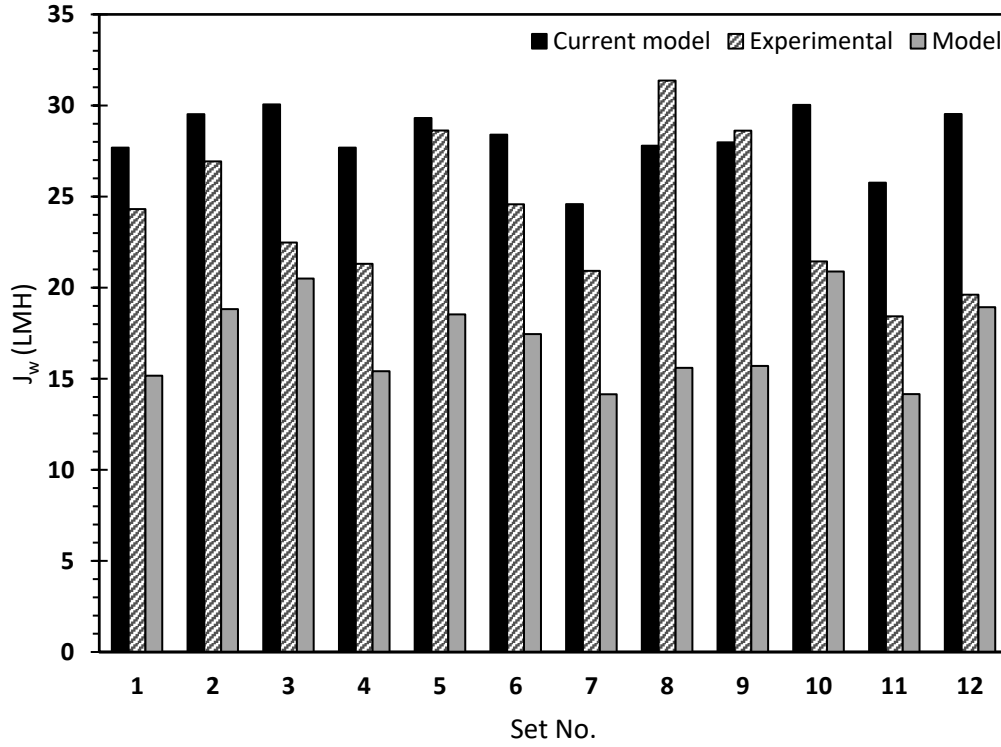


Figure 3.1: Comparison of water flux between developed model and experimental work results.

3.1.2 RO system model

FO desalination system requires a regeneration unit to achieve a clean water. In this study RO technology is used to accomplish this goal. In same way, a mathematical model is built to study RO system performance. Unlike FO system, RO needs a high hydraulic pressure to reverse the phenomenon of osmosis. Only one inlet stream is pressurized against the membrane and so a clean water is obtained. The other outlet stream is concentrated and discharged. The total mass and solute balance of the whole unit gives [48], [49]:

$$Q_{f,RO} = Q_{P,RO} + Q_{c,RO} \quad 3.23$$

$$C_{f,RO}Q_{f,RO} = C_{P,RO}Q_{P,RO} + C_{c,RO}Q_{c,RO} \quad 3.24$$

The above equations are mass balance of RO system. Where Q and C are flow rate and concentration of RO system, respectively. Subscripts f , P and c represent feed stream, permeate stream, and concentrate stream (brine), respectively. From literature, the concentrate stream is always large than the permeate.

The flux of the RO system is almost same as FO system, except that in RO, the flux is calculated between the two flows of feed and permeate as shown below [50]:

$$J_{w,RO} = A_{w,RO}(P_{f,RO} - P_{p,RO} - \pi_{f,RO} + \pi_{p,RO}) \quad 3.25$$

Where J_w is water flux, A_w is water permeability coefficient, P and π are pressure and the osmotic pressure, respectively.

The osmotic pressure of feed, permeate and the brine of RO are calculated by:

$$\pi_{f,RO} = \beta_{RO}R_gT_{RO}C_{f,RO} \quad 3.26$$

$$\pi_{p,RO} = \beta_{RO}R_gT_{RO}C_{p,RO} \quad 3.27$$

The salt flux equation or RO is as follows:

$$J_{s,RO} = B_{s,RO}(CP \cdot C_{f,RO} - C_{p,RO}) \quad 3.28$$

Where B_s is the solute permeability coefficient, CP is the concentration polarization factor, it's the ratio of membrane surface concentration to bulk concentration $C_{f,RO}$.

For spiral wound RO membranes with fully developed turbulent flow, the mass transfer coefficient within the feed spacer channel can be anticipated using the following correlation [15], [51]:

$$CP = \frac{C_{m,RO}}{C_{b,RO}} = e^{\frac{J_{w,RO}}{k_{RO}}} \quad 3.29$$

$$k_{RO} = 0.023 \frac{D_{RO}}{d_{h,RO}} Re_{RO}^{0.83} Sc_{RO}^{0.33} \quad 3.30$$

Here k_{RO} is the mass transfer coefficient, which is the hydrodynamic diffusion coefficient of the solute to the thickness boundary layer. D is solute diffusion coefficient. d_h is channel hydrodynamic parameter. Re is Reynolds number. Sc is Schmidt number.

$$w_{RO} = A_{m,RO}/l_{RO} \quad 3.31$$

$$V_{RO} = Q_{f,RO}/(h_{RO}w_{RO}) \quad 3.32$$

If we consider spiral wound RO membranes and fully developed turbulent flow, we can use the following equation to estimate the mass transfer coefficient in the channel of the feed spacer [52], [53]:

$$Re_{RO} = \frac{\rho_{RO} V_{RO} d_{h,RO}}{\mu_{RO}} \quad 3.33$$

$$Sc_{RO} = (\mu_{RO}/\rho_{RO})/D_{RO} \quad 3.34$$

$$d_{h,RO} = 2h_{RO} \quad 3.35$$

Reverse solute flux can be expressed and calculated by:

$$M_{s,RO} = J_{s,RO} w_{RO} l_{RO} \quad 3.36$$

The expression for water productivity is articulated as follows [53]:

$$Q_{p,RO} = J_{w,RO} w_{RO} l_{RO} \quad 3.37$$

The mass balance equation of RO can be conducted by the following:

$$C_{c,RO} = \frac{(C_{f,RO} Q_{f,RO} - M_{s,RO})}{Q_{c,RO}} \quad 3.38$$

Recovery rate and rejection rate are expressed by [48]:

$$RR = \frac{Q_{p,RO}}{Q_{f,RO}} \quad 3.39$$

$$Rj = 1 - \frac{C_p}{C_f} \quad 3.40$$

3.1.2.1 RO model validation.

The built model was validated using a work data from literature done by Altaee [54]. In Figure 3.2, four RO elements are examined connected in a series. The obtained results of this work are close with the model of that study as well as for ROSA (Reverse Osmosis System Analysis), the one used to validate his work. The flow rate is decreasing as far the number of elements increases, since the elements are in series ordering and the feed flow is entered once at element number one, and so the brine of that element, which is concentrated, enters the next element and so on. This agreement with results indicates that the model had been built is feasible.

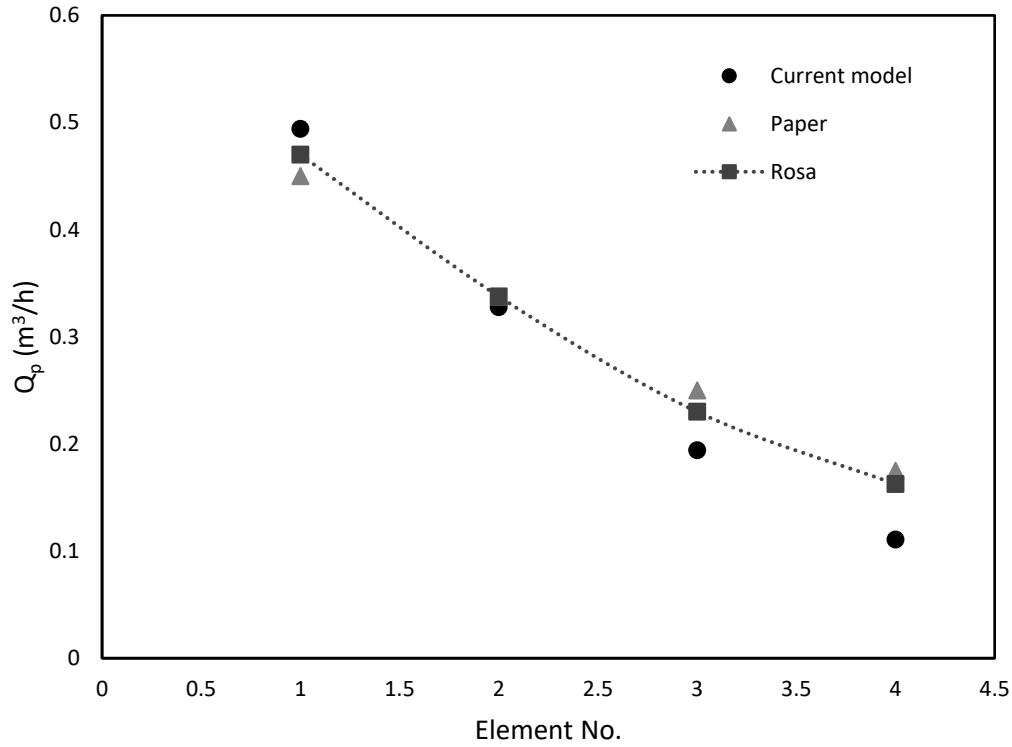


Figure 3.2: Comparison of flow rate between current model and validation work results.

3.1.3 Specific energy consumption.

Two distinct categories of specific energy are linked to membrane desalination technologies, and these categories are defined by the energy source employed by the system: 1) The STEC, 2) The SEEC.

STEC often referred to as specific heat consumption, serves as a metric to gauge the quantity of thermal energy required for producing a single unit of freshwater. This metric is intricately tied to the initial temperature of the feedwater, meaning that the energy demands can significantly vary based on the temperature of the source water. This

particular performance criterion finds its application in the evaluation of how efficiently heat is utilized in systems such as the performance of MD technology [55].

SEEC is a key performance metric that quantifies the quantity of electrical energy expended to generate a unit of pure water. This metric plays a vital role in assessing the efficiency and sustainability of desalination and water purification processes that rely on electrical energy as a primary energy source. By evaluating the specific electrical energy consumption, it becomes possible to make informed comparisons with other processes that utilize electrical energy [56], [57].

In the current research, we are employing the second type of SEC. This is particularly relevant in the context of the FO-RO system under investigation, where only electrical energy plays a role, and heat is not a contributing factor to the process. Therefore, for simplification energy will be denoted by SEC instead of SEEC.

The system involves two processes and so the evaluation would be combined of both. SEC for hybrid system is considered as follow [3]:

$$SEC_{hybrid} = \frac{Q_{f,RO_o}(\Delta P_{RO_o} - P_{d,FO_o})/HP_{eff} - Q_{f,RO_i} \cdot \Delta P_{RO_i} \cdot ERD_{eff} + Q_{f,FO_o} \cdot P_{f,FO_o} + Q_{d,FO_o} \cdot P_{d,FO_o}}{Q_{p,RO}} \quad 3.41$$

Where SEC_{hybrid} is SEC of the hybrid FO-RO process considering both FO and RO energy consumptions (kWh/m³). Q_{f,RO_o} & Q_{f,RO_i} are the initial and final feed flow rate of RO process, respectively (m³/s). ΔP_{RO_o} & ΔP_{RO_i} are initial and brine RO hydraulic pressures (Pa), respectively. P_{f,FO_o} & P_{d,FO_o} are applied hydraulic pressures of feed side and draw side

of FO, respectively (Pa). Q_{f,FO_0} & Q_{d,FO_0} are initial feed and draw flow rates, respectively (m^3/s). $Q_{p,RO}$ is the permeate flow rate of RO (m^3/s). HP_{eff} is the efficiency of high-pressure pump. ERD_{eff} is the efficiency of energy recovery device.

3.1.4 Economic analysis model

A comprehensive economic analysis is essential for determining the financial feasibility and effectiveness of integrating FO with RO in the context of water treatment applications. The economic evaluation of a combined FO-RO system entails a detailed examination of the financial aspects linked to its setup and functioning. This assessment typically covers expense evaluations, operational costs, and various other economic factors. The assessment of the economic sustainability of FO-RO systems is imperative for decision-makers, providing them with the necessary insights to make well-informed decisions about the viability and endurance of deploying such water purification methods. This process includes an analysis of both the initial capital investments and long-term operational expenditures, taking into account factors such as membrane costs, energy consumption, maintenance expenses, specific water cost.

The techno-economic viability of a large-scale integrated FO and RO process was evaluated based on the following stated in Table 3.2.

- Capital expenditure:

The capital expenditure associated with seawater intake and pretreatment is represented by the following cost expression [52]:

Table 3.2:

CAPEX and OPEX calculations values.

Parameter	Value	Unit	Ref.
FO membrane cost	25	\$/m ²	[58]
RO membrane cost	25	\$/m ²	[58]
MRF	10	%	[59]
Labor cost	0.05	\$/m ³	[60]
Electricity cost	0.08	\$/kWh	[61]
Lifetime	20	Years	[62]
Interest rate	6	%	[62]

$$CC_{swip} = 0.1 \cdot 996 \cdot Q_{FO}^{0.8} \quad 3.42$$

In contrast to RO, the feed solution in the FO system is not pressurized. As a result, the pretreatment cost appears to be relatively inexpensive when compared to a traditional RO system. Specifically, the pretreatment cost for this system is estimated to be 0.1 times that of a conventional RO system [63].

The FO & RO membrane's capital cost were computed by [41]:

$$CC_{Mem,FO} = N_{FO} \cdot A_{m,FO} \cdot CE_{Mem,FO} \quad 3.43$$

$$CC_{Mem,RO} = N_{RO} \cdot A_{m,RO} \cdot CE_{Mem,RO} \quad 3.44$$

The calculation of pumps costs are as follows, [64], [65]:

$$CC_{pump,FOFS} = 52 \cdot Q_{f,FO} \cdot \Delta P_{FS} \quad 3.45$$

$$CC_{pump,FODS} = 52 \cdot Q_{d,FO} \cdot \Delta P_{DS} \quad 3.46$$

$$CC_{pump,RO} = 52 \cdot Q_{f,RO} \cdot \Delta P_{HP} \quad 3.47$$

The cost correlation between flow rate and operating pressure of an ERD was initially established for a reversely running centrifugal pump. This correlation has the potential to be extended for estimating the cost of various other ERDs [66].

$$CC_{ERD} = \frac{Q_{c,RO}}{450} (393,000 + 10,710 \cdot \Delta P_{HP}) \quad 3.48$$

The TCC is determined by aggregating both direct and indirect capital expenditures. This involves the summation of costs directly associated with the project, such as equipment and materials (direct capital costs), along with additional costs indirectly incurred, encompassing items like engineering, labor, and overhead expenses (indirect capital costs). The comprehensive calculation of TCC provides a holistic view of the overall financial investment required for the project, considering both direct and indirect elements that contribute to the capital expenditure [52], [67]:

$$TCC = 1.411(CC_{swip} + CC_{Memb,FO} + CC_{Memb,RO} + CC_{pump,FOFS} + CC_{pump,FODS} + CC_{pump,RO} + CC_{ERD}) \quad 3.49$$

The determination of the TACC involves the use of an amortization factor. This factor accounts for the spreading out or allocation of the total capital cost over the project's expected lifespan. The TACC calculation is crucial for assessing the annualized financial commitment associated with the capital investment. By applying an amortization factor, the total capital cost is distributed across the anticipated life of the project, providing a

more manageable representation of the annualized financial burden. This approach enables a comprehensive understanding of the ongoing capital expenditure required to sustain the project over its operational lifespan [52], [67].

$$a = \frac{i(i+1)^n}{(i+1)^{n-1}} \quad 3.50$$

$$TACC = a \cdot TCC \quad 3.51$$

- Operating expenditure:

The cost of electricity can be computed as a function of SEC, which includes both pumping power and the cost of electricity per kilowatt-hour (kWh). Consequently, the annual energy cost is determined by [68]:

$$OC_{elec} = Q_p \cdot SEC \cdot D_{elec} \cdot 365 \cdot L_f \quad 3.52$$

The annual expense for membrane replacement is [69]:

$$OC_{Memb,FO} = 0.1 \cdot CC_{Memb,FO} \quad 3.53$$

$$OC_{Memb,RO} = 0.1 \cdot CC_{Memb,RO} \quad 3.54$$

Where membrane replacement factor ranges from 5% to 20% [59].

Insurance costs are not constant and can vary significantly. Typically, they are considered to be 0.5% of the capital cost [60], [65]:

$$OC_{insurance} = 0.005 \cdot TCC \quad 3.55$$

The annual calculation of labor cost can be expressed as [68]:

$$OC_{labor} = CE_{labor} \cdot Q_p \cdot 365 \cdot L_f \quad 3.56$$

The formula for estimating operational cost is given by:

$$TAOC = OC_{elec} + OC_{Memb,FO} + OC_{Memb,RO} + OC_{insurance} + OC_{labor} \quad 3.57$$

The total annualized cost is determined as follows [52], [59], [51]:

$$TAC = TACC + TAOC \quad 3.58$$

It is crucial to note that all the annual costs discussed above are utilized in the computation of cost per unit volume. The unit product cost is determined by:

$$SWC = \frac{TAC}{Q_p \cdot 365 \cdot L_f} \quad 3.59$$

3.2 Engineering Equation Solver (EES) Software.

In the case of doing a modelling and designing code, there are many tools can be used to conduct such a work. There are well-known programs are widely utilized, including without limitation, MatLab, Python, EES, etc. The latter one was used to accomplish the mathematical model in this research. EES (pronounced ‘ease’) program is a numerical based solver that can execute numerous of nonlinear algebraic equations. Moreover, it has a capability to solve differential equations as well as integral equations. In addition, it can be used doing optimization, carrying out a linear and nonlinear regression, provide uncertainty analyses, check unit consistency, and generating publication quality plots. EES has one more feature adjective upon other programs is high accurate transport property and thermodynamic database [70].

3.3 Membrane selection

The selection of the membrane undergoes to many factors that determine the performance of the desalination system through the capability of the membrane to handle the specification of the system. The membrane must possess high flux, high salt rejection, low tendency to fouling, and high draw solute rejection to restrain reverse salt flux. The membrane be made up of two layers, active and support layers. The former has to be thin and dense to uphold high flux and solute rejection [71]. The latter intensely reduces the osmotic pressure gradient in the active layer, acting as a diffusive boundary layer [72]. The suitable membrane for FO should have (1 LMH bar^{-1}) water permeability, high rejection of both FS and DS and low structural parameter [16]. Nowadays, three types configuration of membrane components are exist (plate and frame/flat sheet PFFO, spiral wound SWFO, and hollow fibre HFFO) [73], [74], [75].

Since 1980, polymeric/organic membranes have been the primary choice in the global market due to their remarkable effectiveness and affordability. In recent times, the market has been predominantly influenced by TFC membranes, which offer exceptional performance. Notable polymers utilized in the production of RO membranes include polyamides, cellulose acetate, cellulose diacetate, cellulose triacetate, and piperazine. Polyamide is a large molecule composed of recurring amide ($-\text{CO}-\text{NH}-$) groups and can be found naturally or artificially. Natural polyamides include wool, silk, and angora. The preparation of cellulose-based polymers is typically carried out using the phase inversion method [76].

The present study involves the use of two membranes, which were chosen on the basis of the models from which they were built and subsequently validated.

3.3.1 FO membrane

In FO unit, a Toray FO 8040 membrane is utilized, which is a type of spiral wound membrane produced by Toray Chemical Korea, Inc., a leading manufacturer of water treatment membranes. The "8040" in the name refers to the dimensions of the membrane element. The FO 8040 membrane is designed for use in various industrial and commercial applications, including desalination, water purification, and wastewater treatment. It is widely used in large-scale systems to remove impurities, salts, and other contaminants from water, producing high-quality permeate.

The key characteristics of the Toray FO 8040 membrane include:

1. **High Salt Rejection:** The membrane offers excellent salt rejection capabilities, typically above 99%. It effectively removes dissolved salts and minerals from water, making it suitable for desalination applications.
2. **Spiral Wound Configuration:** The membrane is manufactured in a spiral wound configuration, which consists of multiple layers of membrane sheets wound around a permeate collection tube. This design maximizes the membrane surface area within a compact module.
3. **TFC Membrane:** The FO 8040 membrane is a TFC membrane, which means it has a thin, dense polyamide layer that serves as the active barrier for separating contaminants. The TFC design provides high permeability and salt rejection properties.

4. Dimensions: The membrane element has an 8-inch diameter and a length of 40 inches, hence the designation "8040." This sizing is a common industry standard and allows for easy integration into standard RO systems.
5. Operating Conditions: The Toray FO 8040 membrane operates under typical RO conditions, including feed water hydraulic pressures ranging from 150 to 600 psi (10.3 to 41.4 bar) and operating temperatures of around 77°F (25°C).

It's important to note that specific performance and operating parameters may vary based on the application, feed water quality, system design, and other factors. If you're considering the use of the Toray FO 8040 membrane in a particular project or application, it's advisable to consult Toray or a qualified water treatment professional to ensure it meets your specific requirements. Table 3.3 illustrates FO characteristics utilized in this research.

Table 3.3:
FO membrane characterization.

Parameter	Value	Unit
Membrane module	<i>FO 8040</i>	-
Supplier	<i>Toray Chemical Korea, Inc.</i>	-
Water permeability, A_w	1.59×10^{-11}	$m \cdot s^{-1} \cdot Pa^{-1}$
Salt permeability, B_s	3.87×10^{-7}	$m \cdot s^{-1}$
Solute diffusion coefficient, D	1.29×10^{-9}	$m^2 \cdot s$
Length, L	1.016	m
structural parameter, S	280	μm

3.3.2 RO membrane

The SW30HRLE-400i membrane is a specific type of polymeric TFC membrane commonly used in RO applications. It is designed to deliver high-performance water filtration with exceptional salt rejection capabilities.

The key characteristics of the SW30HRLE-400i membrane include:

1. **High Salt Rejection:** This membrane demonstrates excellent salt rejection properties, allowing it to effectively remove dissolved salts and other impurities from water sources. It is particularly efficient at rejecting monovalent ions, such as sodium and chloride, which contribute to high-quality water production.
2. **Low Energy Consumption:** The SW30HRLE-400i membrane is engineered to minimize energy requirements during the water filtration process. Its design enables efficient permeate production while maintaining high salt rejection, resulting in reduced operating costs and energy consumption.
3. **Enhanced Flux Rates:** This membrane exhibits a relatively high-water permeability, enabling it to deliver increased water production rates. The enhanced flux rates contribute to improved productivity and efficiency in RO systems, making it a desirable choice for various water treatment applications.
4. **Long-Term Durability:** The SW30HRLE-400i membrane is known for its robust construction and long-lasting performance. It offers excellent resistance to fouling, scaling, and chemical degradation, ensuring sustained filtration efficiency and extended operational lifespan.

5. **Broad Compatibility:** The membrane is compatible with a wide range of water sources, including brackish water and certain types of wastewaters. It is suitable for various industrial, commercial, and residential applications, such as desalination, water purification, and process water treatment.

Overall, the SW30HRLE-400i membrane combines high salt rejection rate about 99.75 % to NaCl, low energy consumption, and durable performance, making it a reliable choice for achieving efficient and effective water filtration in RO systems. Table 3.4 illustrates FO characteristics utilized in this research.

Table 3.4:

RO membrane characterization.

Parameter	Value	Unit
Membrane module	<i>SWROHRLE-400i</i>	-
Supplier	<i>DOW FILMTECK, US</i>	-
Water permeability, k_w	1.056	$L/m^2 \cdot h \cdot bar$
Salt permeability, k_s	0.00189	m/d
Length, L	1.016	m
Effective membrane area, A_m	37.2	m^2

CHAPTER 4

RESULTS AND DISCUSSION

In this research, the results related to the hybrid desalination system using FO and RO technologies will be presented and discussed. The effectiveness of these integrated technologies will be evaluated by reconfiguring them in a specific way to achieve high efficiency in water production and minimizing energy consumption. This work will be carried out through a mathematical model for the proposed integrated FO-RO system.

The specific objectives and summary of the proposed research work are as follows:

- a) Modelling FO process consists of water flux prediction, solute flux, and concentrated and diluted flow rates, taking in consideration the effect of ECP and ICP to obtain further accuracies.
- b) FO requires a regeneration desalination process to accomplish a drinkable water. In this research, a RO model is utilized, and a mathematical model is developed.
- c) Estimate a FO-RO desalination system performance for better water flux. This can be attained by identify relevant data such as the properties of the feed and draw solutions, water salinities, temperature, membrane characteristics, selectivity, permeability, etc., and operating conditions like hydraulic pressure, flow rates, etc.
- d) Evaluate the specific energy consumption for the new system. Take in account energy inputs required for the system. In present research, high pressure pump is used along utilize an energy recovery device.

- e) Study the performance of the system with different positions of RO with the FO system. the positioning of the RO unit within the FO system was found to have a significant impact on system performance. By evaluating various RO positions relative to the FO system, including placement among or after the FO stages, the study shed light on the effects on water productivity and overall system effectiveness.

4.1 Forward Osmosis Units Integrated with A Single Reverse Osmosis Unit Located at The End.

The proposed configuration stated that number of FO process units are connected in series as a pre-treatment process before entering downstream RO unit as a final separation process for water desalination. The aim of this configuration is to dilute sea water as much as possible by FO units, this because FO has low fouling tendency compared to RO, and low energy consumption as well. These are main advantages of utilizing FO as pre-treatment process. In Figure 4.1, six FO units are considered and connected in series with one RO unit. The proposed configuration is studied starting by one FO unit and RO unit, and in every scenario one FO unit is added to the system previous to RO unit and the performance is evaluated. Six different systems are obtained and permeate flow rate, recovery rate and specific energy consumption are evaluated for each system. The operation conditions for these scenarios are stated in Table 4.1.

Table 4.1:

Operating conditions of FO-RO system.

Process	Parameter	Value	Unit
FO	Feed flow rate, Q_f	<i>1.803</i>	m^3/h
	Feed concentration, C_f	<i>10,000</i>	mg/l (ppm)
	Draw flow rate, Q_d	<i>0.416</i>	m^3/h
	Draw concentration, C_d	<i>42,000</i>	mg/l (ppm)
	Temperature, T	<i>25</i>	$^{\circ}C$
RO	Feed flow rate, Q_f	<i>Q_{dd} of FO unit</i>	m^3/h
	Feed concentration, C_f	<i>C_{dd} of FO unit</i>	mg/l (ppm)
	Hydraulic pressure, P_f	<i>31</i>	<i>bar</i>
	Temperature, T	<i>25</i>	$^{\circ}C$

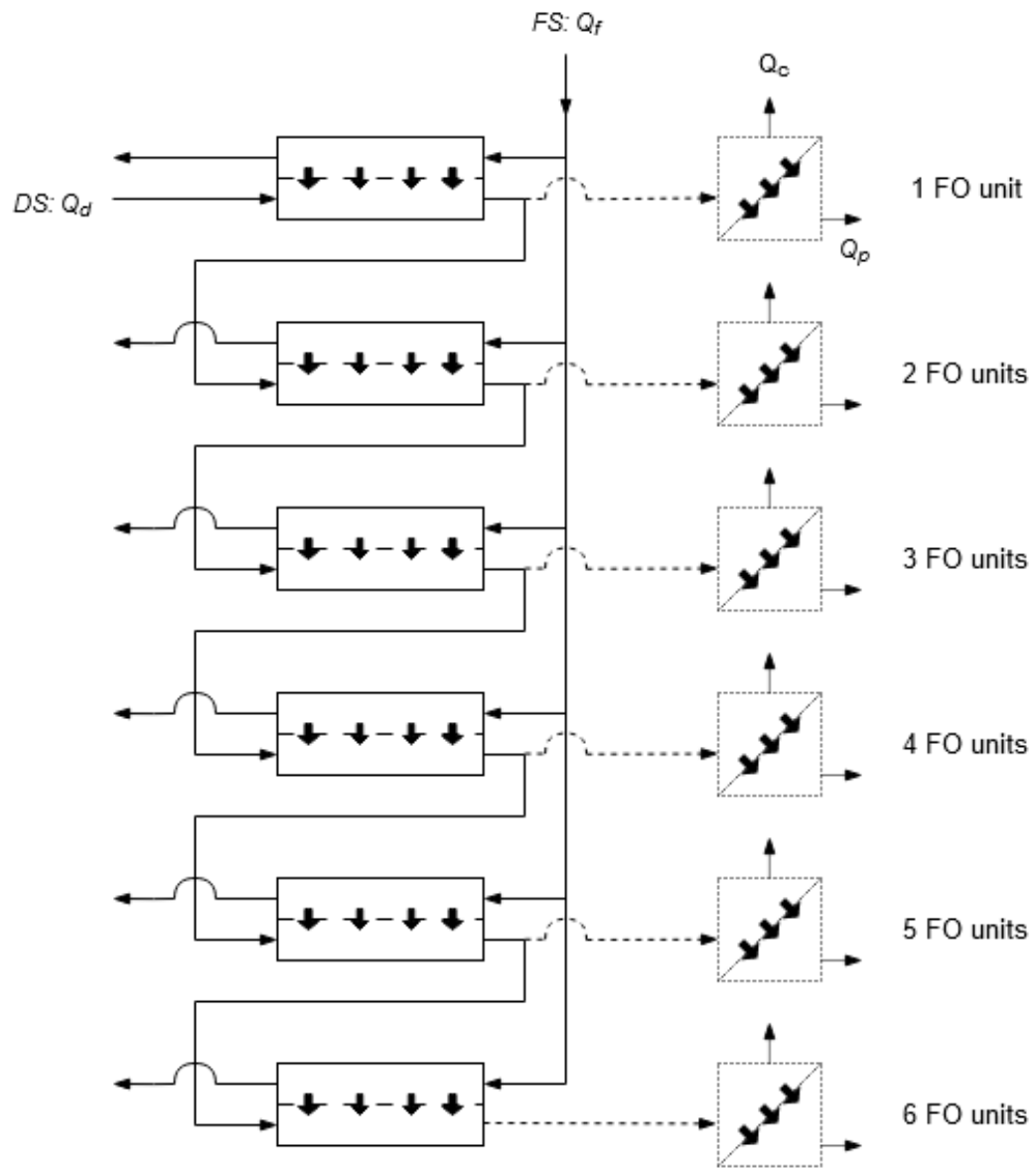


Figure 4.1: FO-RO configuration connected in series.

4.1.1 The effect of draw solution flow rates on water productivity with respect to the number of forward osmosis units.

In this section, the focus will be on the number of proposed FO units connected in series with a single RO unit and their impact on water productivity. Starting from one unit and progressively increasing number of units in each different scenario. It can be seen from Figure 4.2 an increase in water productivity by RO unit with increasing number of FO units connected in series. It is evident that water production increases significantly in case using small number units and follows a slight increase with large number of units. In case DS flow rate of $0.416 \text{ m}^3/\text{h}$, upgrading FO from one unit to two units resulted in a high increase from 0.24 to $0.42 \text{ m}^3/\text{h}$, respectively, and $0.52 \text{ m}^3/\text{h}$ when use three units. Surprisingly, the increase in water productivity when using four to six FO units ranged from 0.59 to $0.67 \text{ m}^3/\text{h}$. This can be attributed to a decrease in water flux in FO units with an increasing number of units as seen in Figure 4.3. Water flux decreases due to a decrease in the osmotic pressure difference across the membrane. This decrease occurs as the concentration in draw side decreases further with number of FO units due to dilution, while concentration on the feed side remains unchanged.

Furthermore, as seen in Figure 4.3 the water flux of FO units in integrated FO-RO system is influenced by the draw solution flow rate. As DS flow rate increases, water flux per unit of FO membrane area also increases.

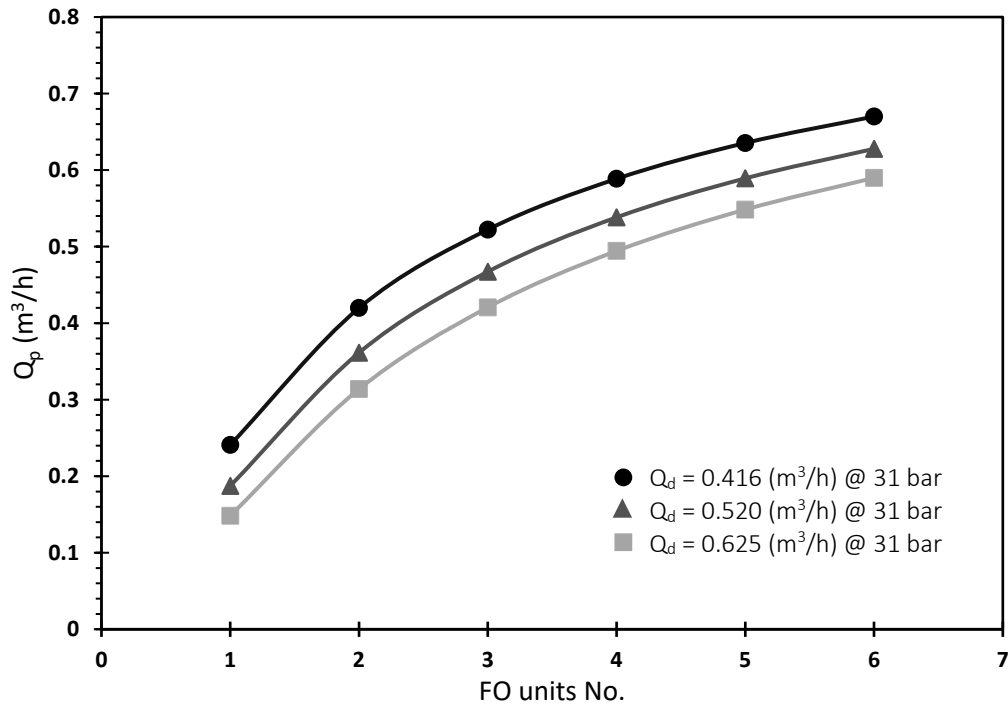


Figure 4.2: Draw solution flow rate effect on water productivity for FO units No. connected with RO.

In RO process, it is well known that increasing the feed flow rate generally leads to a higher water flux. This occurs because a larger volume of feed water is pushed through the RO membrane, resulting in an increased permeation of water through the membrane. As a result, the water flux is elevated, allowing for higher production rates of product water. However, it's important to note that increasing the feed flow rate usually requires higher hydraulic pressures to maintain the desired water flux. The applied hydraulic pressure helps overcome hydraulic resistance, facilitating the passage of water through the membrane. Therefore, adjusting both the hydraulic pressure and the feed flow rate becomes necessary to maintain the desired water flux in an RO system. In contrast, in this research as seen in Figure 4.2, water productivity decreases as DS flow rate increases, this can be justified by that hydraulic resistance is not overcome, since applied hydraulic pressure is maintained

fixed in this case and not increased to compensate for the increased feed flow rate. This can result in a decrease in water flux because the water molecules will struggle to pass through the membrane effectively, see Figure 4.3. Also, draw solution concentration continuously decreases less with high DS flow rate, consequently the osmotic pressure difference is low, with each FO unit while maintaining the same feed solution flow rate. Then the feed stream to downstream RO unit is higher with high FO DS flow rate and higher feed solution concentration as well. In addition to the former one explained previously, the latter limits RO water flux, since high feed concentration generates high osmotic pressure difference across RO membrane, and this requires high applied hydraulic pressure to overcome it.

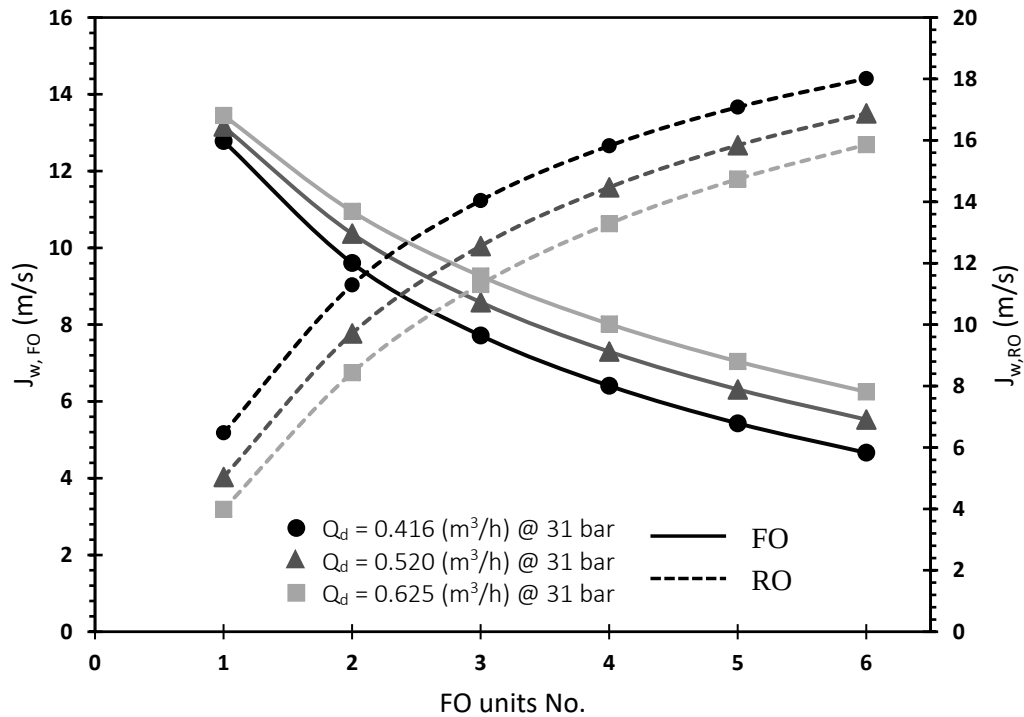


Figure 4.3: Water flux for each FO unit & RO units for different draw solution flow rates.

4.1.2 The effect of draw solution flow rate on recovery rate with respect to the number of forward osmosis units.

The recovery rate in the RO process, which represents the proportion of feed water that is transformed into drinkable product water, depends directly on the permeate flow rate, which is also influenced directly by the draw solution flow rate, as mentioned earlier, section 4.1.1. Then recovery rate is also affected by the draw solution flow rate. It can be seen from Figure 4.4 that recovery rate dramatically increases when the number of FO units is increased. This can be attributed to the high-water permeation that is attained when more FO units are utilized. In case DS flow rate of $0.416 \text{ m}^3/\text{h}$, upgrading from one unit to two units, the rate of increase exceeds 40%. This occurs because the concentration of the draw solution decreases significantly in the first unit due to the high osmotic pressure difference between membrane sides, which decreases with the increase in the number of FO units due to the dilution process occurring in the unit. However, when using more than three units, the rate change of recovery rate starts to decrease. This is due to the increase in the flow rate enters RO unit, which is inversely proportional to the recovery rate. The optimum scenario is reached when using four units of FO. However, the recovery rate begins to decrease when using five units or more of FO. The particular reason is that diluted flow rate coming from FO units increases at a higher flow rate than resulted permeated water flow rate.

Moreover, recovery rate is affected by DS flow rate. Increasing DS flow rate leads to a decrease in recovery rate as shown in Figure 4.4, this can be justified that water permeation flow rate decreases, as mentioned in section 0. All three tested DS flow rates follow same trend, however, the optimum system's FO unit changes as DS flow rate increases. As

mentioned above, the optimum number of FO units for 0.416 m³/h DS flow rate is four units, whereas for 0.520 and 0.625 m³/h are five and six FO units, respectively.

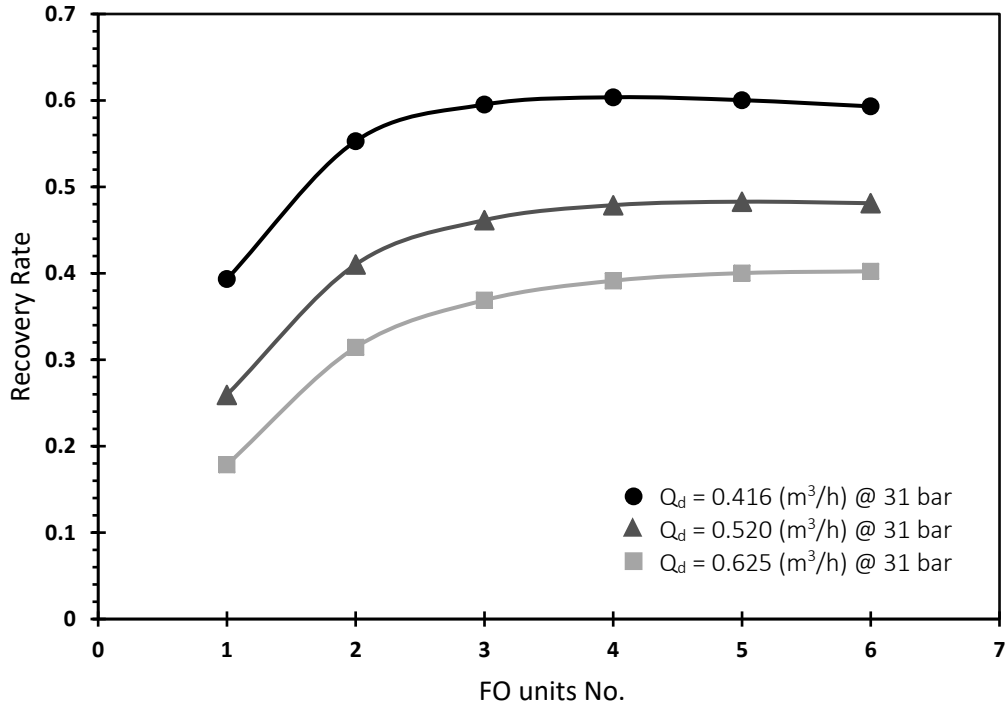


Figure 4.4: Effect of FO units No. connected with RO on the recovery rate.

4.1.3 The effect of draw solution flow rate on specific energy consumption with respect to the number of forward osmosis units.

The main objective of this research is SEC in the desalination process calculations. In this system, SEC of both FO and RO processes was considered. It is well knowing SEC for FO process is very low compared to RO, however it needs to be taken into account particularly with an increase in the number of FO units. This research adopted two scenarios in calculating SEC: without installed ERD and with.

Based on the performance evaluation of FO-RO, SEC of the process was determined by employing a high-pressure pump with 85% efficiency in the RO stage. Since SEC is predominantly influenced by water productivity, higher productivity typically leads to reduced energy consumption. Figure 4.5 illustrates that SEC declines as the number of FO units increases. This can be attributed to the enhancement of water productivity resulting from the dilution process occurring in the FO units. In case of $0.416 \text{ m}^3/\text{h}$ when a single FO unit is utilized, the SEC is approximately 2.75 kWh/m^3 . It decreases by 30% to 1.94 kWh/m^3 when two FO units are employed. However, this substantial decrease is not observed when three units are used, as the SEC only decreases by 7% to 1.79 kWh/m^3 . This can be explained by the diminishing increase in water productivity as the number of units increases, see Figure 4.2. Additionally, employing more than three units exhibits a negligible difference in SEC. Interestingly, using six units increases the SEC despite the enhanced productivity, which can be ascribed to the relatively small rate of increase in water productivity compared to the flow rate.

An ERD with an efficiency of 97% is incorporated [77], which plays a role in reducing the SEC. According to Figure 4.5, the SEC exhibits a similar trend to the case without an ERD. However, a notable reduction of approximately 45%, equivalent to 1.51 kWh/m^3 , is observed when using a single FO unit. Subsequently, the SEC decreases slightly for two FO units and remains relatively unchanged for the remaining units.

The effect of DS flow rate on SEC can be seen in Figure 4.6. In contrast to water productivity and recovery rate, SEC increases as DS flow rate increases. This is due to the direct proportionality between the feed flow rate entering RO unit and the DS flow rate, where SEC is directly related to the RO feed flow rate, because pump utilized high energy.

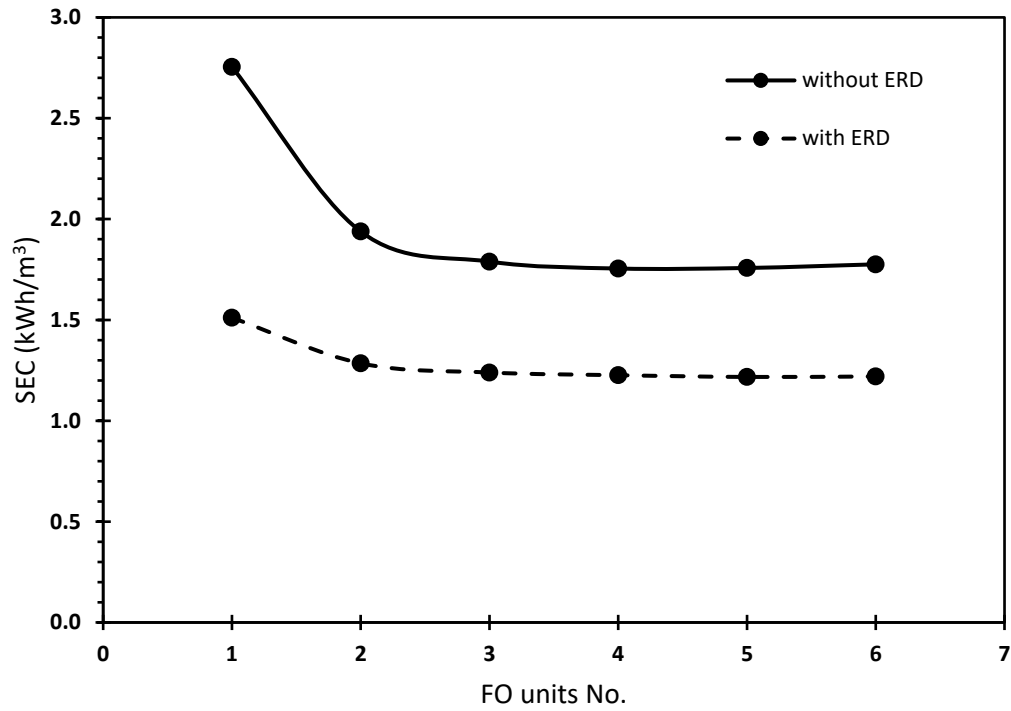


Figure 4.5: Effect of FO units No. connected with RO on the SEC with & without ERD at draw flow rate $0.416 \text{ m}^3/\text{h}$ and $P = 31 \text{ bar}$.

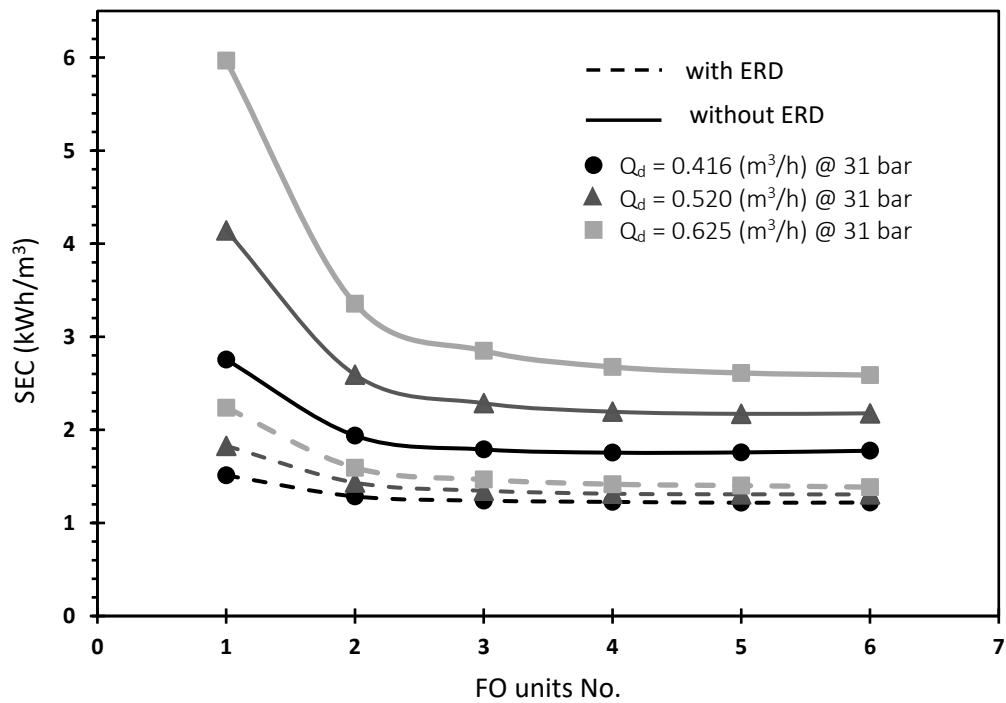


Figure 4.6: Effect of FO units No. connected with RO on the SEC with & without ERD for various DS flow rates.

4.1.4 The effect of draw solution flow rate on economic feasibility with respect to the number of forward osmosis units.

Economic feasibility of FO systems is a crucial factor to consider when evaluating the number of FO units integrated with RO unit. The draw solution flow rate directly impacts the performance and cost-effectiveness of FO systems. By adjusting the flow rate of the draw solution, the overall water flux, recovery rate, and energy consumption of the FO-RO processes can be influenced as mentioned previously. Consequently, economic feasibility of the FO-RO system is affected.

The economic feasibility of FO-RO system is a complex assessment that involves various factors, including the capital and operational costs, energy consumption, membrane fouling, and the specific requirements of the application. Therefore, FO units affect the capital and operational costs. However, it's important to consider the trade-off between water flux and operational costs. Increasing the draw solution flow rate also means higher energy consumption for circulating the draw solution and subsequent regeneration or disposal.

Consequently, capital costs associated with the purchase and installation of FO units can be reduced. Conversely, if a lower draw solution flow rate is employed, more FO units may be necessary to achieve the desired water production rate, which increases the capital costs. Apart from capital costs, operational costs are also influenced by the number of FO units. Each FO unit requires maintenance, monitoring, and replacement of membranes, and these costs increase with the number of units. Therefore, the optimal balance between the number

of FO units and the draw solution flow rate needs to be determined based on comprehensive economic analysis, considering both capital and operational expenses.

The productivity of water is affected by the number of FO units, as depicted in Figure 4.2. A significant increase in water productivity occurs when a small number of FO units are used, but the rate of increase becomes less pronounced with a larger number of units. Eventually, adding more FO units reaches a point where the water productivity stabilizes. Therefore, the selection of the appropriate number of FO units is determined by the SEC. According to Figure 4.5, the lowest SEC is achieved when using five FO units, but using six units is also acceptable since the difference is not significant. However, increasing the number of FO units will lead to higher SEC. Ultimately, the decision regarding the number of FO units should be based on an economic assessment.

DS flow rates significantly affect the system performance and economic assessment as well. In Figure 4.7, the SWC is illustrated for three distinct draw solution flow rates, both with and without the implementation of an ERD. This visual representation allows for a comparison of SWC under different conditions and the impact of ERD on the desalination process. At 0.416 m³/h draw flow rate, it illustrates that SWC experiences a significant decrease when going from one to two FO units, resulting in an approximate 28% reduction in the use of ERD. Beyond two units, the remaining FO units show minimal difference in SWC, except for an increase in SWC after four units. Specifically, when transitioning from two to three units, there is a decrease of nearly 7% in SWC. Furthermore, the decline persists at a similar pace when employing four units, albeit with a minor variance. However, the inclusion of five units results in a slightly upward trajectory that deviates

from the previous trend. Nevertheless, these differences are negligible in comparison to the volume of water produced through the addition of multiple units of FO.

Increasing DS flow rate results in higher SWC since it directly associates with the SEC. In section 4.1.3, the relationship between incoming feed flow rate into RO unit and flow rate of DS are presented in Figure 4.6. SEC is directly linked to feed flow rate of RO unit where the pump requires higher energy for higher stream volume. Also, it's well known that operational expenses consider the electricity cost needed for the pump to deliver high flow rates. This can be justified the reason SWC increases as DS flow rate increases.

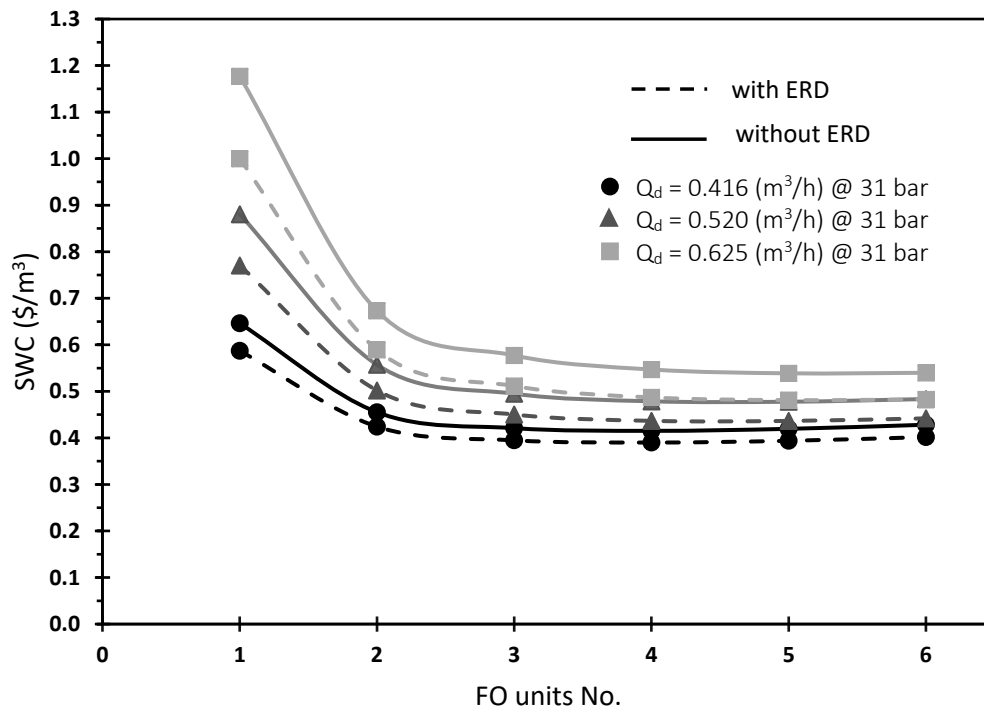


Figure 4.7: Effect of FO units No. connected with RO on the SWC with & without ERD for various DS flow rates.

The implementation of an ERD impacts the economic aspect, by the lower SEC associated with it, as demonstrated in Figure 4.7. The inclusion of ERD results in a noticeable decrease

of around 15% for $0.625 \text{ m}^3/\text{h}$, 12.5% for $0.520 \text{ m}^3/\text{h}$ and 9% for $0.416 \text{ m}^3/\text{h}$ compared to a system that does not utilize ERD almost for all scenarios.

As mentioned above, the optimum FO units number based on SWC is four units. Then a detailed discussion will be for scenario of four FO units and a RO unit at draw flow rate of $0.416 \text{ m}^3/\text{h}$. Figure 4.8 illustrates the capital expenditures of the four FO units with RO unit. Sea water pretreatment costs the most part of the system, follows by FO membrane cost and high pump cost, respectively. RO membrane cost is lower than FO because only one membrane is utilized compared to four FO membranes. ERD with efficiency of 97% cost is half lower than HP pump used for RO unit. Feed and draw pumps mostly are not worth much compared to others.

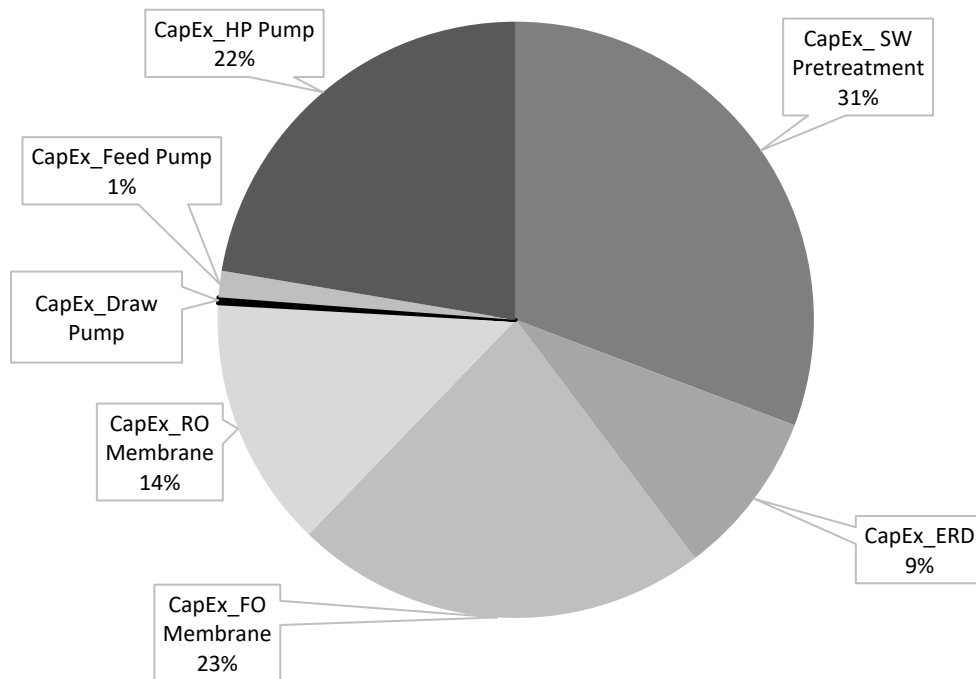


Figure 4.8: Capital Cost of four FO units with RO unit.

Usually, each system requires annual financial operation, several key factors that are considered when evaluating the financial aspects of the system. These factors include the operational cost of the pumps associated with the system, labor and maintenance costs, and the expense of replacing membranes for each unit in the system, etc.

Figure 4.9 illustrates the distribution of operating expenses. It states that approximately 46% of the operating cost is attributed to energy consumption, indicating that a significant portion of the expenses is allocated to powering the system. Additionally, it shows that 24% of the operating cost is dedicated to labor and maintenance expenses yearly. Furthermore, a notable discrepancy in the cost distribution between different types of units. It states that the cost of replacing membranes is higher for FO units, accounting for 16% of the operating cost, compared to 9% for RO unit.

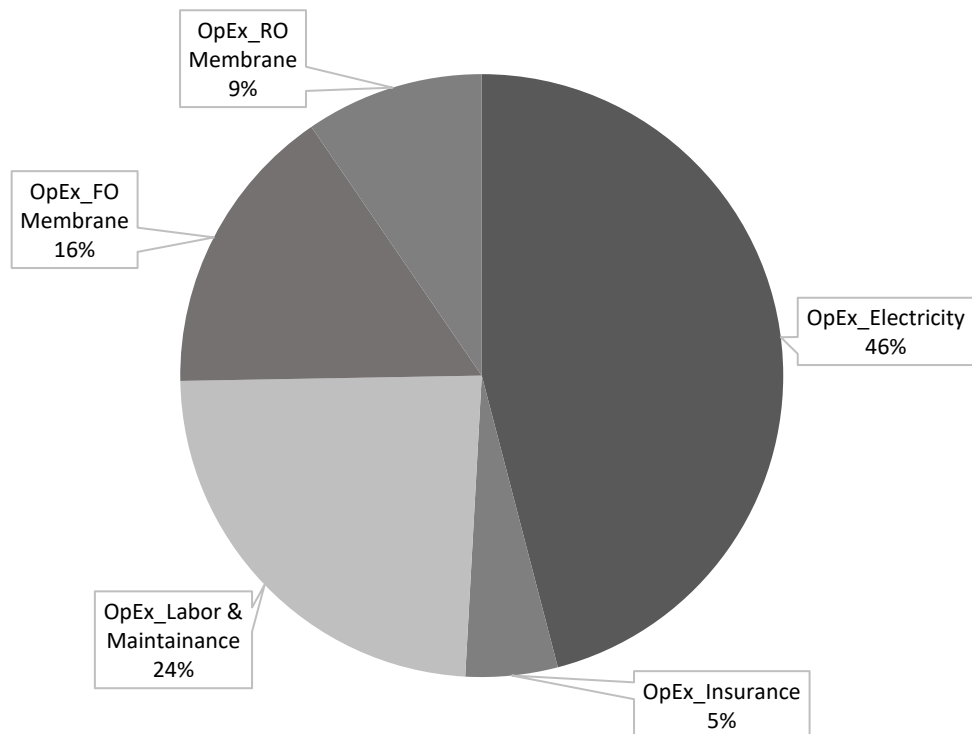


Figure 4.9: Operational Cost of four FO units with RO unit.

The annualized expenses are the expenses of capital expenditures accounting the annual factor which indicates the lifetime of the project and the interest rate associated during project period. A lifetime of 20 years is considered in this project and 6% of interest rate is accounted. All capital expenditures same as in Figure 4.8 are summed for all FO unit number scenarios and multiplied by the annual factor to obtain the TACC, which is the overall expense of capital investments needed for a project, spread out over its expected useful life on an annual basis. Same as TACC, TAOC, which is the total expenses incurred during each year of the project's operation. These two expenses are summed to result a TAC, that refers to the comprehensive sum of all costs associated with a project, distributed over its anticipated useful life on an annual basis.

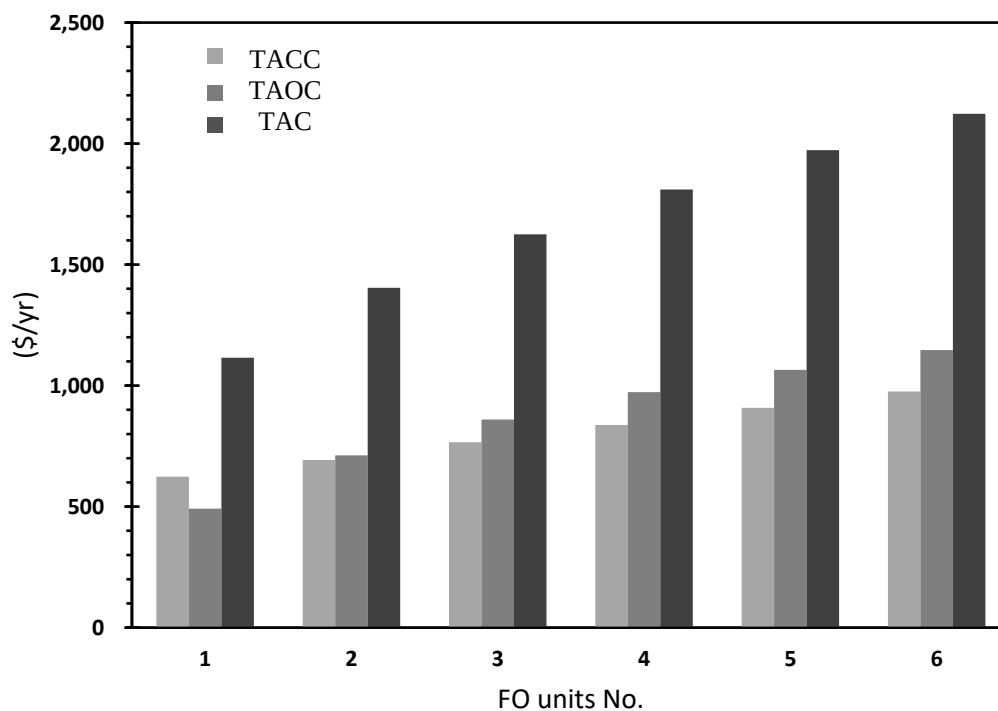


Figure 4.10: Total Annualized expenses with respect to FO units.

Figure 4.10 shows that increasing FO units number results in higher TAC. The reason behind this is mainly the number of FO units cost associated with large number. Also, HP

pump capacity changes for large FO units' number, due to high amount of diluted DS flow rate needs to be delivered to downstream RO unit.

4.1.5 Hydraulic pressure effect on FO-RO system performance.

In the earlier, the hydraulic pressure was consistently maintained at 31 bar, resulting in a less than optimal system performance, particularly when the draw flow rates were increased. This was attributed to the hydraulic pressure not being sufficiently elevated to meet the evolving demands of the system. To overcome this limitation and achieve a more desirable recovery rate of 60%, adjustments were made by increasing the hydraulic pressure. At draw flow rates of 0.520 m³/h and 0.625 m³/h, the hydraulic pressure was raised by approximately 11% to reach 34 bar and by 22.5% to attain 38 bar, respectively. This strategic adjustment in hydraulic pressure aimed to enhance the overall efficiency of the system, ensuring that the recovery rate aligns with the specified target. These modifications demonstrate the importance of fine-tuning operational parameters to achieve optimal performance in the FO-RO system, particularly in instances where recovery rates are a key consideration.

Figure 4.11 demonstrates the water productivity across various draw flow rates, taking into account the adjustment of hydraulic pressure to optimize system performance. The graph provides a visual representation of how changes in draw flow rates impact water productivity, with a particular focus on the compensatory effects of adjusting hydraulic pressure. Similarly, water productivity exhibits the same pattern observed under fixed hydraulic pressure conditions, with significant increases when employing two FO units and subsequent decreases as the number of FO units is incremented.

At draw flow rates of 0.520 m³/h and 0.625 m³/h, the water productivity stands at 0.3185 m³/h and 0.4104 m³/h, respectively, when employing a single FO unit. With the incorporation of two FO units, there is a notable increase of approximately 56%, resulting in water productivities of 0.497 m³/h and 0.585 m³/h for the respective draw flow rates. However, the system demonstrates remarkable water productivity of 0.7648 m³/h and 0.8639 m³/h for draw flow rates of 0.520 m³/h and 0.625 m³/h, respectively, when utilizing six FO units. This underscores the positive correlation between the number of FO units and water productivity, highlighting the potential for substantial enhancements in the overall efficiency of the FO-RO system.

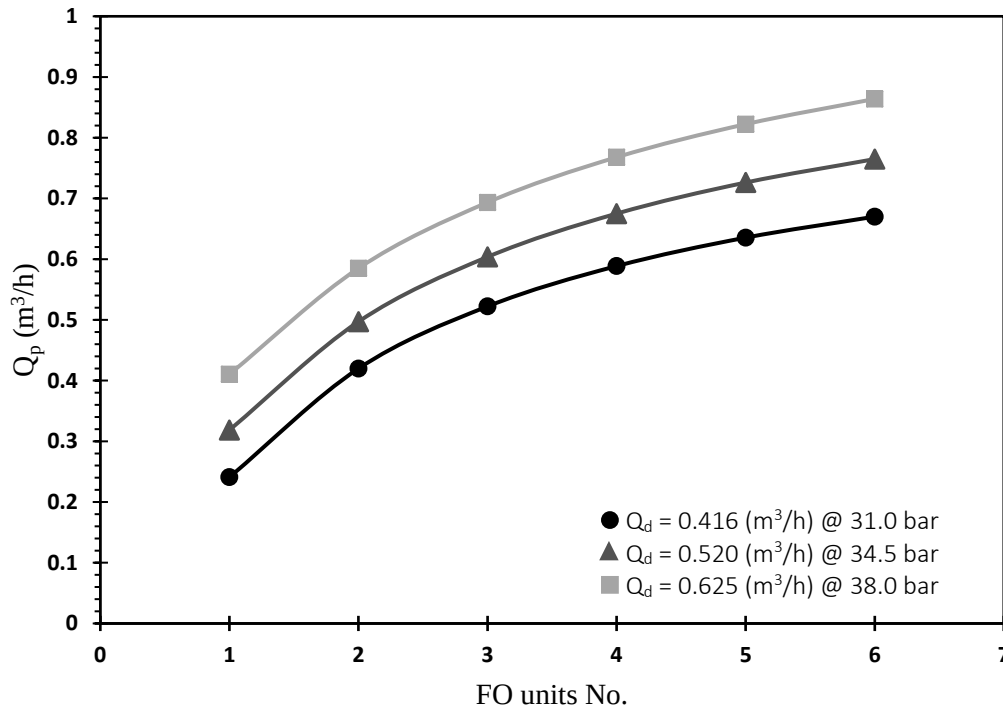


Figure 4.11: Pressure effect on FO-RO system water productivity at different draw flow rates: 31 bar for $Q_d = 0.416$ m³/h, 34.5 bar for $Q_d = 0.520$ m³/h, and 38 bar for $Q_d = 0.625$ m³/h.

It is well known that hydraulic pressure is directly proportional to SEC. Figure 4.12 shows SEC of FO-RO system. Generally, SEC increased as draw flow rate increased, since hydraulic pressure is compensated and maintained high recovery rate around 60% see Figure 4.13. while considering SEC without ERD only at a single FO unit, SEC is greater at 0.416 m³/h than other flow rates. This can be attributed to very low water productivity since SEC is inversely proportional to water productivity.

The direct correlation between hydraulic pressure and SEC is a well-established understanding. Figure 4.12 illustrates the SEC of the FO-RO system, showcasing a general trend where SEC increases with higher draw flow rates. This observation aligns with the compensatory adjustment of hydraulic pressure to maintain a high recovery rate of around 60%, as depicted in Figure 4.13. Notably, when considering SEC without ERD and at a single FO unit, SEC is highest at draw flow rate of 0.416 m³/h compared to other flow rates. This discrepancy can be attributed to the notably low water productivity at a single FO unit, given the inverse relationship between SEC and water productivity. Then as the number of FO units increases along with water productivity, the pattern of SEC undergoes correction. Particularly, at higher draw flow rates, there is an increase in SEC. At draw flow rates of 0.520 m³/h and 0.625 m³/h, there is a noticeable reduction in SEC when employing two FO units, approximately 23% and 16.7%, respectively. However, these reductions are less significant when compared to the draw flow rate of 0.416 m³/h, where a reduction of SEC by about 30% is achieved. Furthermore, at a larger number of FO units, the difference in SEC reduction between draw flow rates of 0.520 m³/h and 0.625 m³/h compared to 0.416 m³/h is approximately 10% and 20%, respectively. This suggests that

the impact of increasing FO units on SEC reduction is more pronounced at lower draw flow rates.

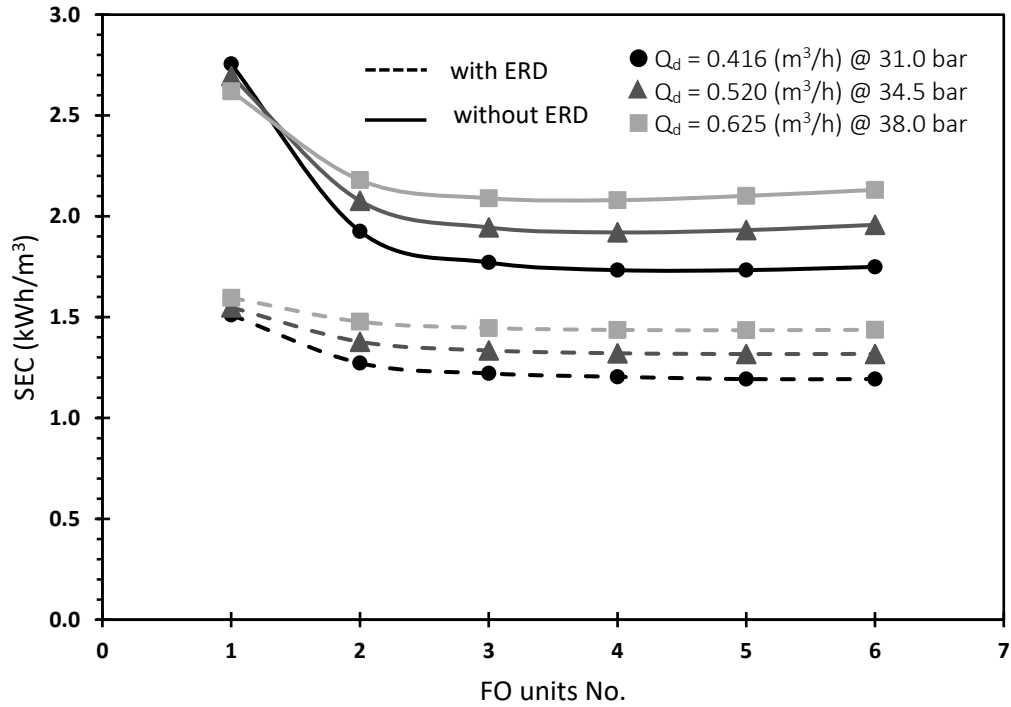


Figure 4.12: Pressure effect on FO-RO system's SEC with & without ERD at different draw flow rates: 31 bar for $Q_d = 0.416 \text{ m}^3/\text{h}$, 34.5 bar for $Q_d = 0.520 \text{ m}^3/\text{h}$, and 38 bar for $Q_d = 0.625 \text{ m}^3/\text{h}$.

Figure 4.14 illustrates the SWC for FO-RO system. The results illustrate a noticeable improvement in performance as draw flow rates increase. This enhancement can be attributed to the high-water productivity generated by an increased flow rate entering the RO process, where high hydraulic pressure is applied to overcome elevated draw flow rate. Additionally, a significant reduction in SWC is observed when the system utilizes two FO units, indicating substantial dilution before progressing downstream to the RO stage for water purification. Interestingly, SWC reaches a point of stabilization when three or more FO units are utilized, suggesting a saturation effect in terms of SWC.

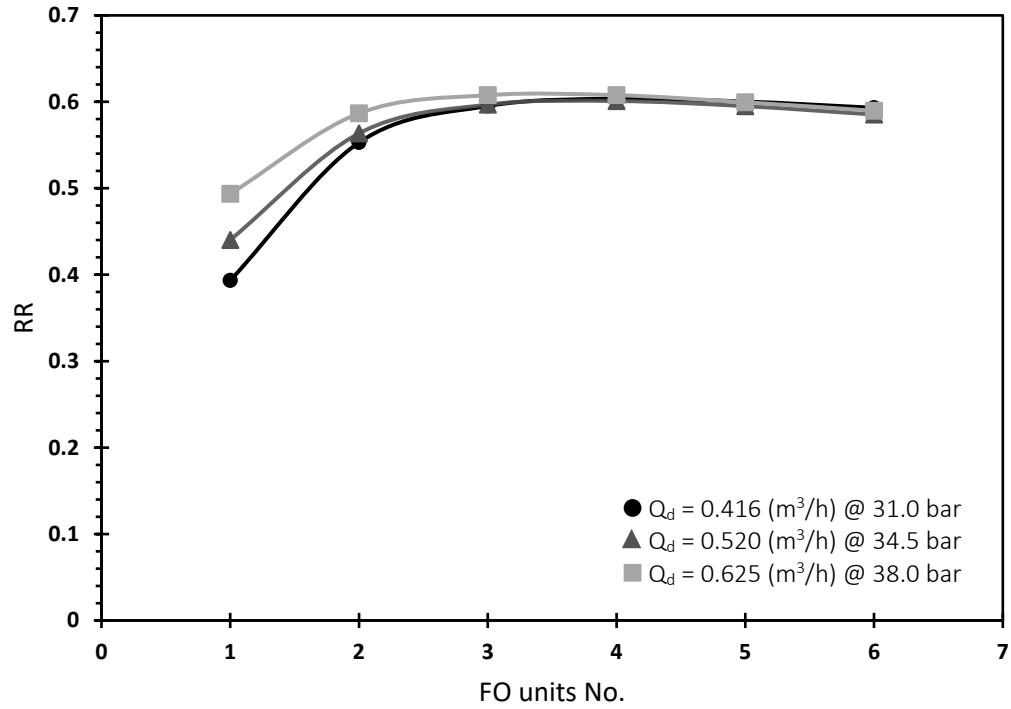


Figure 4.13: Recovery rate of FO-RO system at different draw flow rates: 31 bar for $Q_d = 0.416$ m³/h, 34.5 bar for $Q_d = 0.520$ m³/h, and 38 bar for $Q_d = 0.625$ m³/h.

Moreover, it is noteworthy that all draw flow rates exhibit nearly identical trends for both scenarios, whether the ERD is incorporated or not. On the other hand, incorporating ERD enhanced SWC, however, the difference approximately 14%, 16% and 15% for draw flow rates of 0.416 m³/h, 0.520 m³/h and 0.625 m³/h. This indicates that the existence of ERD does not significantly impact the draw flow rates in this context.

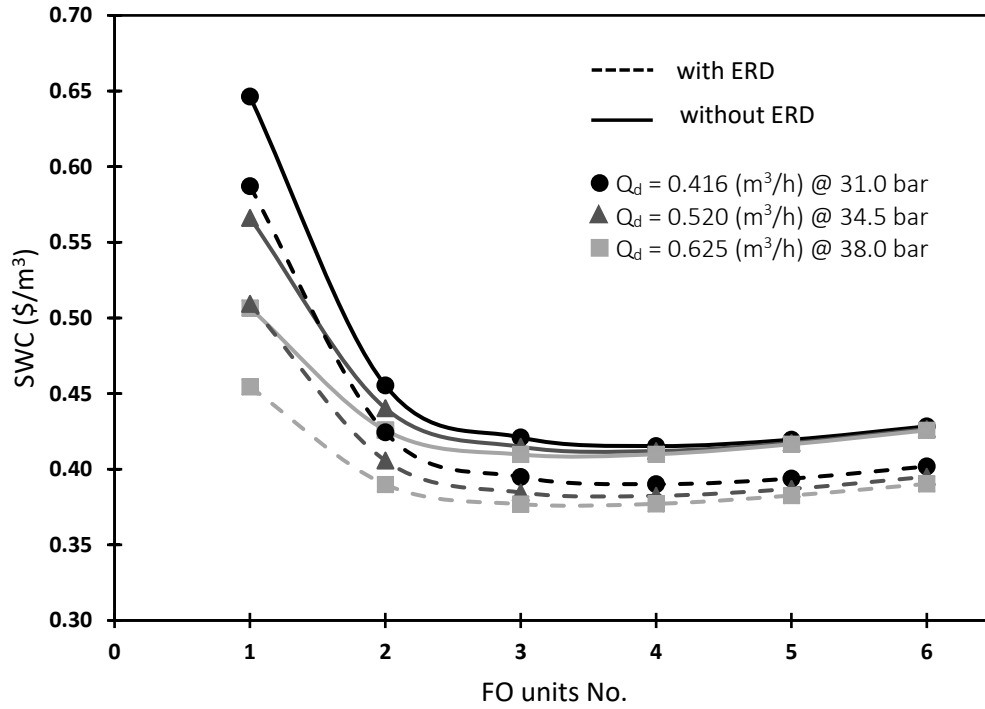


Figure 4.14: Pressure effect on FO-RO system SEC with & without ERD at different draw flow rates: 31 bar for $Q_d = 0.416 \text{ m}^3/\text{h}$, 34.5 bar for $Q_d = 0.520 \text{ m}^3/\text{h}$, and 38 bar for $Q_d = 0.625 \text{ m}^3/\text{h}$.

4.2 Six Forward Osmosis Units Integrated with A Single Reverse Osmosis Unit Located After First FO Unit.

A different system configuration is under consideration, involving the arrangement of six FO units and one RO unit connected in a series. However, what sets this configuration apart is that the RO unit is positioned after the initial FO unit. This results in the inlet flow rate being diluted by the first FO unit, while the five remaining FO units are connected in series after the RO unit, as illustrated in Figure 4.15.

What's particularly intriguing about this setup is how it manages the outlet streams from the six FO units. Rather than disposing of them separately, they are mixed and directed back to the first FO unit, serving as a feed flow rate. This recirculation process presents an opportunity for further treatment of the diluted stream.

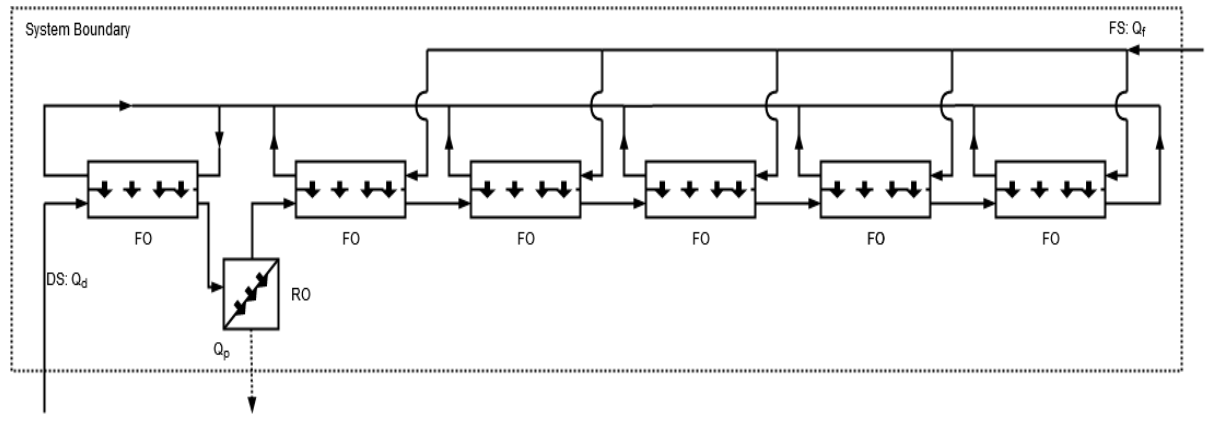
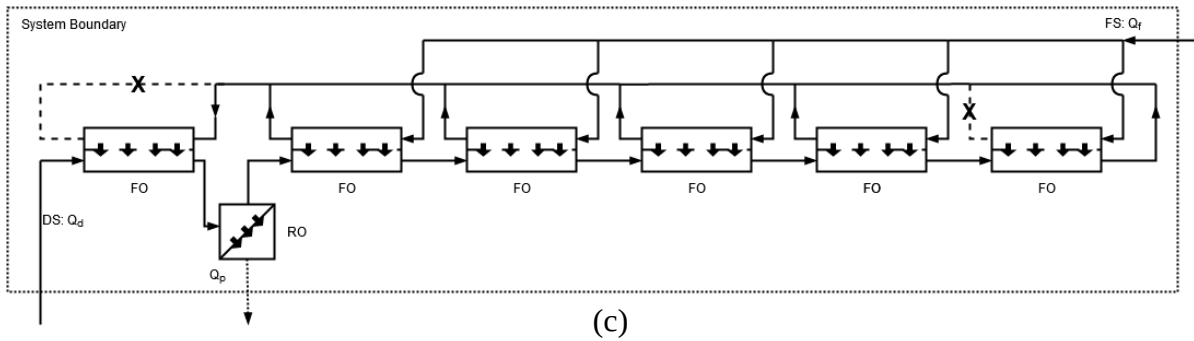
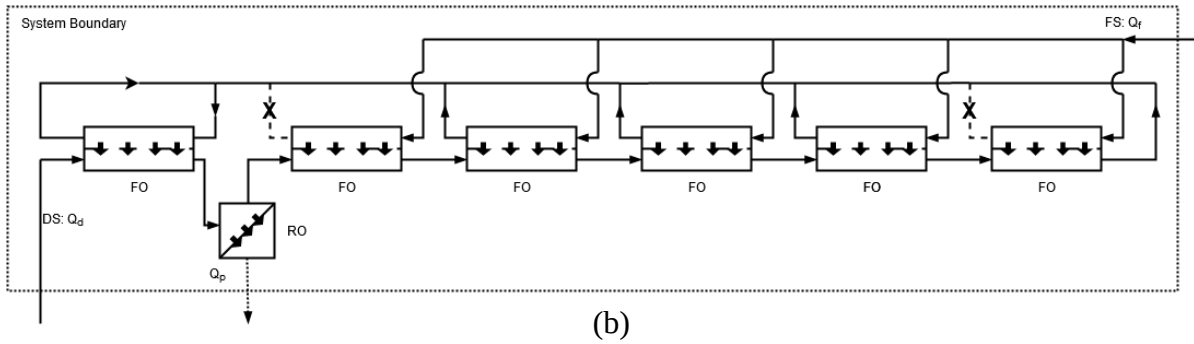
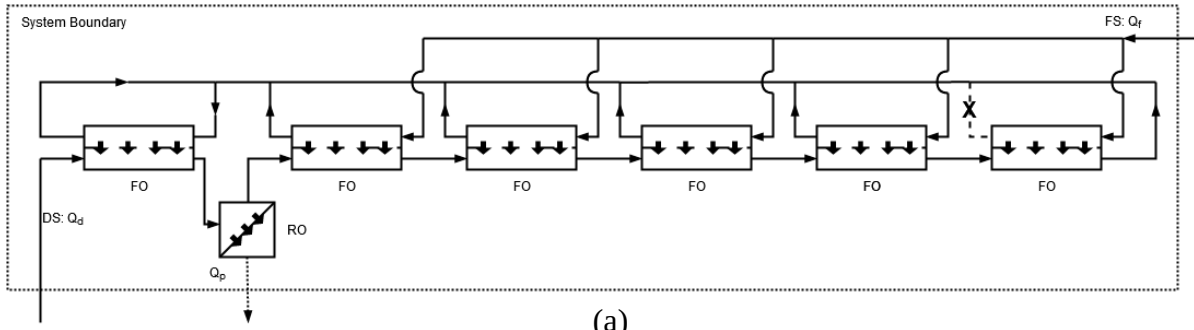


Figure 4.15: Six FO units connected with RO unit.

In total, this specific configuration, shown in Figure 4.15 generates seven distinct outlet streams. These streams, usually are discharged out, can be combined in 127 different ways, creating diverse configurations of combinations. These combinations serve as valuable test cases to assess the system's performance and analyse results. All these configurations were tested so that the concentration level of draw side resulted from the first FO unit prior to RO unit is less than the one before system outlet streams recirculated. The results showed that out of these 127 configurations only 48 combinations are found to be suitable for recirculation and meet the defined criteria, as a result the concentration of the flow rate enters RO unit is being decreasing. These selected combinations have the unique ability to yield lower integrated concentrations compared to the concentration achieved in the initial trial. Also, this crucial aspect ensures continuous dilution and, consequently, generates a

high osmotic pressure difference each time the outlets are reintroduced to the first FO unit as a feed solution. For simplification, not all approved configurations are considered, whereas out of 48 configurations only the most six configurations with high flow rates and low concentrations are selected, since the remaining locate between the six logically will be less efficient.



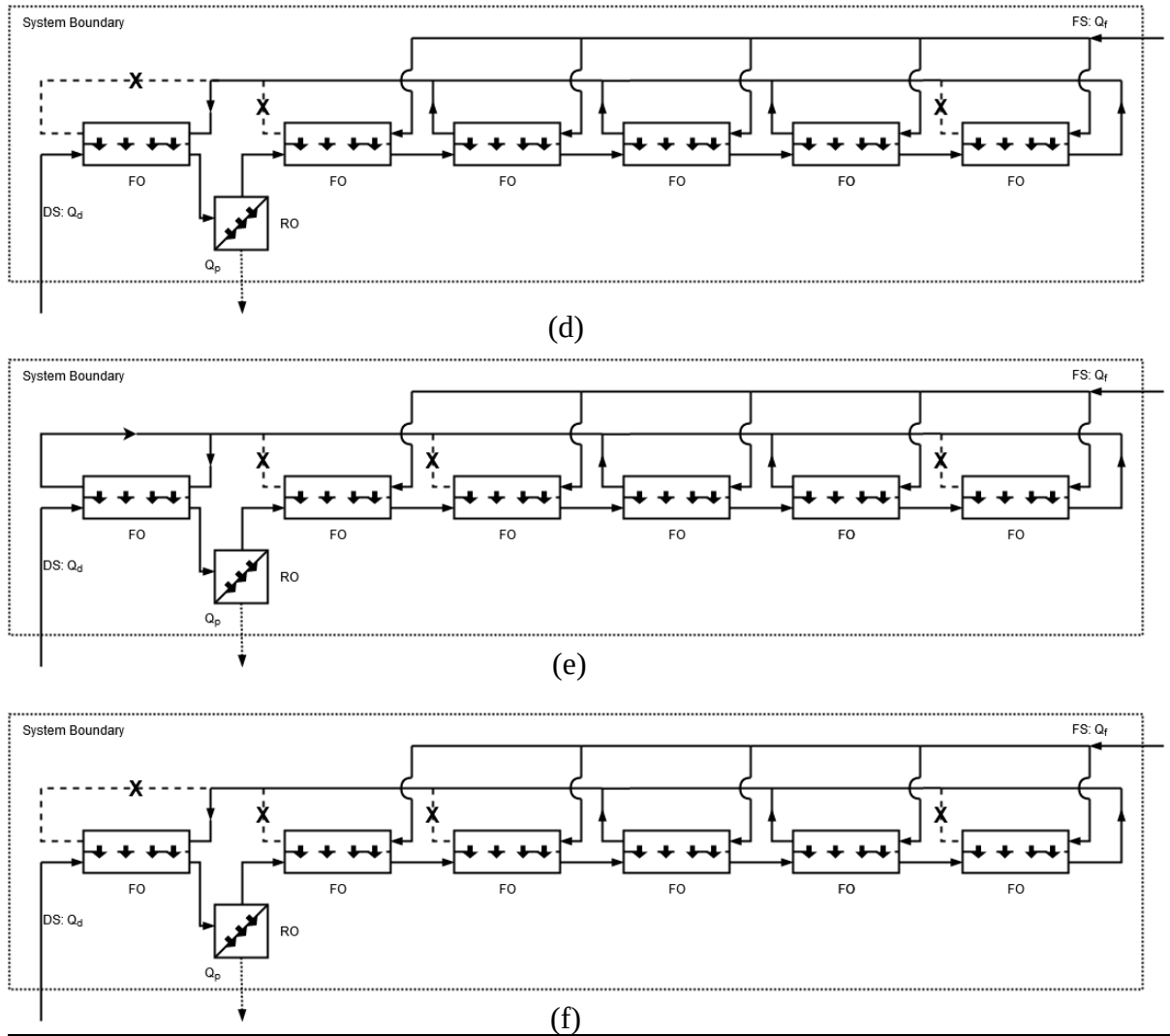


Figure 4.16: Six different configuration of recirculating FO-RO system.

The first configuration of suitable combinations consists of the outlet streams from the concentrated feed of first five units excluding the sixth unit and including the diluted draw solution exiting the sixth unit, see Figure 4.16.a. Meanwhile, the next configuration includes all elements mentioned previously, with the exception of the concentrated feed solution stream exiting the second unit, see Figure 4.16.b. The third configuration has all stream outlets excluding the first and last unit's outlets of concentrated feed flow rates, whereas the fourth one has same outlets in addition excluding the second outlet of second

unit after RO unit (see Figure 4.16.c and d). the fifth configuration excluded the second, third and sixth outlets from the system (see Figure 4.16.e). The last selected configuration involves only three outlets of fourth and fifth concentrated feed solutions and sixth diluted feed solutions.

From previously, it can be recognised that the number of outlets does not in case of importance since the first configuration has six outlets, whereas the last configuration has only three outlets although there is combination involved all seven outlets, however it did not meet criteria mentioned above. The key behind is the flow rate amount and the concentration resulted of mixing stream outlets.

An important advantage of these novel configurations, compared to previous ones, lies in the significant reduction of brine discharge from the system. This reduction in brine discharge is not only environmentally friendly but also aligns with sustainability goals, contributing to an eco-friendlier approach to water treatment processes. As environmental concerns continue to gain prominence, these innovative system designs hold the potential to make a positive impact by minimizing their ecological footprint.

4.2.1 Effect of FO-RO configurations on water productivity.

As previously mentioned, we're considering only six configurations out of 48 configurations, which satisfied the criteria of inlet feed concentration is being decreasing as input to RO unit, for recirculating as a feed solution in the initial unit before using RO. In following, configurations are ordered based on the number outlets accounted. First, couple of runs were done for all selected configurations at different draw flow rates. A

three flow rates were considered 0.416, 0.520, and 0.625 m³/h, and hydraulic pressure of 34 bar.

Figure 4.17 illustrates the water productivity for all six configurations at a draw flow rate of 0.416 m³/h. It is evident that the second configuration exhibits higher water productivity compared to the others, despite having fewer outlets connected to the feed solutions of FO units than the first configuration, which has a higher number of outlets. This superiority of the second configuration can be attributed to its lower concentration compared to the first configuration. This lower concentration results in reduced osmotic pressure, consequently leading to a greater osmotic pressure differential across the membrane of the initial FO unit, resulting in a higher water flux. It's important to note that while the first configuration has one additional outlet, the difference in flow rates between the two configurations is minimal. This observation underscores the significance of concentration as the primary determinant of water productivity in this context.

Moving on to the third configuration, it shares the same number of outlets as the second one, resulting in nearly identical flow rates. However, it lags in terms of efficiency due to its higher concentration levels. This disparity highlights the crucial role concentration plays in affecting water productivity; higher concentrations can impede water flux even with similar flow rates.

The fourth configuration ranking as the second most efficient of water productivity at a draw flow rate of 0.416 m³/h. Despite it has a lower concentration than the second configuration, it also operates with a reduced feed flow rate. Also, fourth and fifth configurations have same number of outlets resulting in nearly identical flow rates. However, former one has lower level of concentration making it more efficient. The last

configuration demonstrates lowest efficiency, although it maintains lowest concentration level. Since it involves only three outlets out of seven outlets consequently very low feed flow rate and low water flux across FO unit as well.

Now, let's focus on the last configuration, which demonstrates the lowest efficiency in terms of water productivity. Conversely, this configuration maintains the lowest concentration level among all configurations. However, a deeper examination reveals the key factor behind its reduced efficiency. It involves only three outlets out of the total seven outlets available. Consequently, this results in a very low feed flow rate, and subsequently, a low water flux across the FO unit.

In summary, it can be highlighted the importance of striking a balance between concentration and flow rate when optimizing the performance of FO systems.

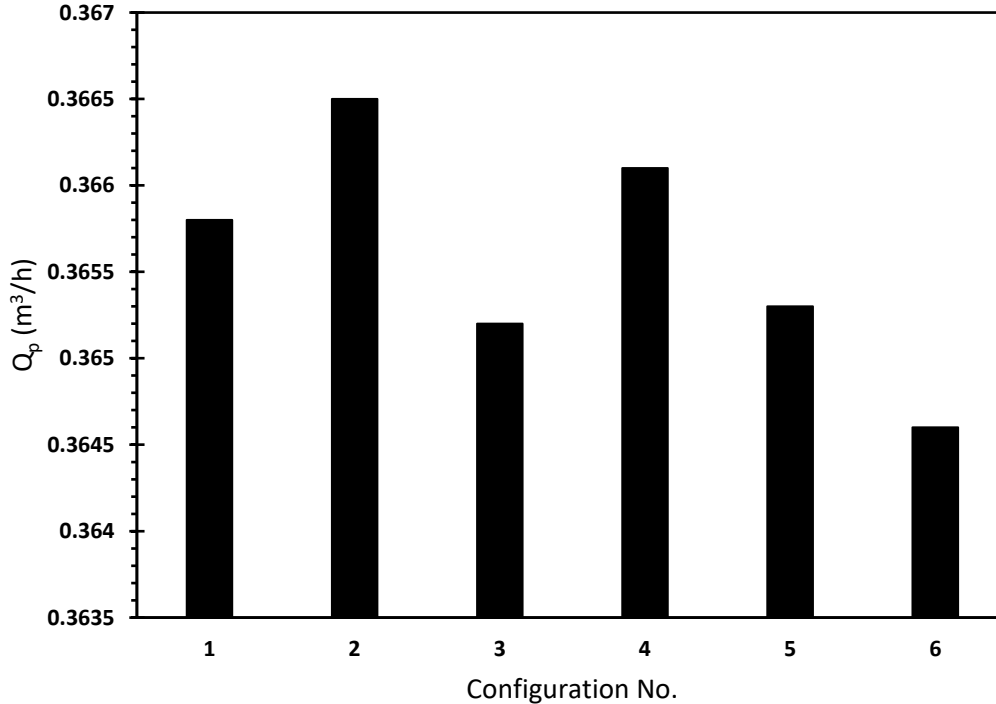


Figure 4.17: Water productivity for six configurations at $Q_d = 0.416 \text{ m}^3/\text{h}$, $P = 34 \text{ bar}$.

In case the draw flow rate is increased to $0.520 \text{ m}^3/\text{h}$, the six selected configurations act unlike in case of $0.416 \text{ m}^3/\text{h}$. Figure 4.18 illustrates that the first and second configurations are producing same fresh water. This identical approach achieved because the first configuration has higher amount of feed solution, its clearly since it has more outlets number, and higher feed concentration as well, whereas the second one has lower feed flow rate and concentration. This balance between feed flow rate and concentration level optimized the water productivity. Although the third configuration has same number of outlets as second one with slight low feed flow rate, it has low water productivity compared to second configuration. Then it can be attributed to the high feed concentration which plays the role of determining water productivity since it induces concentration polarization that affects water permeation across the membrane. Fourth and fifth configurations are almost identical in feed flow rate because same number of outlets are involved. The former one ranked secondly after first and second configurations in water productivity. This can be justified by low feed concentration it has. The latter one shows low water productivity because feed concentration is more than the fourth configuration which decreases the osmotic pressure and consequently water permeation is decreased due to low osmotic pressure difference exist. Figure 4.19 shows water productivity of all six configurations at draw flow rate of $0.625 \text{ m}^3/\text{h}$ as it decreases with number of involved outlets decrease. The first one possesses higher feed flow rate and higher feed concentration as well; however, it exhibits the most efficient of water productivity. This superiority resulted because the diluted feed produced from the first FO unit and entered RO unit has higher flow rate due to high water flux existed and lowest feed concentration solution. Water productivity is decreased as the number of involved outlets decreases, although some configurations have

same number of outlets, feed concentration balanced the resulted diluted draw solution of the first FO unit that transferred to RO unit.

In Figure 4.20, comparison is shown of all selected six configurations at different draw flow rates, 0.416, 0.520, and 0.625 m³/h. It is clear that minimal draw flow rate exhibited the highest water productivity. This can be attributed to fixed hydraulic pressure maintained. The gap between results of lowest draw flow to next one 0.520 m³/h approximately 18.5% increment, whereas the increment of water productivity of 0.520 m³/h to 0.625 m³/h reaches nearly 16%. It can be noted that water productivity minimizes as draw flow rate increases where dilution process diminishes at fixed feed and draw concentrations.

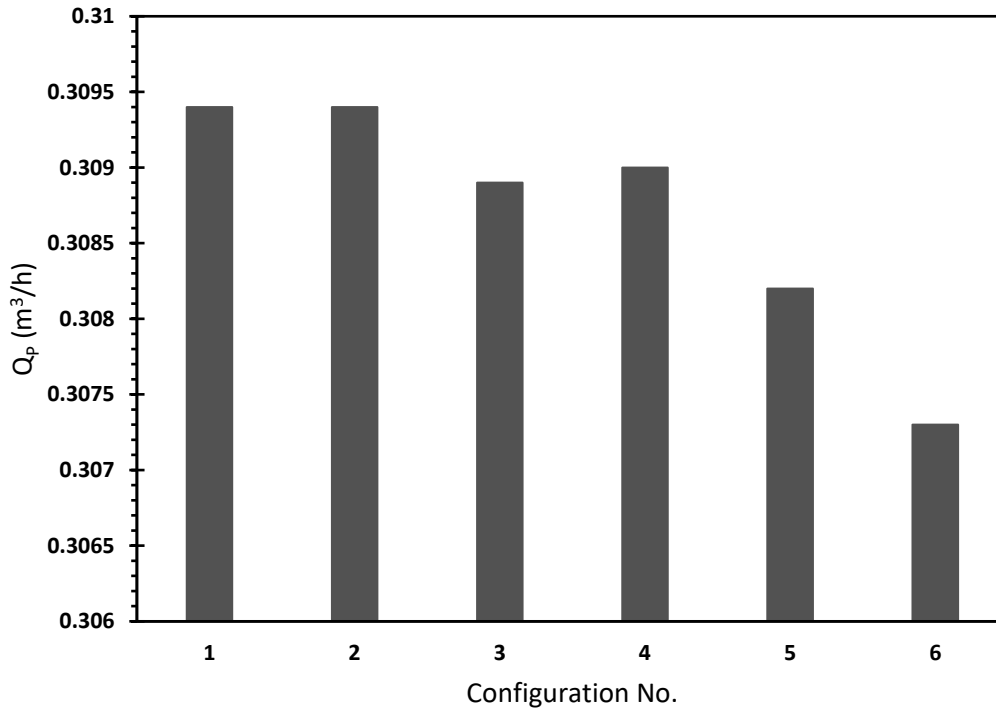


Figure 4.18: Water productivity for six configurations at $Q_d = 0.520$ m³/h, $P = 34$ bar.

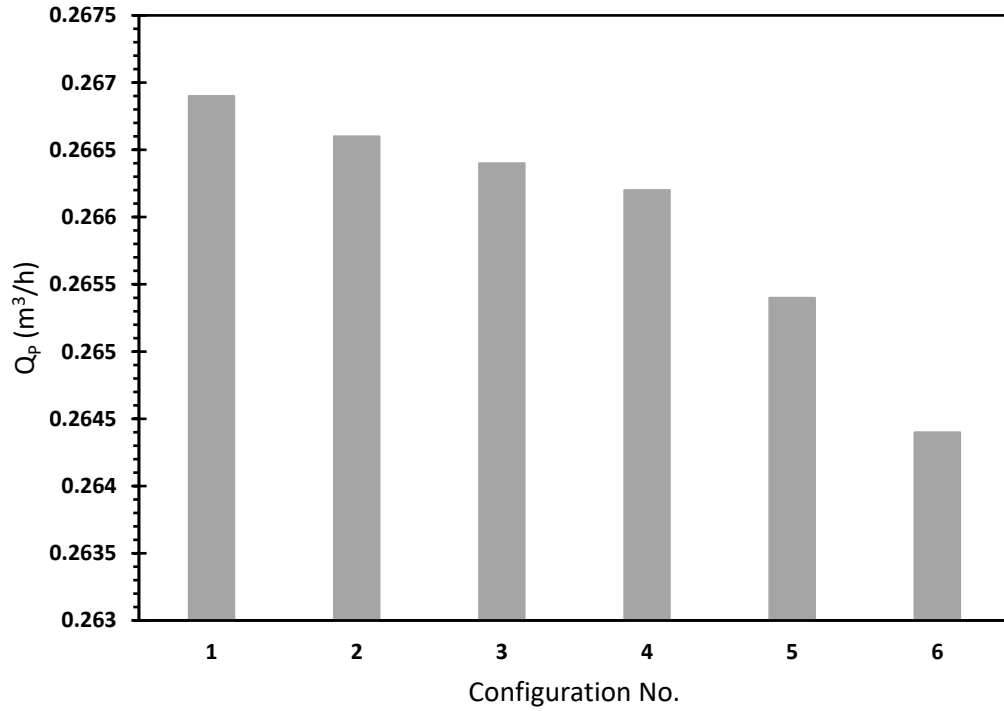


Figure 4.19: Water productivity for six configurations at $Q_d = 0.625 \text{ m}^3/\text{h}$, $P = 34 \text{ bar}$.

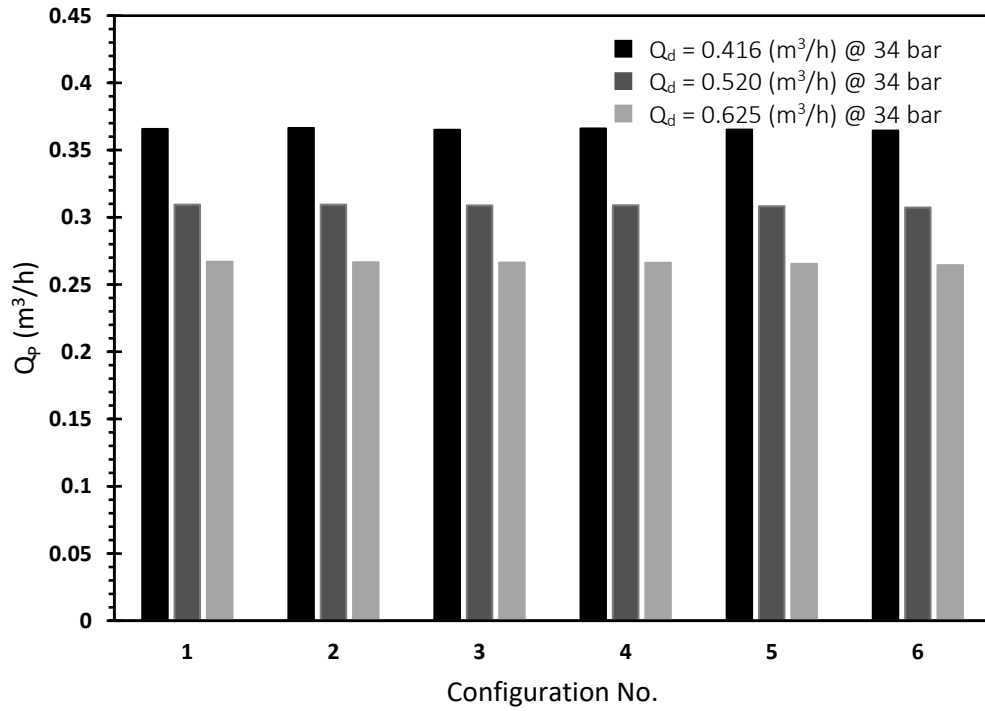


Figure 4.20: Water productivity comparison for six configurations at $Q_d = 0.416, 0.520$ and $0.625 \text{ m}^3/\text{h}$.

4.2.2 Effect of FO-RO configurations on recovery rate.

Recovery rate is directly affected by the water productivity to feed flow rate. Results follow same water productivity trend. In case of draw flow rate of $0.416 \text{ m}^3/\text{h}$, Figure 4.21 shows that recovery rate for second configuration reached up to 59.13 %. This very promising percentage commercially can be achieved. Figure 4.22 illustrates recovery rate at $0.520 \text{ m}^3/\text{h}$ draw flow rate. In section 4.2.1, first and second configurations showed identical water productivity, however, first one exhibits slightly high recovery rate compared to second. This is due to high downstream feed flow rate the latter one has, although the first one has more involved number of outlets but as indicated previously feed concentration to first FO unit is the key behind this behaviour. In last case of draw flow rate of $0.625 \text{ m}^3/\text{h}$, Figure 4.23 illustrates that first configuration reached high recovery rate compared to other configurations. This is because it has higher water productivity, although all configurations use almost same amount of feed flow rate and despite feed concentration.

Since recovery rate is directly and inversely proportional to water productivity and feed flow rate, respectively, Figure 4.24 shows that at high draw flow rate recovery rate is low where high downstream feed solution to RO unit did not overcome by hydraulic pressure, and water productivity decreases as draw flow rate increases, see section 4.2.1. The reduction of recovery rate is more than 28% as draw flow rate increases from $0.416 \text{ m}^3/\text{h}$ to $0.520 \text{ m}^3/\text{h}$ and approximately 25% when increases to $0.625 \text{ m}^3/\text{h}$.

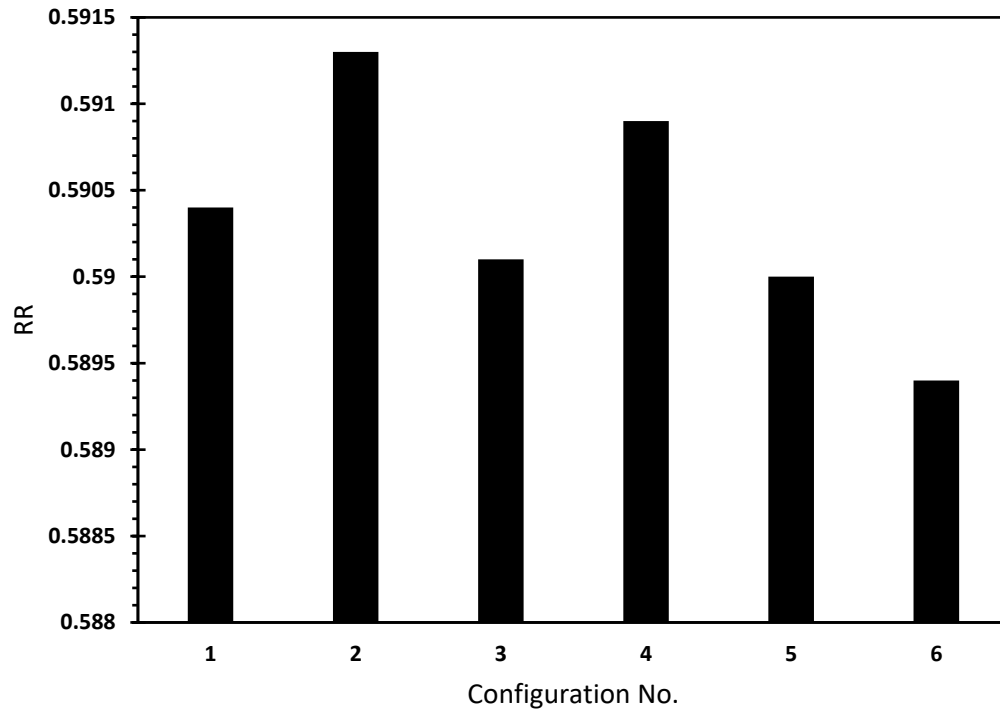


Figure 4.21: Recovery rate for six configurations at $Q_d = 0.416 \text{ m}^3/\text{h}$, $P = 34 \text{ bar}$.

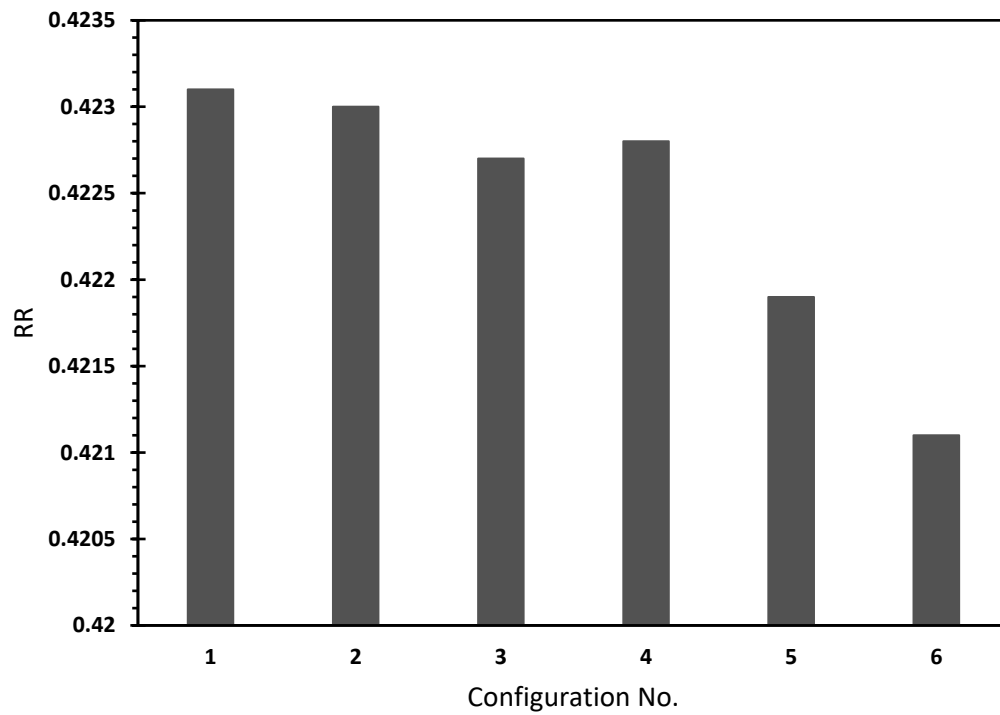


Figure 4.22: Recovery rate for six configurations at $Q_d = 0.520 \text{ m}^3/\text{h}$, $P = 34 \text{ bar}$.

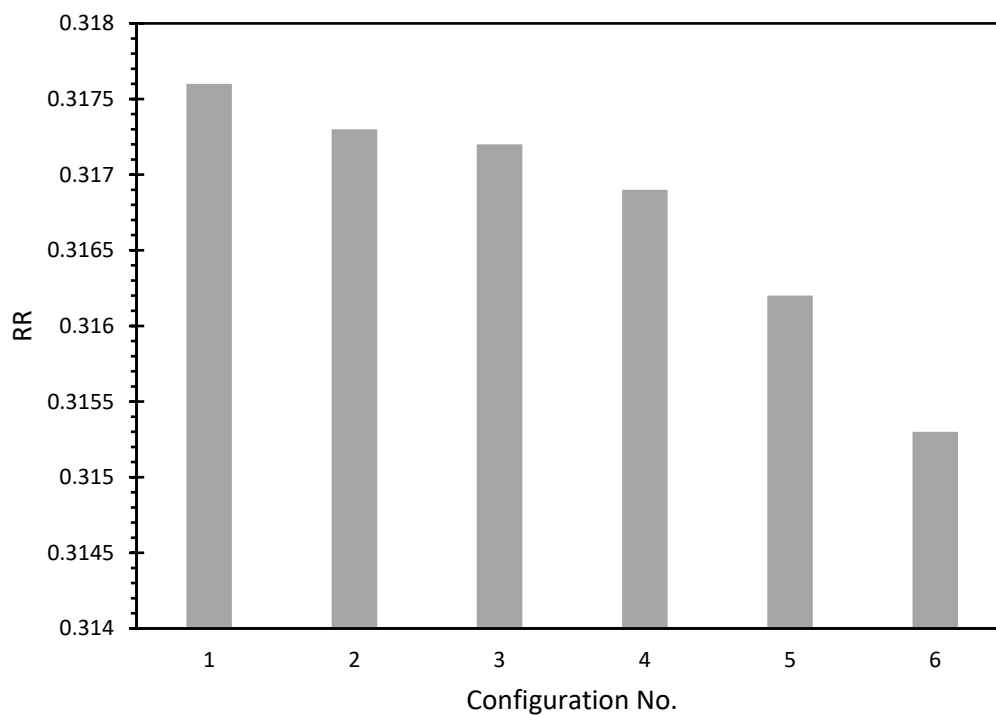


Figure 4.23: Recovery rate for six configurations at $Q_d = 0.625 \text{ m}^3/\text{h}$.

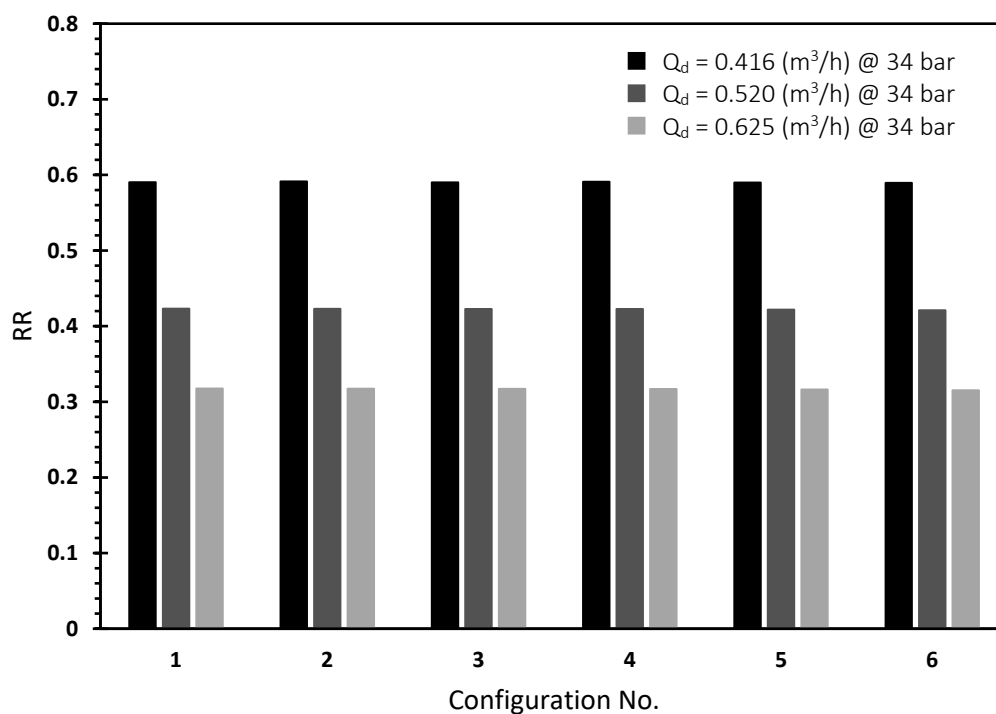


Figure 4.24: Recovery rate comparison for six configurations at $Q_d = 0.416, 0.520$ and $0.625 \text{ m}^3/\text{h}$.

4.2.3 Effect of FO-RO configurations on specific energy consumption.

The SEC of all six configurations were evaluated considering two scenarios: without utilizing ERD and with ERD. In case not considering ERD at 0.416 m³/h draw flow rate, the first one consumes the most energy among other configurations, because it has the highest level of feed solution entered first FO unit, hence SEC is considered for FO units although FO process does not consume high energy as RO process, and not high-water productivity. Figure 4.25 shows that SEC decreases as the number of considered outlets decreases, where FO feed flow rate decreases as well. The last configuration stands out by having the lowest SEC. This is primarily due to its configuration, where only three outlets are considered for water processing. As a result, the flow rate is inherently low, and this has significant implications for energy usage, especially in the operation of the pump.

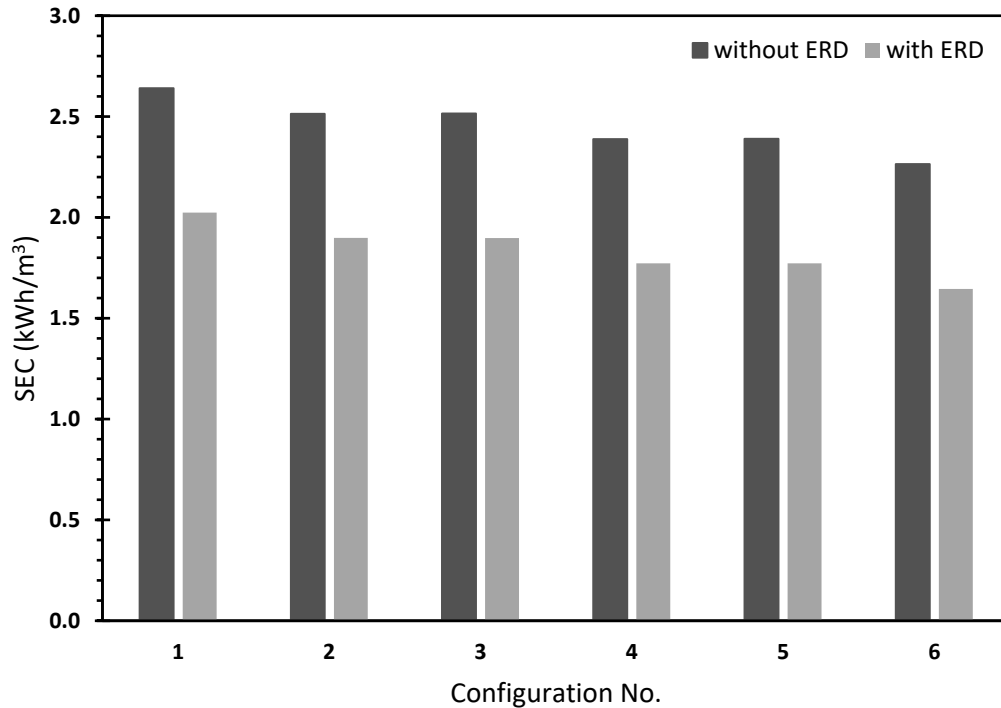


Figure 4.25: Specific energy consumption for six configurations with & without ERD at $Q_d = 0.416$ m³/h, $P = 34$ bar.

When integrating ERD into a FO-RO system, there is a remarkable reduction in SEC, often reaching an average reduction of about 25%. This substantial decrease underscores the significant positive impact that ERD technology has on the overall efficiency of the FO-RO system.

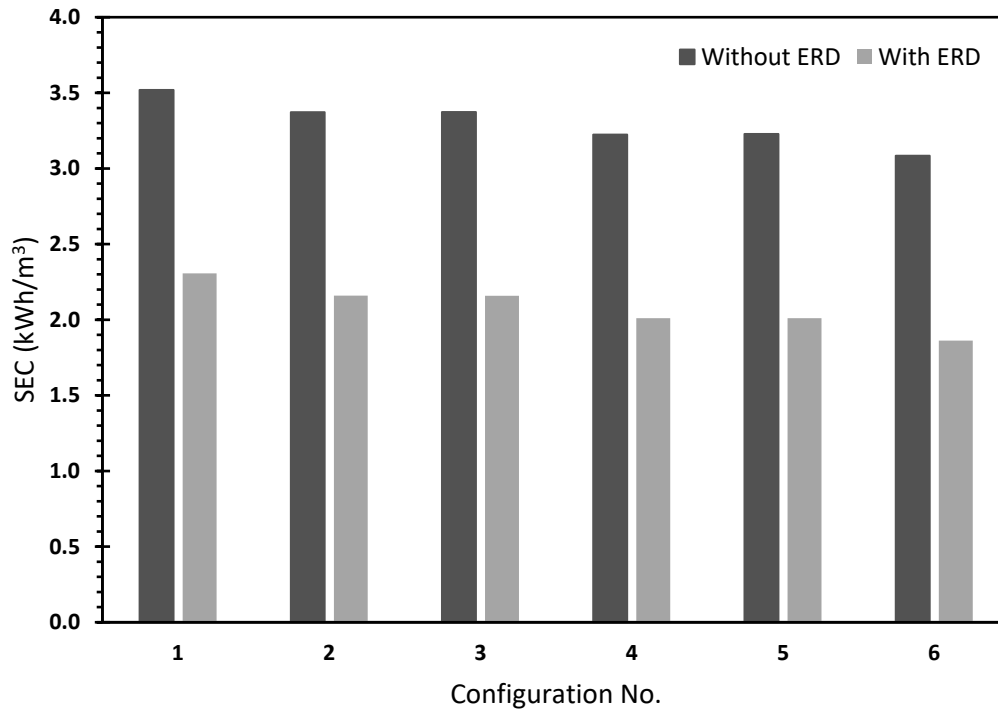


Figure 4.26: Specific energy consumption for six configurations with & without ERD at $Q_d = 0.0520$ m^3/h , $P = 34$ bar

Figure 4.28 provides a comprehensive overview of the SEC for all configurations across three distinct draw flow rates: 0.416, 0.520, and 0.625 m^3/h . Interestingly, whether with or without the use of ERD, the SEC shows an increase as the draw flow rate increases. This is primarily due to the higher flow rate that the system needs to handle at elevated draw flow rates.

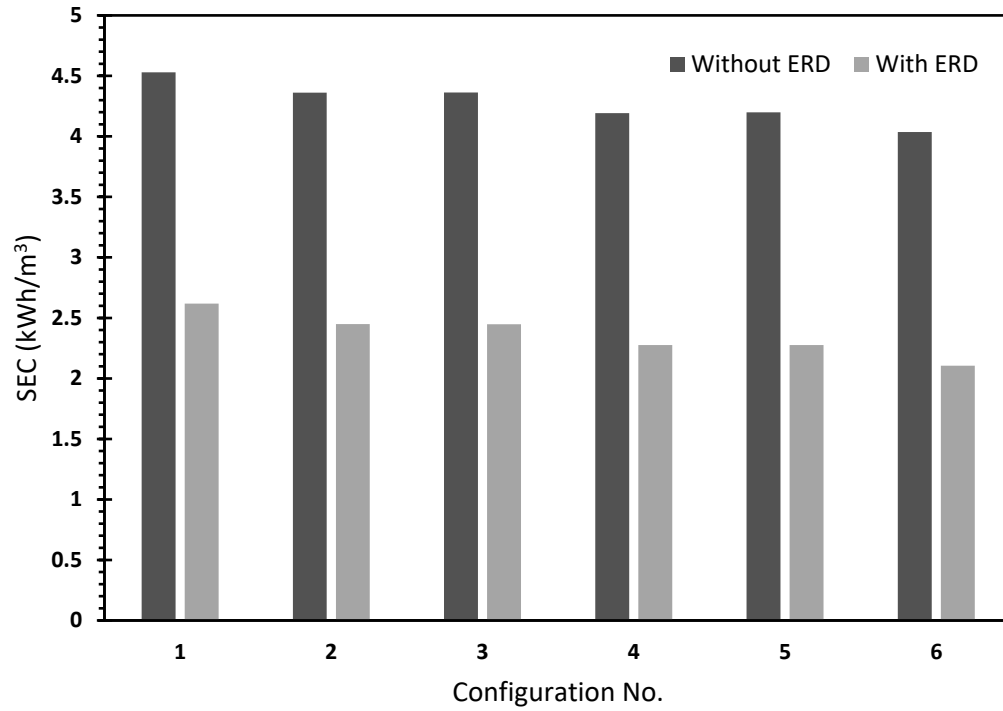


Figure 4.27: Specific energy consumption for six configurations with & without ERD at $Q_d = 0.625$ m³/h, $P = 34$ bar.

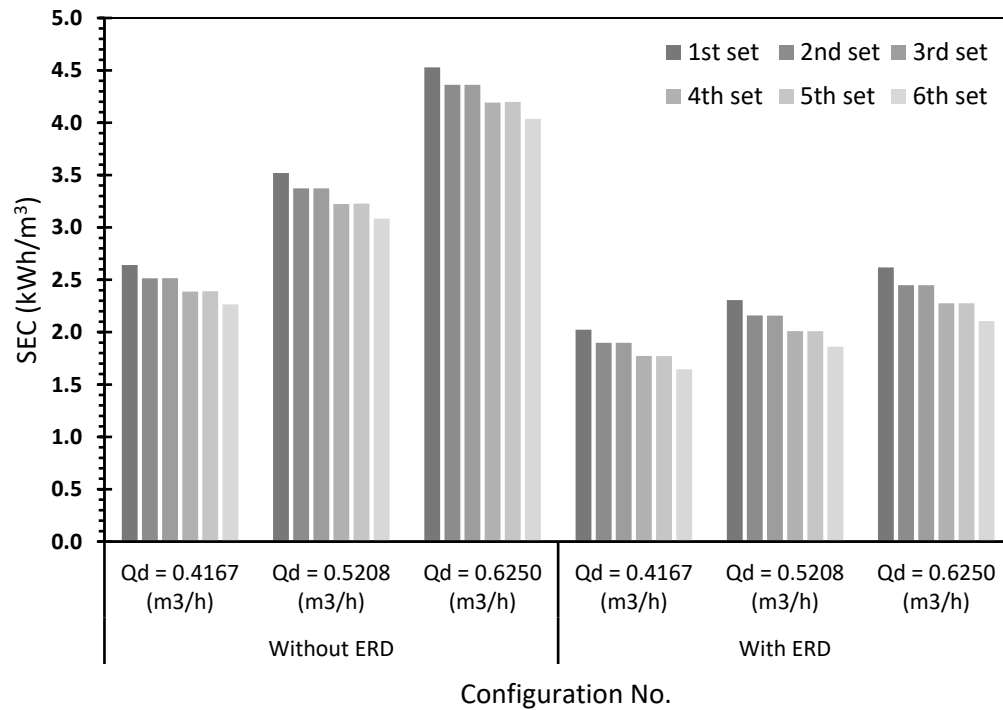


Figure 4.28: Specific energy consumption comparison for six configurations with & without ERD at $Q_d = 0.416, 0.520$ and 0.625 m³/h, $P = 34$ bar.

Moreover, an intriguing observation is that the SEC without ERD at $0.416 \text{ m}^3/\text{h}$ is nearly identical to the SEC with ERD at $0.625 \text{ m}^3/\text{h}$. This similarity suggests a balance between the draw flow rate and its concentration, coupled with the utilization of ERD.

4.2.4 Economic feasibility assessment of FO-RO system.

An economic analysis of FO-RO systems is evaluated for different draw flow rates. Figure 4.29 shows the SWC for all six configurations at different draw flow rates and with and without ERD. In these configurations most parameters involved in economic analysis are fixed such as capital costs and operation costs, where all configurations mostly share same equipment such as FO and RO membranes and pumps. It can be seen that increasing draw flow rate resulted in higher cost, since more power is utilized by the pump which affected SEC. It can be noticed that at $0.416 \text{ m}^3/\text{h}$ draw flow rate, there is not much difference when using ERD or not. This difference enlarged with increase draw flow rates like in case of $0.625 \text{ m}^3/\text{h}$ draw flow rate.

As observed in Figure 4.30, the first configuration exhibits the highest cost among the various configuration when the draw flow rate is $0.416 \text{ m}^3/\text{h}$. This cost disparity can be attributed to the substantial energy consumption associated with the use of a higher flow rate, as discussed earlier. This pattern repeats for draw flow rates of $0.520 \text{ m}^3/\text{h}$, as depicted in Figure 4.31, and $0.625 \text{ m}^3/\text{h}$, as evident in Figure 4.32.

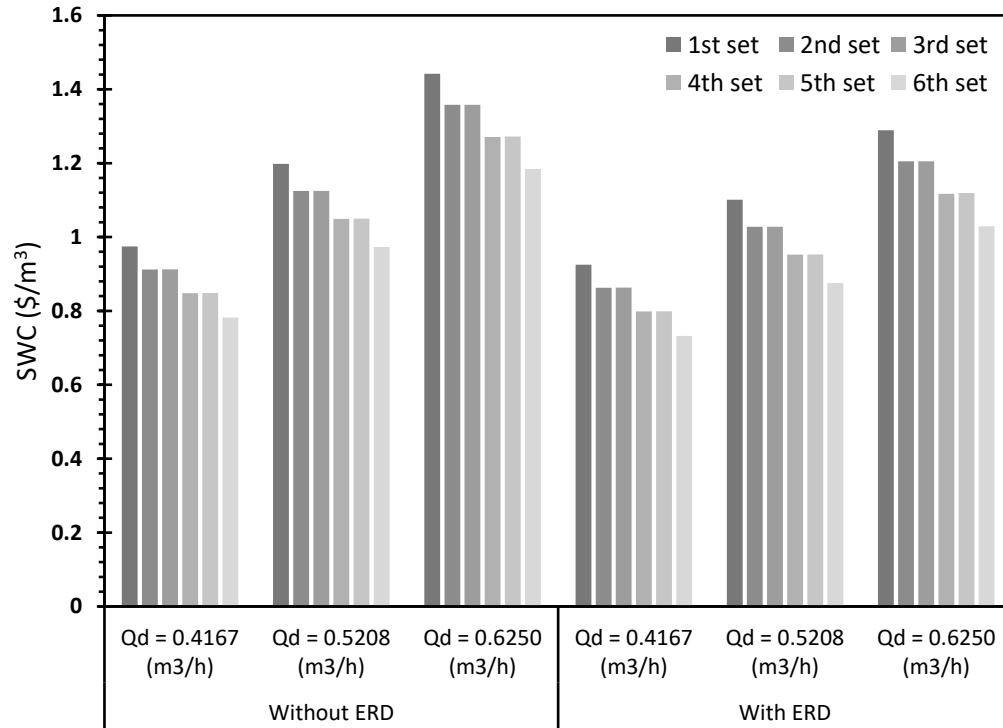


Figure 4.29: Specific water cost comparison for six configurations with & without ERD at $Q_d = 0.416, 0.520$ and $0.625 \text{ m}^3/\text{h}$, $P = 34 \text{ bar}$.

These findings emphasize the significant impact of flow rate on the overall cost of the system. While a higher draw flow rate may be desirable in certain situations, it also translates into higher energy consumption, which directly influences the operational expenses. This information is vital for decision-makers when considering the most cost-effective and energy-efficient configurations in desalination or similar processes. It underscores the need to carefully balance flow rates with energy consumption to achieve optimal economic and operational outcomes.

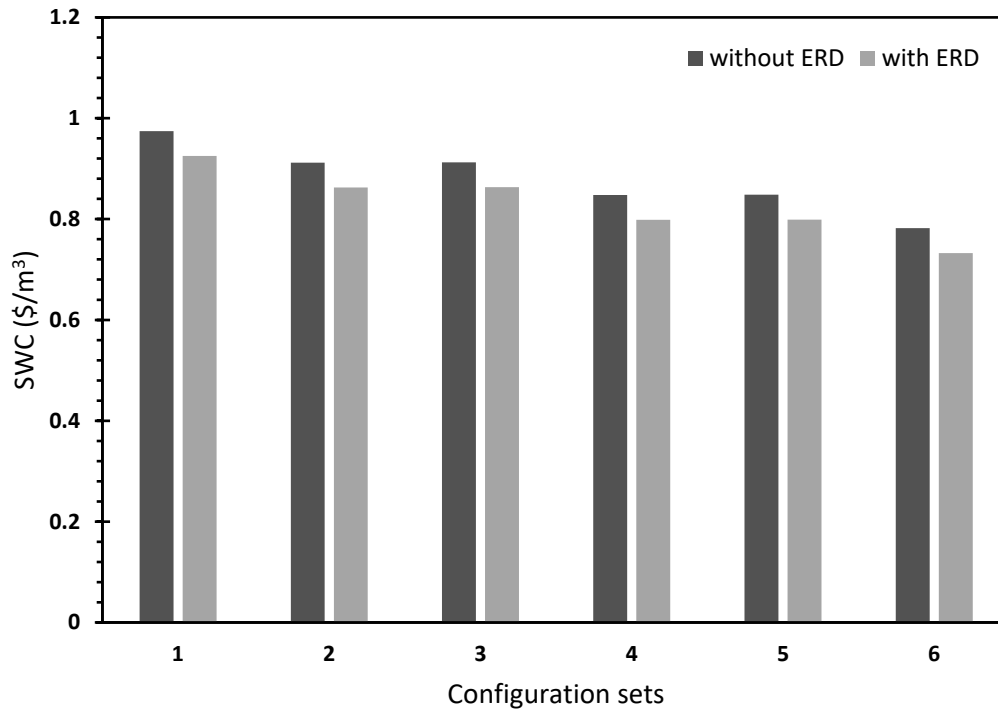


Figure 4.30: Specific water cost for six configurations considering energy consumption with & without ERD at $Q_d = 0.416 \text{ m}^3/\text{h}$, $P = 34 \text{ bar}$.

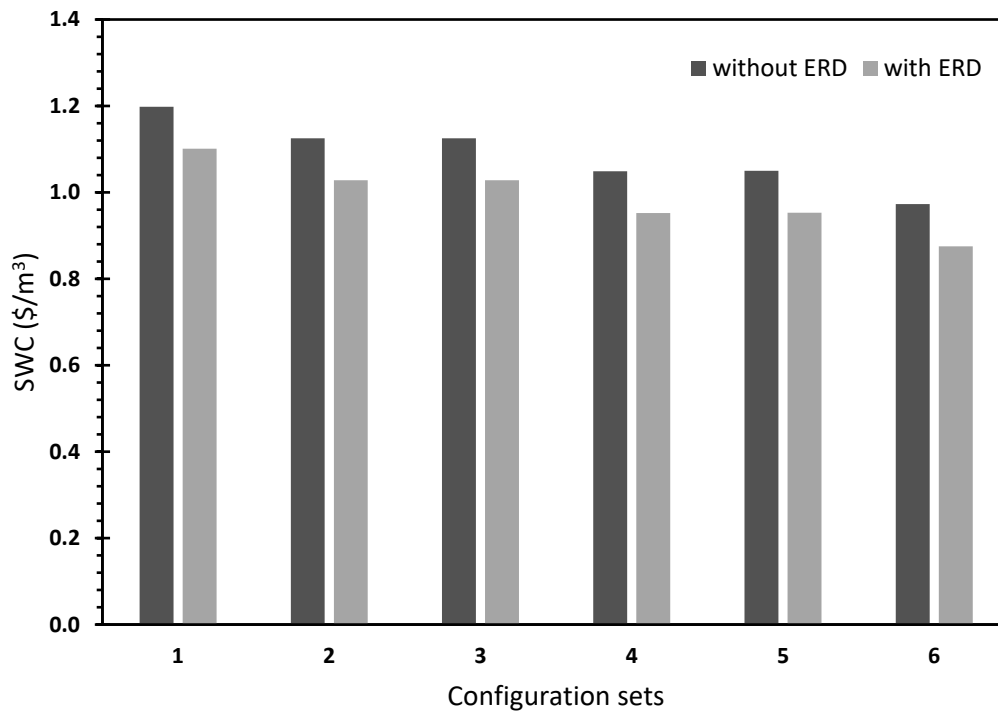


Figure 4.31: Specific water cost for six configurations considering energy consumption with & without ERD at $Q_d = 0.520 \text{ m}^3/\text{h}$, $P = 34 \text{ bar}$.

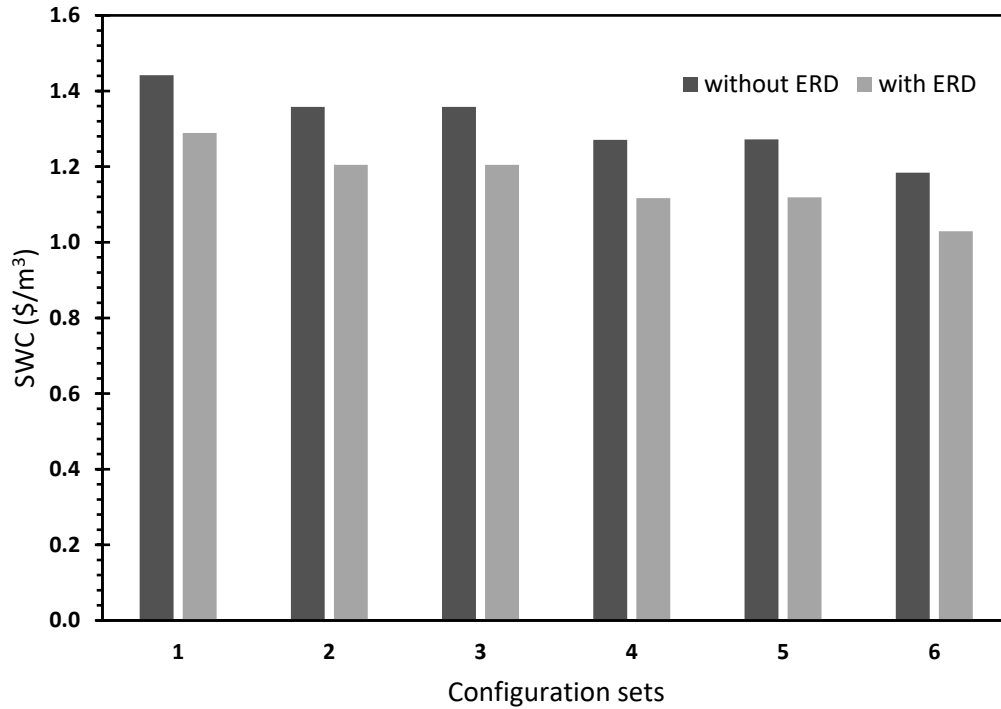


Figure 4.32: Specific water cost for six configurations considering energy consumption with & without ERD at $Q_d = 0.625 \text{ m}^3/\text{h}$, $P = 34 \text{ bar}$.

4.2.5 Hydraulic pressure effect on FO-RO system for different scenarios.

Previously, the hydraulic pressure remained constant, despite the variation in draw flow rates. This constant hydraulic pressure proved to be insufficient, leading to a reduction in water productivity. Conversely, by adjusting and compensating for the hydraulic pressure, the system demonstrated an improved capacity to enhance water productivity, thereby overcoming the challenges posed by increased draw flow rates as seen in Figure 4.33.

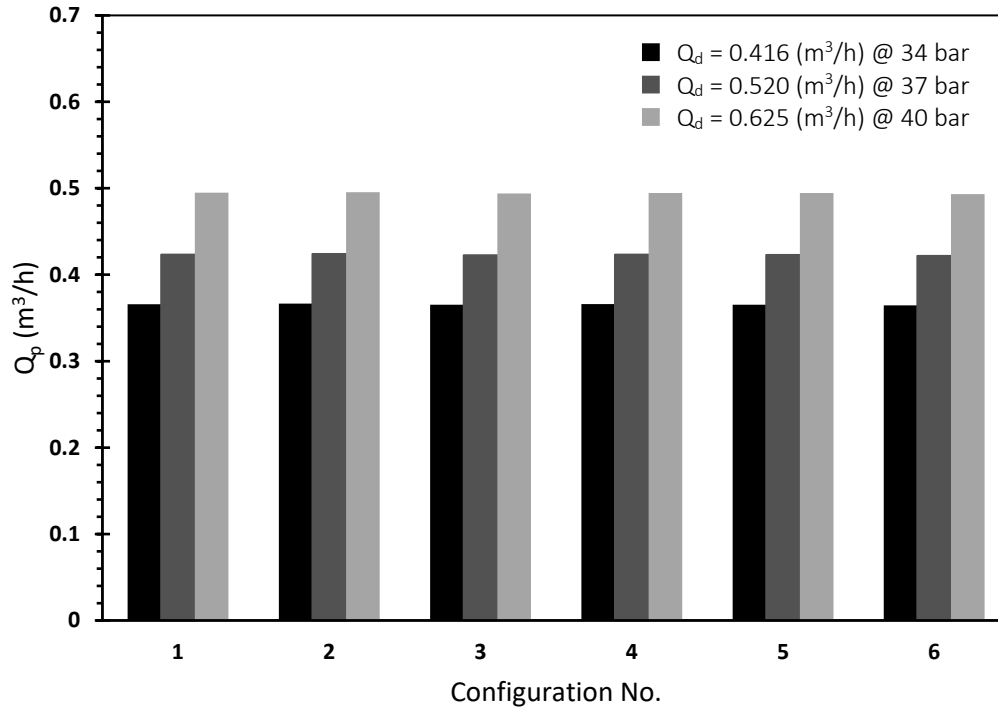


Figure 4.33: Pressure effect on water productivity of FO-RO system for six configurations at different draw flow rates: 34 bar for $Q_d = 0.416 \text{ m}^3/\text{h}$, 37 bar for $Q_d = 0.520 \text{ m}^3/\text{h}$, and 40 bar for $Q_d = 0.625 \text{ m}^3/\text{h}$.

Figure 4.34, Figure 4.35 Figure 4.36 show water productivity at draw flow rates of 0.416, 0.520 and $0.625 \text{ m}^3/\text{h}$, respectively. The second configuration exhibited the highest water productivity among the six configurations. Remarkably, even as the draw flow rate increased, this particular configuration consistently showcased elevated levels of water productivity. The reason is that high flow rate and low concentration level the configuration possessed. These characteristics influenced the osmotic pressure difference, resulting in a substantial increase in water flux through the semi-permeable membrane in the FO process. As a result, a draw solution with a significantly high level of dilution was achieved.

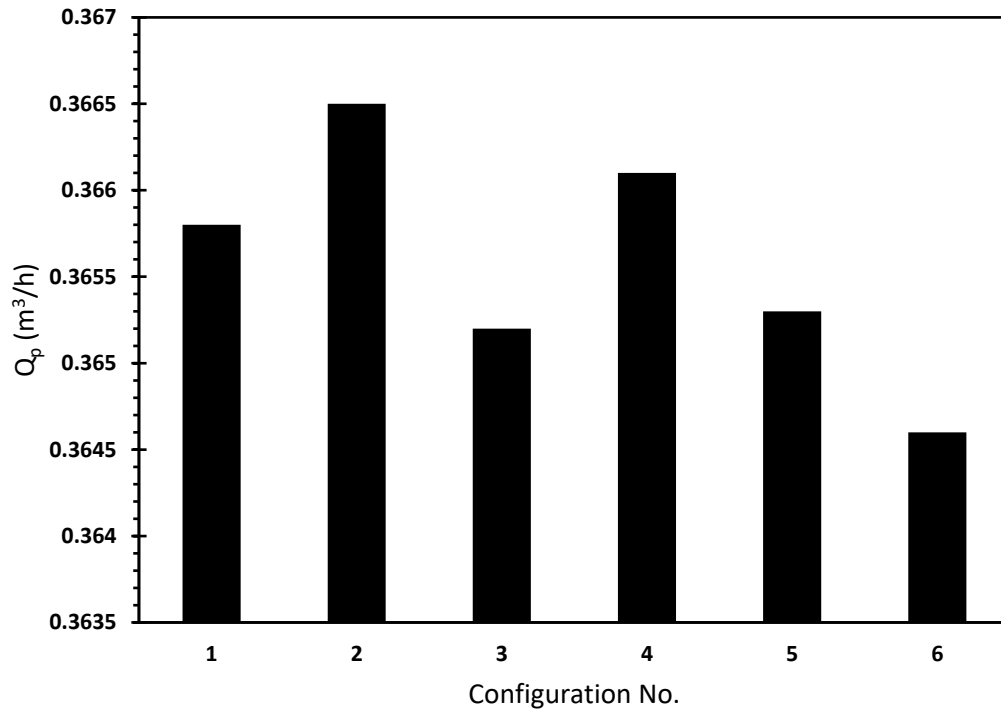


Figure 4.34: Water productivity FO-RO system for six configurations at draw flow rates of $Q_d = 0.416 \text{ m}^3/\text{h}$, $P = 34 \text{ bar}$.

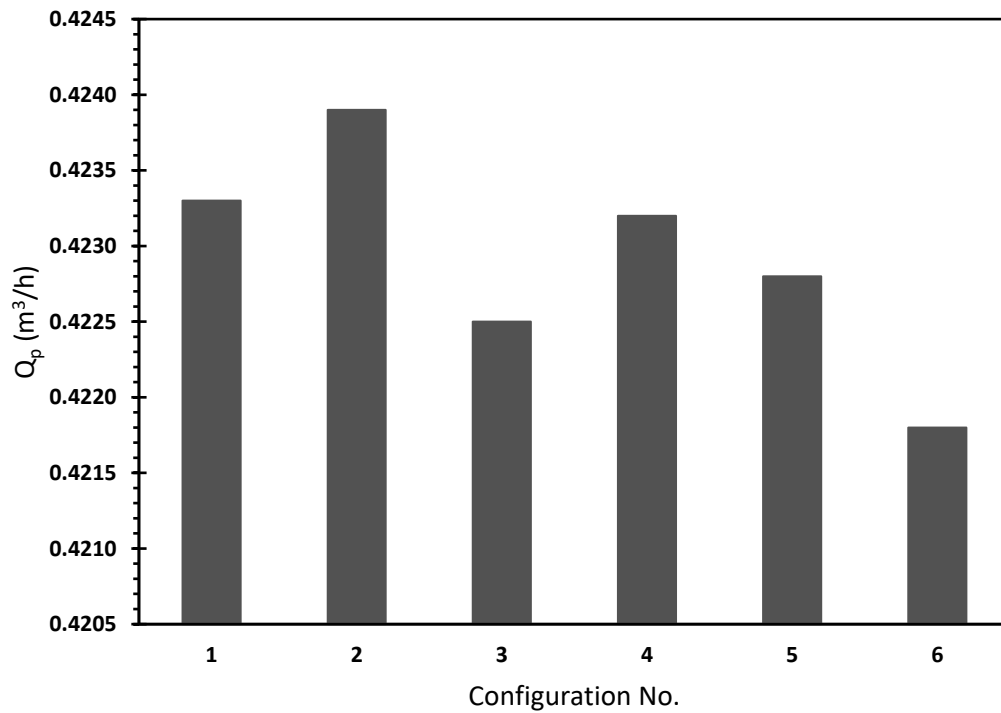


Figure 4.35: Water productivity FO-RO system for six configurations at draw flow rates of $Q_d = 0.520 \text{ m}^3/\text{h}$, $P = 37 \text{ bar}$.

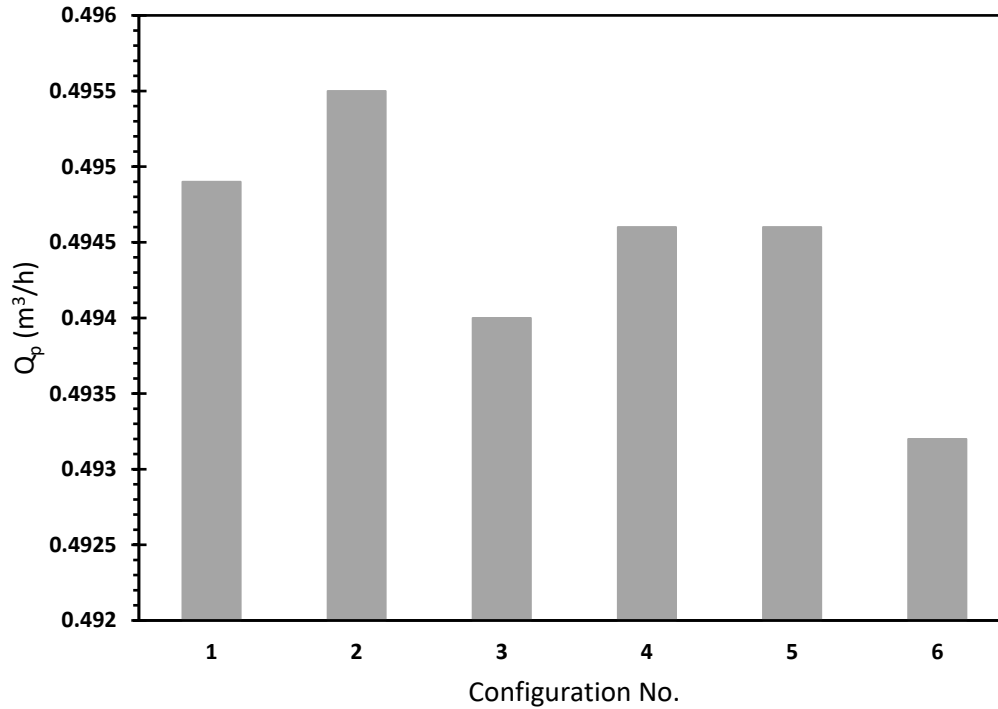


Figure 4.36: Water productivity FO-RO system for six configurations at draw flow rates of $Q_d = 0.625 \text{ m}^3/\text{h}$. and pressure of 40 bar.

SEC for all six configurations is presented in Figure 4.37. It is evident that the draw flow rate does not have a significant influence on the SEC. Despite the high energy requirements associated with high flow rates driven by pumps, the compensatory effect of high-water productivity mitigates the impact on SEC. Furthermore, the incorporation of ERD resulted in substantial variations, leading to an approximate 23% reduction in SEC. This highlights the significant impact of ERD in achieving considerable savings in SEC within the considered system configurations.

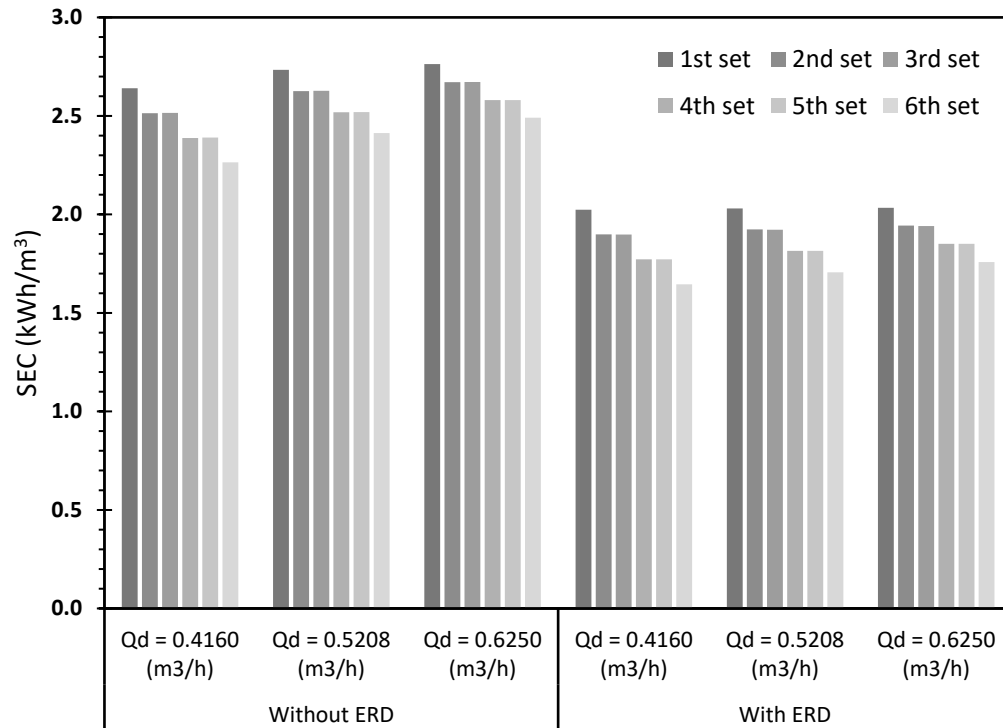


Figure 4.37: Pressure effect on SEC of FO-RO system with & without ERD for six configurations at different draw flow rates: 34 bar for $Q_d = 0.416 \text{ m}^3/h$, 37 bar for $Q_d = 0.520 \text{ m}^3/h$, and 40 bar for $Q_d = 0.625 \text{ m}^3/h$.

Figure 4.38 displays the SWC for three distinct draw flow rates, taking into account SEC both with and without the incorporation of ERD. Clearly, as the flow rate increased, SWC exhibited a corresponding increase. This correlation is attributed to the heightened costs associated with pumps, which are directly linked to flow rates. Notably, the first configuration proved to be the most expensive across all draw flow rates in both scenarios, whether ERD was considered or not.

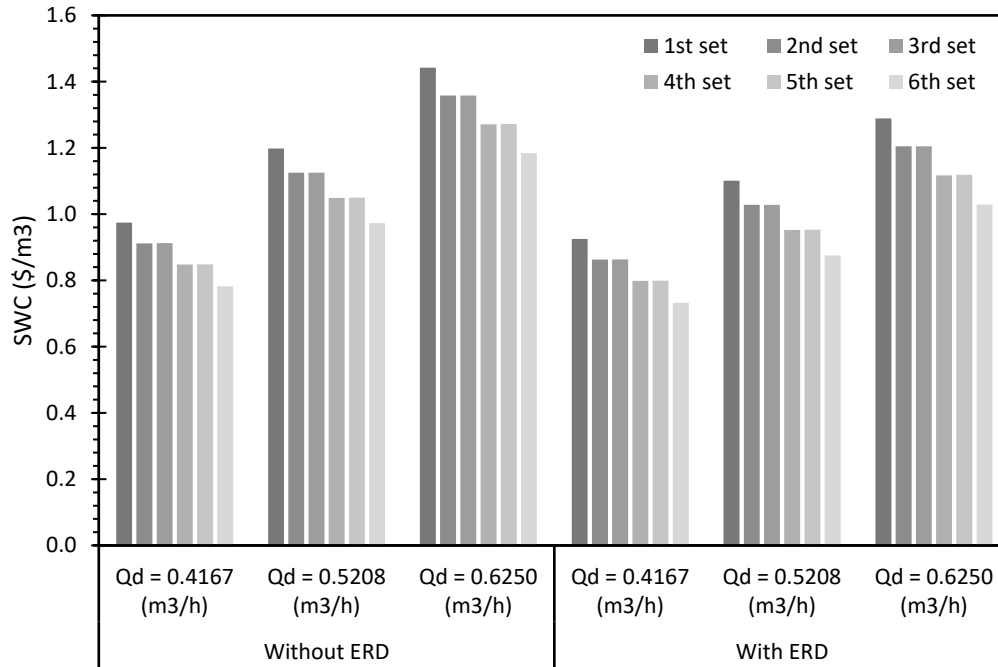


Figure 4.38: Pressure effect on SWC of FO-RO system with & without ERD for six configurations at different draw flow rates: 34 bar for $Q_d = 0.416 \text{ m}^3/\text{h}$, 37 bar for $Q_d = 0.520 \text{ m}^3/\text{h}$, and 40 bar for $Q_d = 0.625 \text{ m}^3/\text{h}$.

4.3 Six Forward Osmosis Units Integrated with A Single Reverse Osmosis Unit Located Prior to last FO Unit.

Another extended system arrangement is being considered, comprising same six FO units and one RO unit interconnected sequentially. Differently, in this configuration, the RO unit is positioned downstream of the fifth FO unit. This arrangement causes the inlet flow rate to undergo dilution by the pre-five FO units, while the subsequent FO unit is linked in series after the RO unit, as depicted in Figure 4.39.

What makes this configuration particularly interesting is its handling of the outlet streams from the six FO units. Instead of being discharged separately, these streams are combined and directed back to the first FO unit, serving as a feed flow rate. This recirculation process creates an opportunity for additional treatment of the diluted stream.

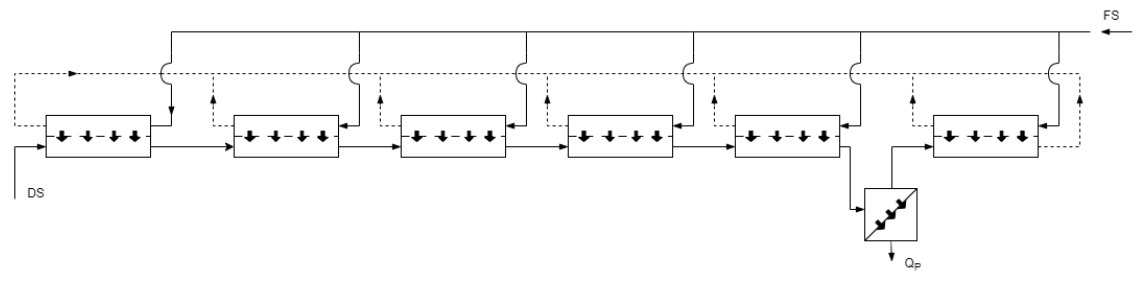
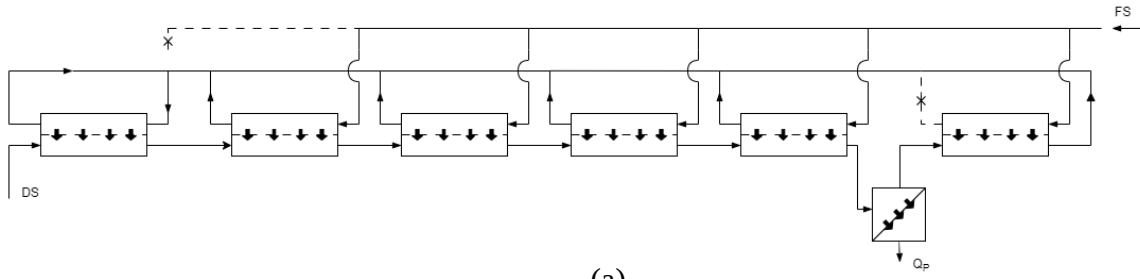
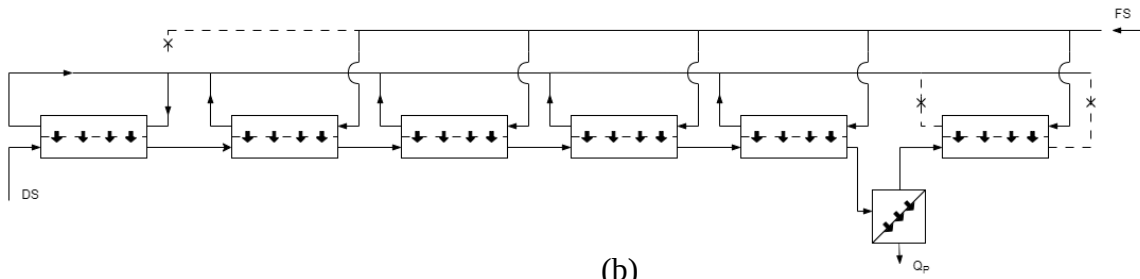


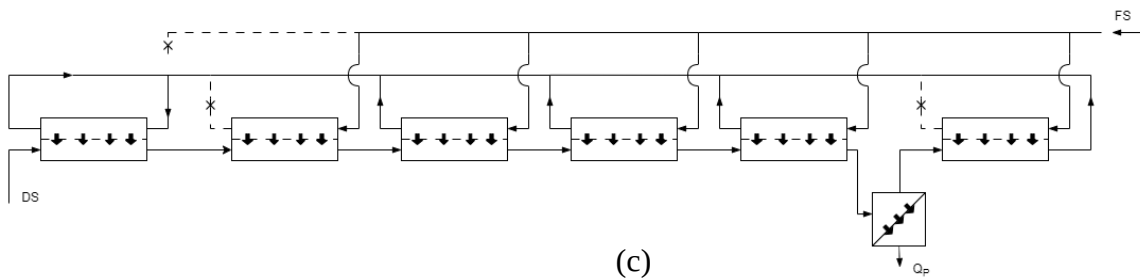
Figure 4.39: Six FO units connected with RO unit located prior to last FO unit.



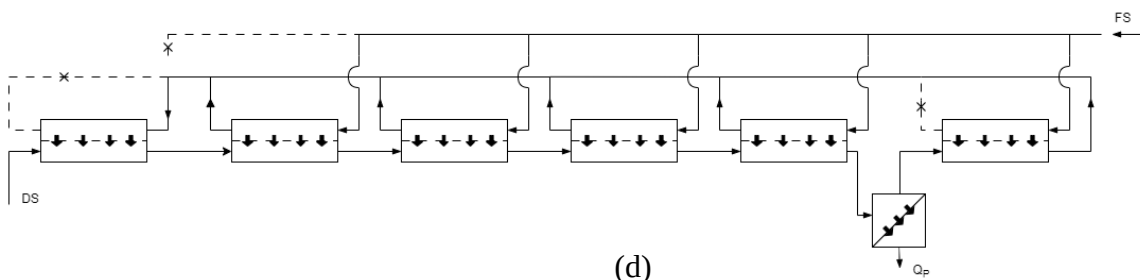
(a)



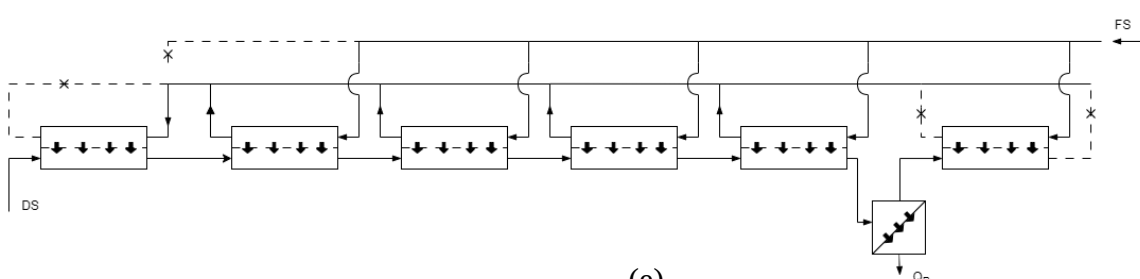
(b)



(c)



(d)



(e)

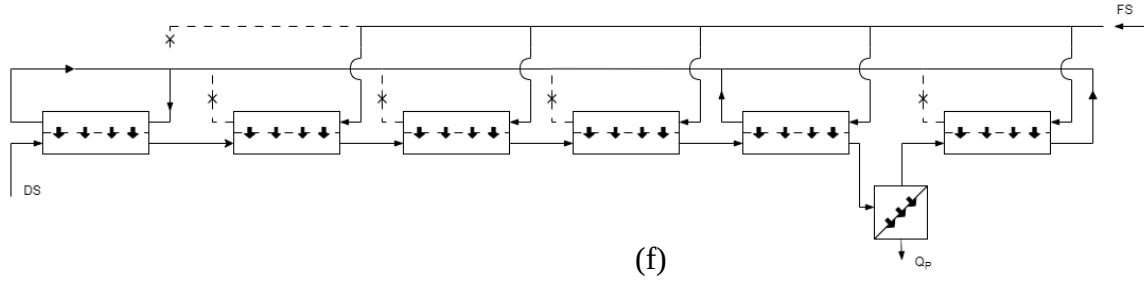


Figure 4.40: Six different configurations of recirculating FO-RO system.

4.3.1 Effect of FO-RO configurations on water productivity.

In Figure 4.41, it is clear that the sixth configuration demonstrates superior water productivity compared to the others, even though it has the fewest outlets connected to the feed solutions of FO units among all configurations. This superiority can be attributed to its lower concentration and the highest flow rate entering the RO unit. The lower concentration and higher feed rate result in an increased water flux across the membrane.

The remaining five configurations, excluding the third one, exhibit identical water productivity. This consistency can be explained by the balance between the feed flow rate and the concentration level that each system manages, despite variations in their specific values.

The third configuration, which shares the same number of outlets as the second and fourth configurations, it shows lower water productivity. This difference underscores the critical role that concentration plays in influencing water productivity.

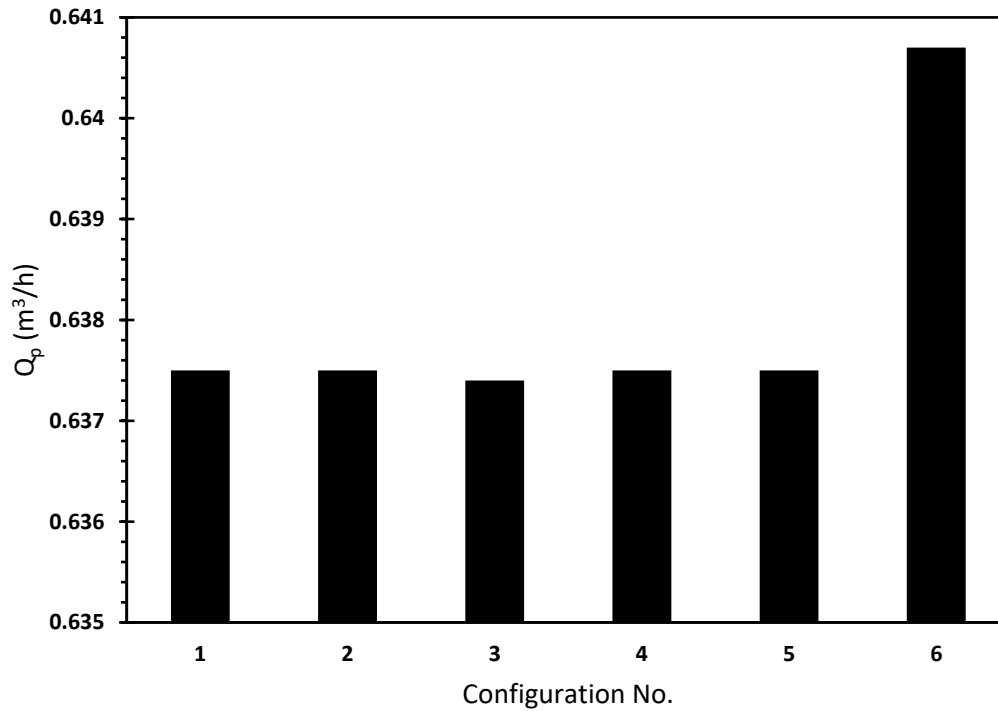


Figure 4.41: Water productivity for six configurations at $Q_d = 0.416 \text{ m}^3/\text{h}$, $P = 31 \text{ bar}$.

If the draw flow rate is increased to $0.520 \text{ m}^3/\text{h}$, the behaviour of the six selected configurations differs from that observed at $0.416 \text{ m}^3/\text{h}$. In Figure 4.42, it is evident that the first to fifth configurations produce the same amount of fresh water. This uniform performance is achieved because the first configuration has a higher amount of feed solution supplied to the first FO unit, as it involves more outlets. However, the latest configuration exhibits lower water productivity due to its higher feed concentration compared to other configurations. This higher concentration decreases the osmotic pressure, resulting in reduced water permeation due to a lower osmotic pressure difference. Figure 4.43 demonstrates a similar pattern to the one observed at a draw flow rate of $0.520 \text{ m}^3/\text{h}$, with decreasing water productivity because the pressure is not compensated.

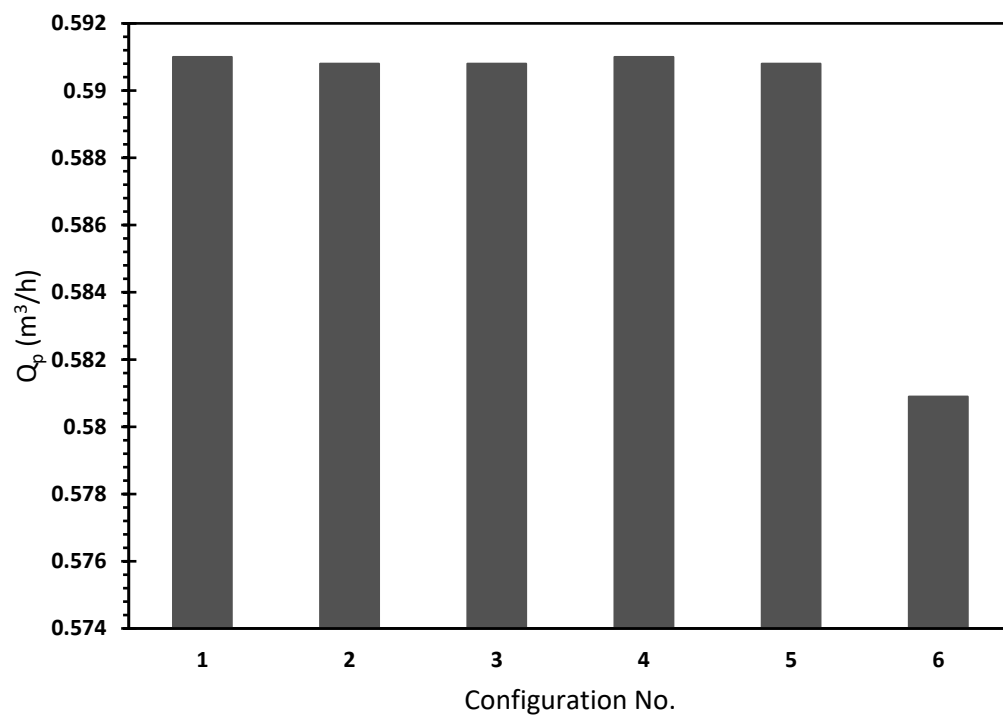


Figure 4.42: Water productivity for six configurations at $Q_d = 0.520 \text{ m}^3\text{/h}$, $P = 31 \text{ bar}$.

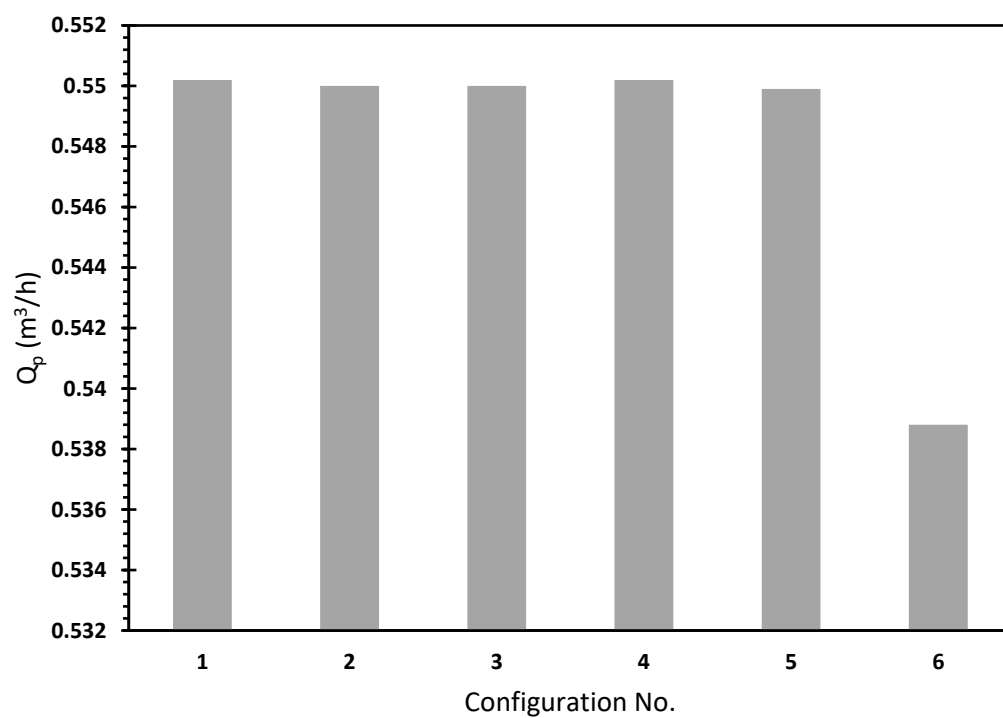


Figure 4.43: Water productivity for six configurations at $Q_d = 0.625 \text{ m}^3\text{/h}$, $P = 31 \text{ bar}$.

In Figure 4.44, a comparison is presented for all six selected configurations at different draw flow rates: 0.416, 0.520, and 0.625 m³/h. It is evident that the configuration with the lowest draw flow rate exhibits the highest water productivity. This is attributed to the fixed hydraulic pressure being maintained. The difference in water productivity between the lowest draw flow rate and the next one, 0.520 m³/h, is approximately 8% for the first five configurations, while the last configuration shows an increment of almost 10%. However, the increment in water productivity from 0.520 m³/h to 0.625 m³/h is nearly 7.5% for the first five configurations and 8% for the last one. It is noteworthy that water productivity decreases as the draw flow rate increases, where the dilution process diminishes at fixed feed and draw concentrations.

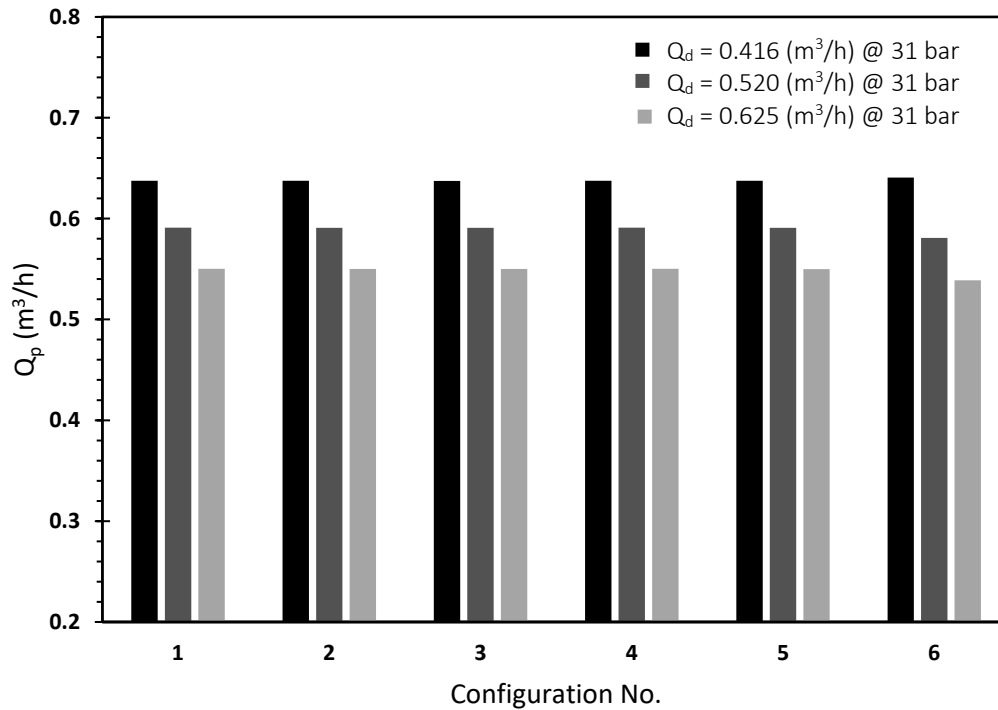


Figure 4.44: Water productivity comparison for six configurations at $Q_d = 0.416, 0.520$ and $0.625 \text{ m}^3/\text{h}$.

4.3.2 Effect of FO-RO configurations on recovery rate.

Recovery rate is directly influenced by the water productivity to feed flow rate ratio. For a draw flow rate of $0.416 \text{ m}^3/\text{h}$, Figure 4.45 demonstrates that the recovery rate for the third configuration reaches up to 60%. In contrast to water productivity, the recovery rate for the last configuration is the lowest, although it yields the highest water productivity. This behaviour is attributed to the dominance of the high feed flow rate entering the RO unit over water productivity.

Figure 4.48 illustrates the recovery rate at a draw flow rate of $0.520 \text{ m}^3/\text{h}$. While the first five configurations showed identical water productivity in Figure 4.42, the recovery rate is highest and identical for the third, fourth, and fifth configurations. This can be attributed to the balance in feed flow rate and water productivity despite differences in feed flow rate and concentration levels. In the case of a draw flow rate of $0.625 \text{ m}^3/\text{h}$, Figure 4.59 illustrates a match between water productivity and recovery rate patterns for the same reasons mentioned above.

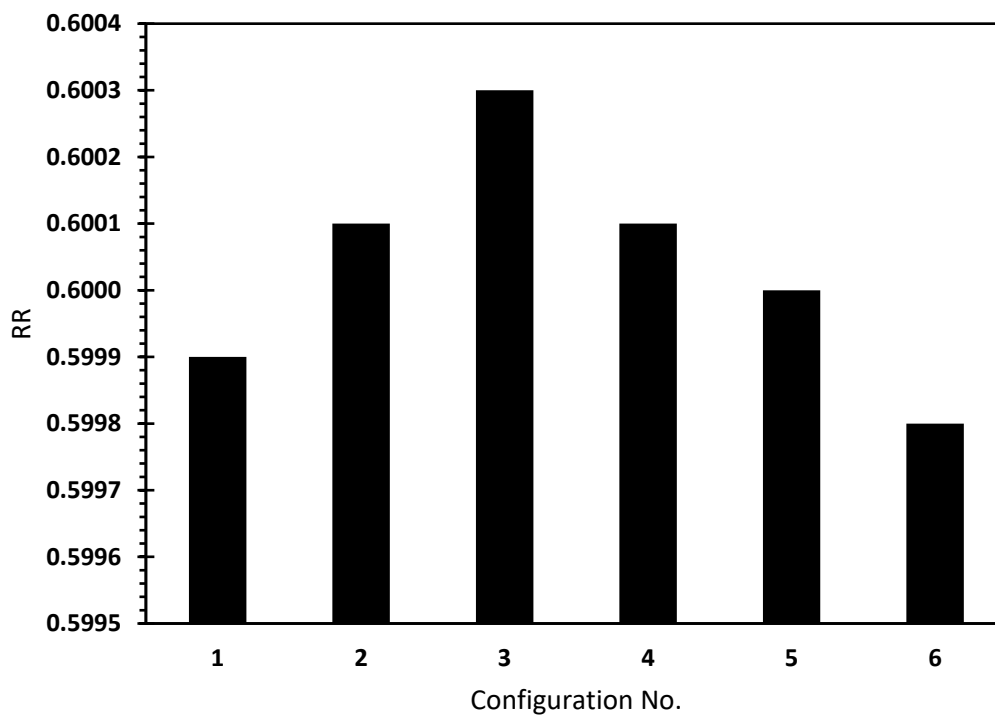


Figure 4.45: Recovery rate for six configurations at $Q_d = 0.416 \text{ m}^3/\text{h}$, $P = 31 \text{ bar}$.

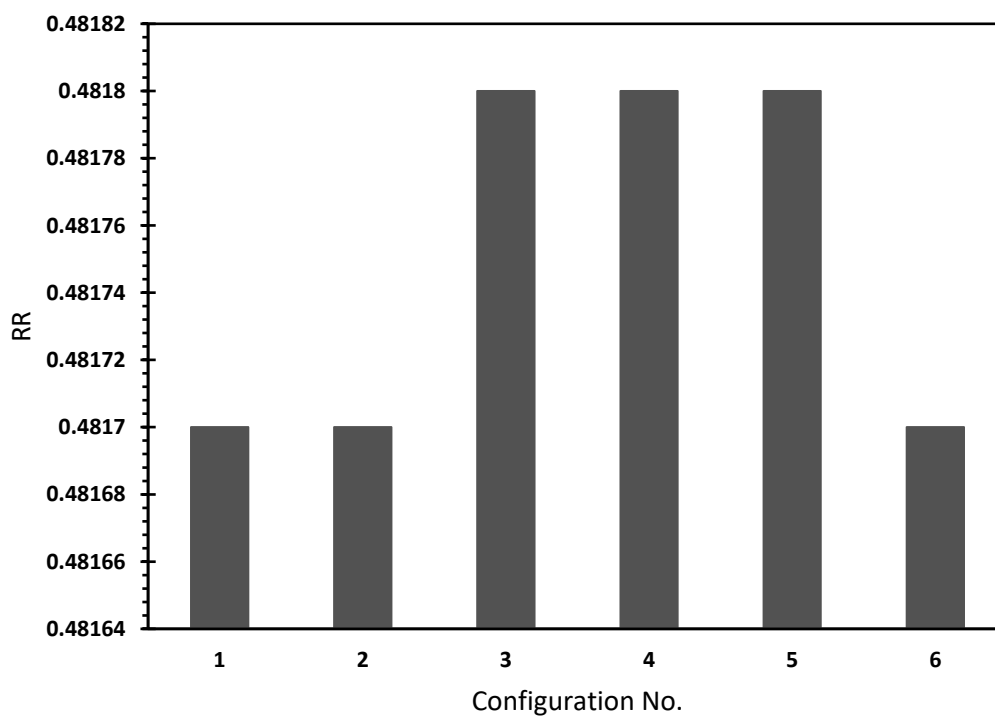


Figure 4.46: Recovery rate for six configurations at $Q_d = 0.520 \text{ m}^3/\text{h}$, $P = 31 \text{ bar}$.

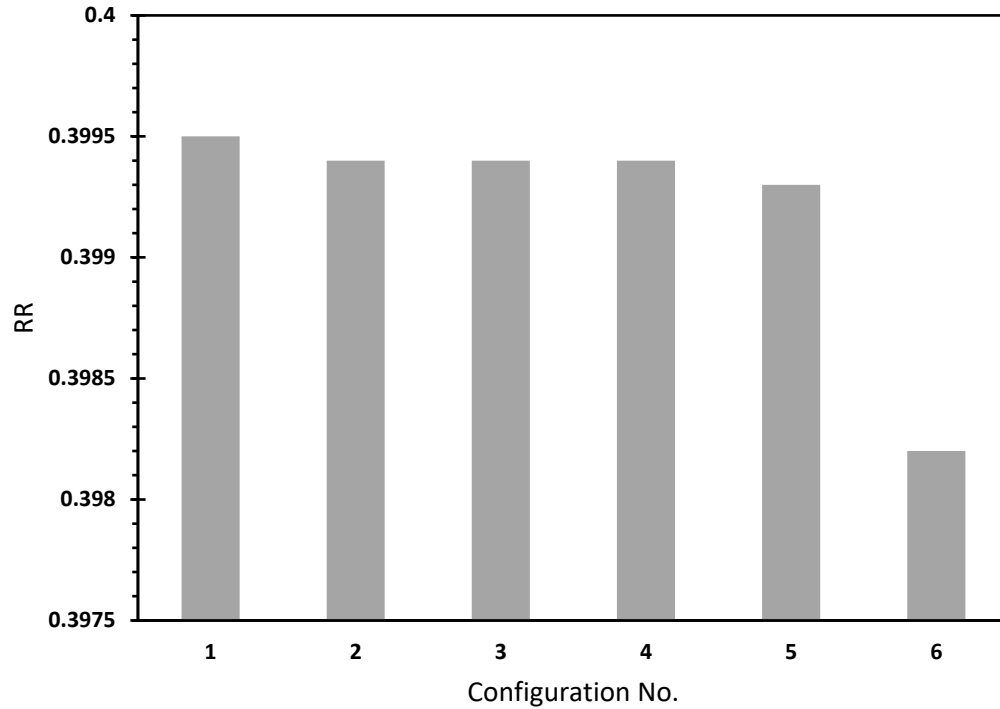


Figure 4.47: Recovery rate for six configurations at $Q_d = 0.0625 \text{ m}^3/\text{h}$, $P = 31 \text{ bar}$.

As recovery rate is directly proportional to water productivity and inversely proportional to feed flow rate, Figure 4.48 illustrates that at high draw flow rates, the recovery rate is low, indicating that the downstream feed solution to the RO unit is not adequately overcome by hydraulic pressure. Consequently, water productivity decreases as draw flow rate increases. In such configurations, the reduction in recovery rate is more than 19.5% as the draw flow rate increases from $0.416 \text{ m}^3/\text{h}$ to $0.520 \text{ m}^3/\text{h}$ and approximately 33.5% when it increases to $0.625 \text{ m}^3/\text{h}$.

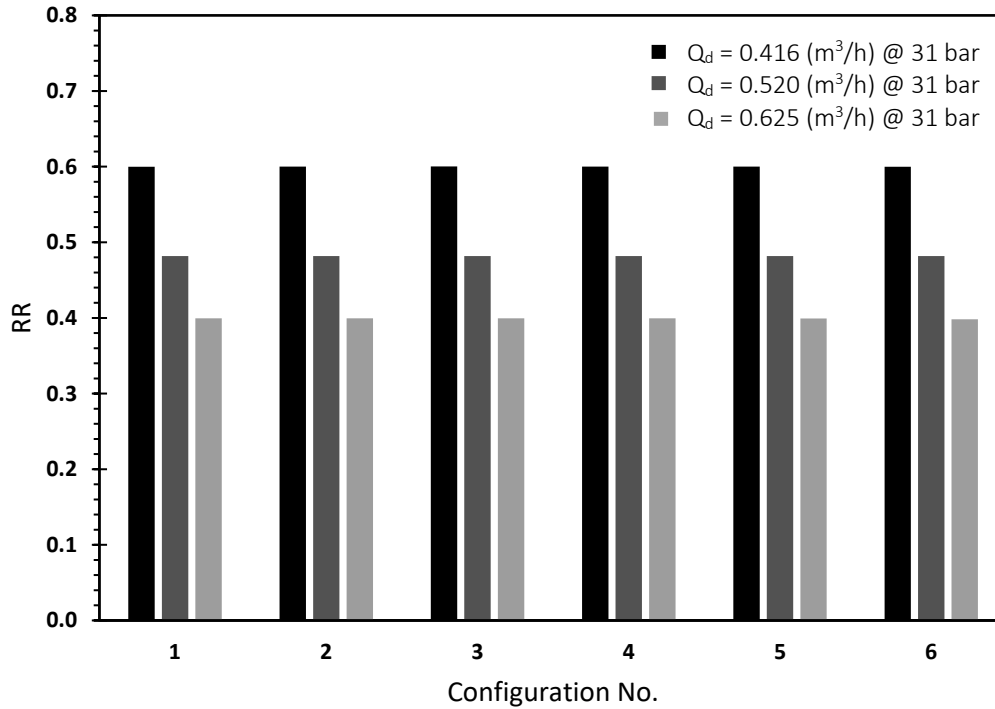


Figure 4.48: Recovery rate comparison for six configurations at $Q_d = 0.416, 0.520$ and $0.625 \text{ m}^3/\text{h}$, $P = 31 \text{ bar}$.

4.3.3 Effect of FO-RO configurations on specific energy consumption.

SEC of all six configurations was assessed under two scenarios: without utilizing an ERD and with ERD. At a draw flow rate of $0.416 \text{ m}^3/\text{h}$, when ERD is not considered, the first configuration consumes the most energy among other configurations due to its high level of feed solution entering the first FO unit. Figure 4.49 illustrates that SEC decreases as the number of considered outlets decreases, resulting in a decrease in FO feed flow rate. The last configuration stands out with the lowest SEC, attributed to its configuration involving only three outlets for water processing. This inherently low flow rate has significant implications for energy usage, particularly in pump operation.

Upon integrating ERD into the FO-RO system, a remarkable reduction in SEC is observed, averaging about 25.5%. This substantial decrease highlights the significant positive impact of ERD technology on the overall efficiency of the FO-RO system.

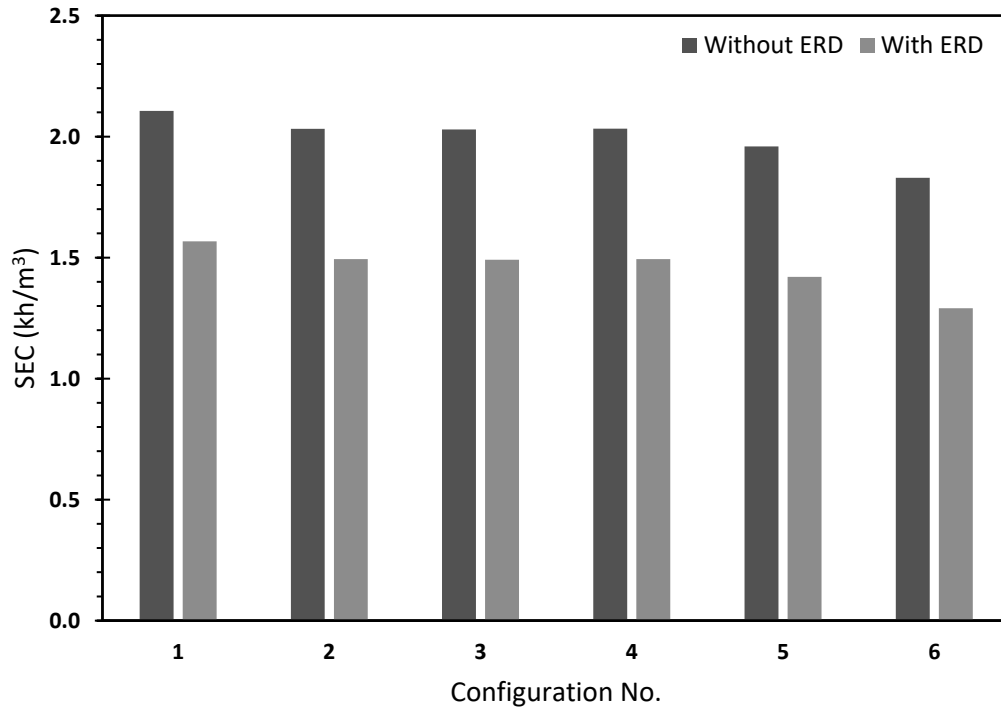


Figure 4.49: Specific energy consumption for six configurations with & without ERD at $Q_d = 0.416$ m³/h, $P = 31$ bar.

Increasing the draw flow rate to 0.520 m³/h results in a notable rise in SEC, as depicted in Figure 4.50. Furthermore, the SEC is directly proportional to the feed volume, and as the number of outlets involved in configurations decreases, the SEC decreases accordingly. Similarly, further elevating the draw flow rate from 0.520 to 0.625 m³/h, as shown in Figure 4.51, leads to notable increments in SEC. These increases in SEC are primarily attributed to the considerably larger volume of water being handled by the pump within the system.

The reason for this increase is that, as the draw flow rate rises, the pump must exert more effort to move a greater volume of water through the system. The workload of the pump is directly proportional to the flow rate it must handle. Therefore, dealing with substantially higher flow rates results in increased energy consumption, subsequently leading to higher SEC, as water productivity decreases.

Upon integrating ERD into the FO-RO system, a remarkable reduction in SEC is observed, averaging about 34% and 40.5% for draw flow rates of 0.520 and 0.625 m³/h, respectively. This substantial decrease underscores the significant positive impact of ERD technology on the overall efficiency of the FO-RO system.

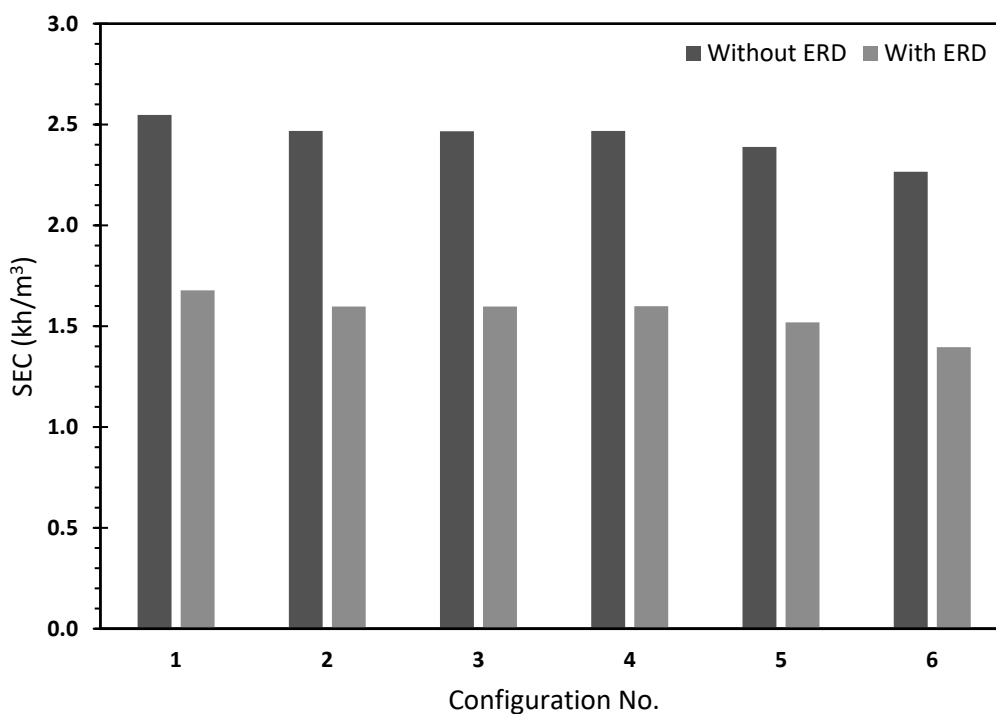


Figure 4.50: Specific energy consumption for six configurations with & without ERD at $Q_d = 0.520$ m³/h, $P = 31$ bar.

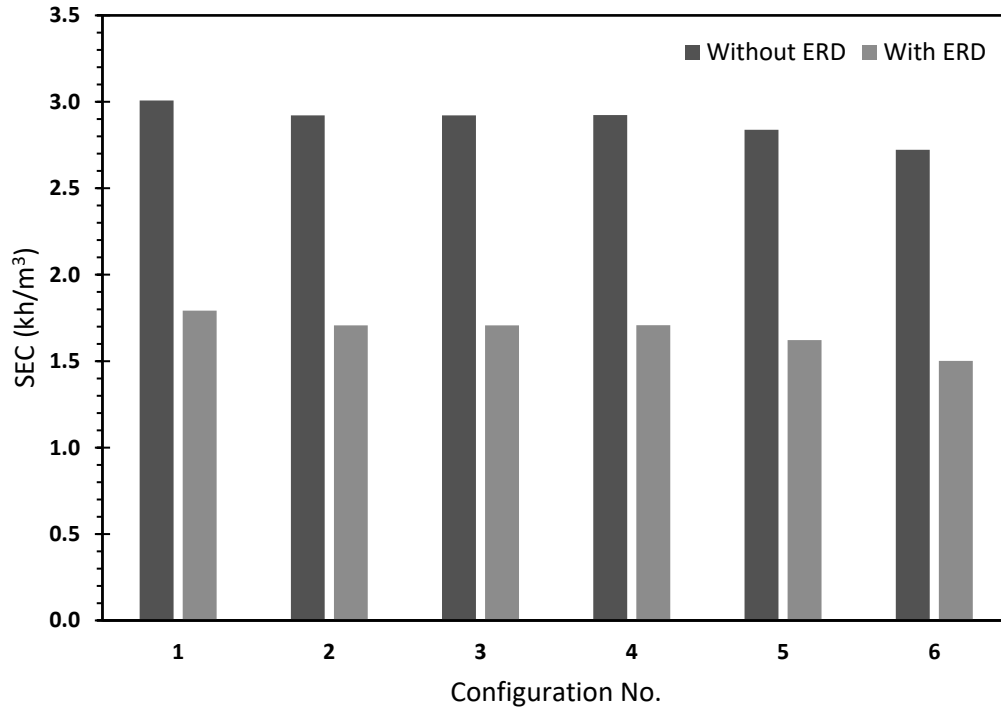


Figure 4.51: Specific energy consumption for six configurations with & without ERD at $Q_d = 0.625$ m³/h, $P = 31$ bar.

Figure 4.52 provides a comprehensive overview of the SEC for all configurations across three distinct draw flow rates: 0.416, 0.520, and 0.625 m³/h. The SEC shows an increase as the draw flow rate increases. This is primarily due to the higher flow rate that the system needs to handle at elevated draw flow rates.

Moreover, an intriguing observation is that the SEC with ERD along with increasing draw flow rates are nearly identical. This similarity suggests a balance between the draw flow rate and its concentration, coupled with the utilization of ERD.

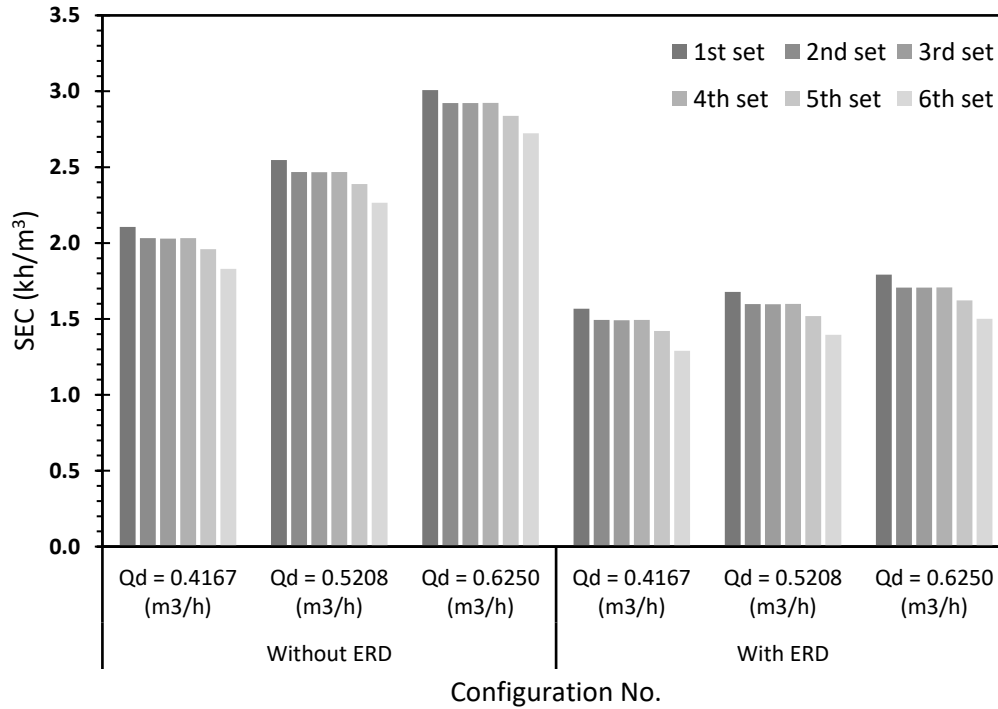


Figure 4.52: Specific energy consumption comparison for six configurations with & without ERD at $Q_d = 0.416, 0.520$ and $0.625 \text{ m}^3/\text{h}$, $P = 31 \text{ bar}$.

4.3.4 Economic feasibility assessment of FO-RO system.

The economic analysis of FO-RO systems is assessed for various draw flow rates, as illustrated in Figure 4.53. The SWC for all six configurations is presented, considering different draw flow rates and the presence or absence of ERD. The figure indicates that an increase in draw flow rate leads to a slightly higher cost, as more power is consumed by the pump, influencing SEC. It is noteworthy that the utilization of ERD or not doesn't exhibit significant differences for all draw flow rates.

As illustrated in Figure 4.54, the first configuration demonstrates the highest cost among the various configurations when the draw flow rate is $0.416 \text{ m}^3/\text{h}$. This cost difference is attributed to the substantial energy consumption associated with the use of a higher flow

rate, as discussed earlier. This trend persists for draw flow rates of 0.520 m³/h, as shown in Figure 4.55, and 0.625 m³/h, as evident in Figure 4.56.

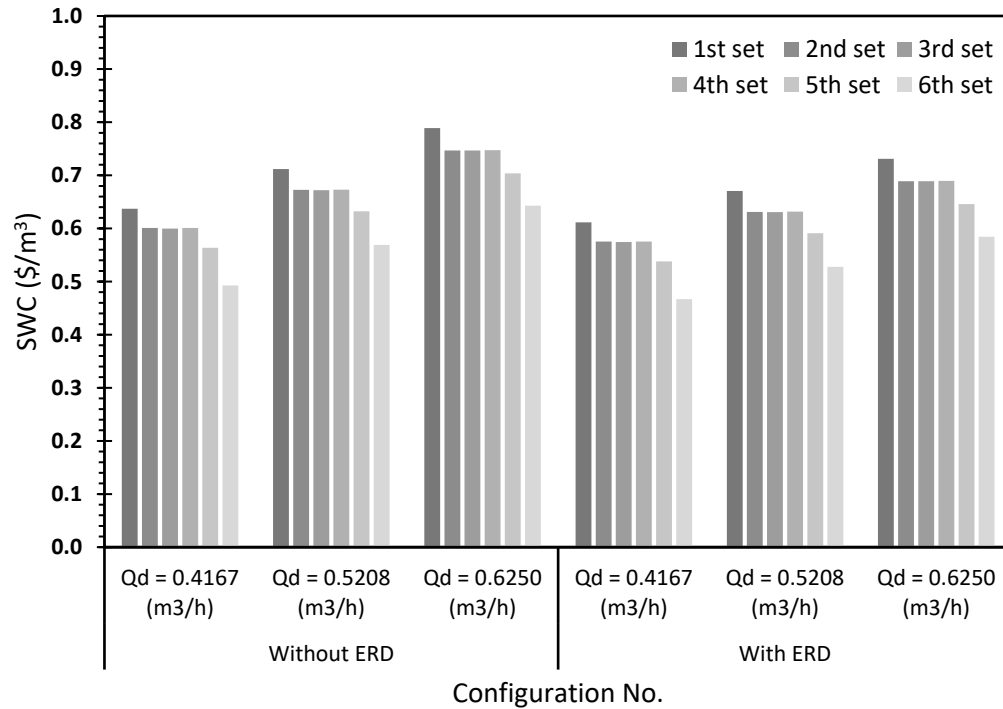


Figure 4.53: Specific water cost comparison for six configurations with & without ERD at $Q_d = 0.416, 0.520$ and $0.625 \text{ m}^3/\text{h}$, $P = 31 \text{ bar}$.

These findings underscore the significant impact of flow rate on the overall cost of the system. While a higher draw flow rate may be desirable in certain situations, it also results in higher energy consumption, directly influencing operational expenses. This information is crucial for decision-makers when evaluating the most cost-effective and energy-efficient configurations in desalination or similar processes. It emphasizes the importance of carefully balancing flow rates with energy consumption to achieve optimal economic and operational outcomes.

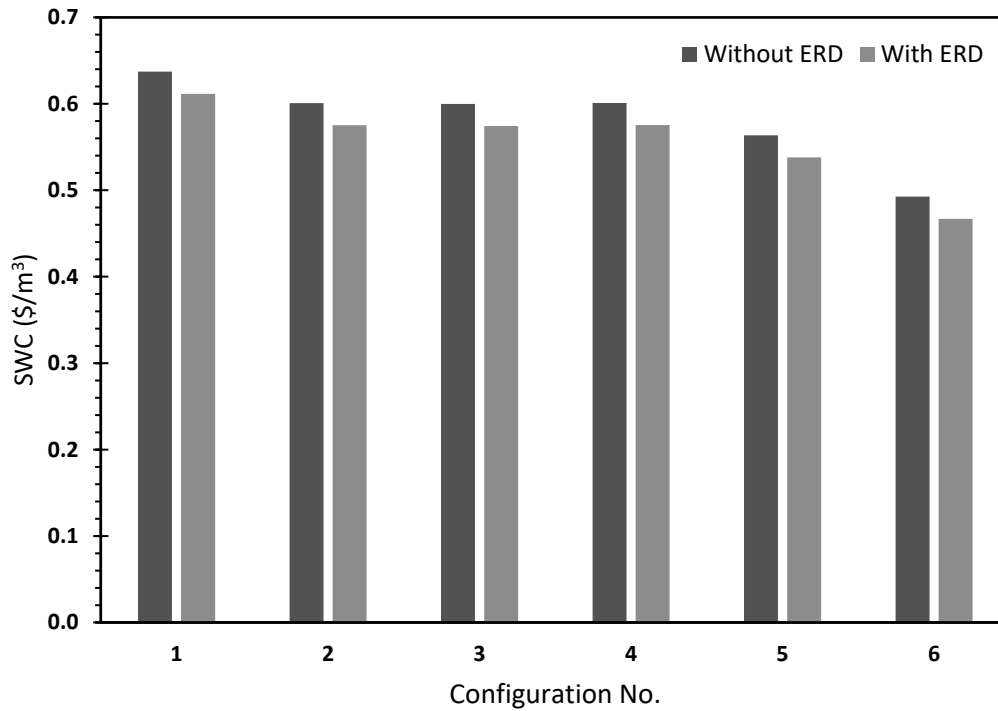


Figure 4.54: Specific water cost for six configurations considering energy consumption with & without ERD at $Q_d = 0.416 \text{ m}^3/\text{h}$, $P = 31 \text{ bar}$.

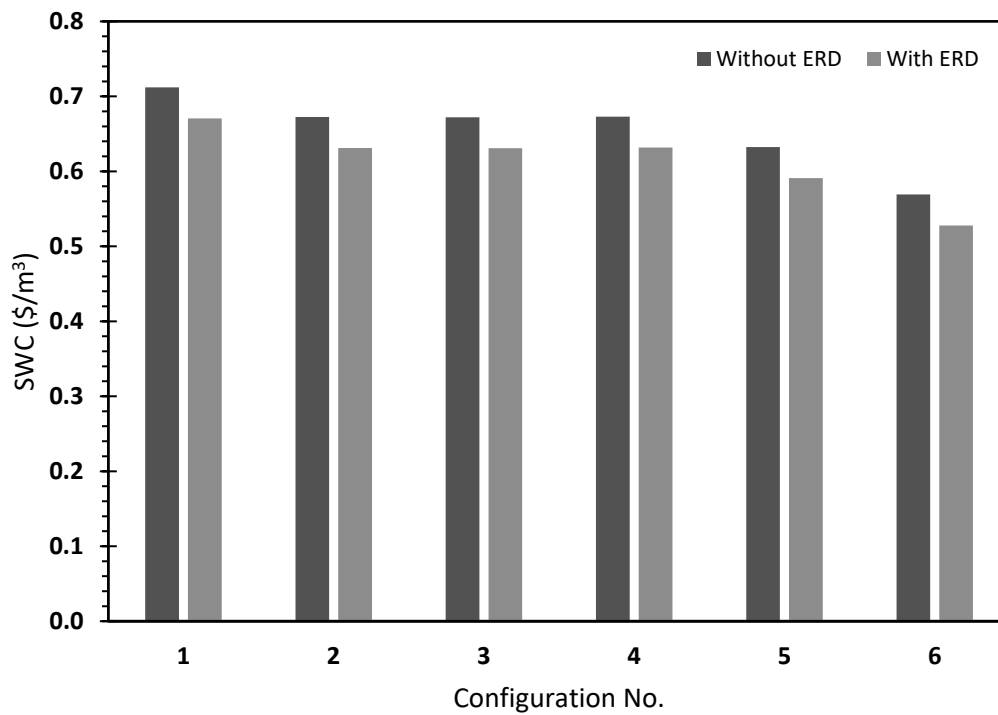


Figure 4.55: Specific water cost for six configurations considering energy consumption with & without ERD at $Q_d = 0.520 \text{ m}^3/\text{h}$, $P = 31 \text{ bar}$.

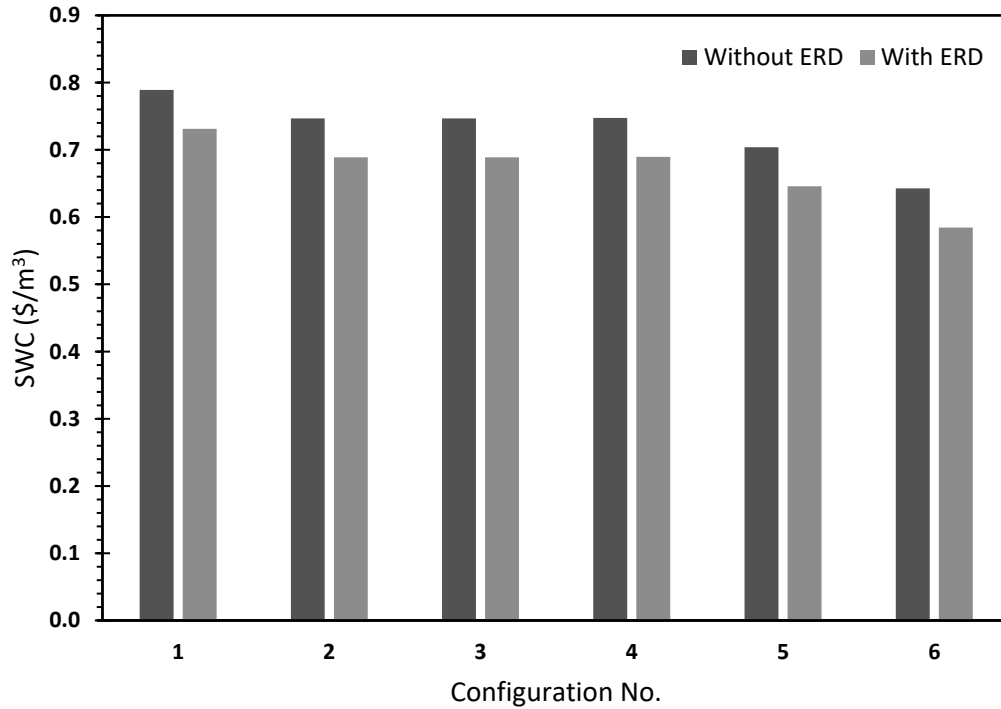


Figure 4.56: Specific water cost for six configurations considering energy consumption with & without ERD at $Q_d = 0.416 \text{ m}^3/\text{h}$, $P = 31 \text{ bar}$.

4.3.5 Hydraulic pressure effect on FO-RO system for different scenarios.

Previously, the hydraulic pressure remained constant at 31 bar, despite the variation in draw flow rates. This constant hydraulic pressure proved to be insufficient, leading to a reduction in water productivity as draw flow rate increased. Conversely, by adjusting and compensating for the hydraulic pressure, the system demonstrated an improved capacity to enhance water productivity, thereby overcoming the challenges posed by increased draw flow rates as seen in Figure 4.57.

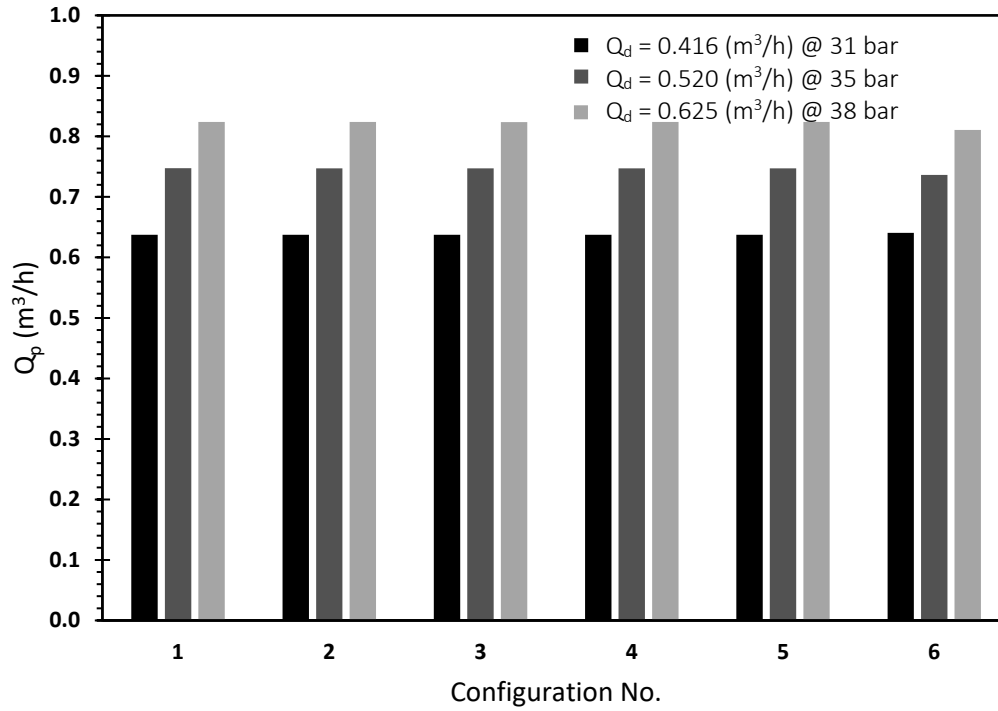


Figure 4.57: Pressure effect on water productivity of FO-RO system for six configurations at different draw flow rates: 31 bar for $Q_d = 0.416 \text{ m}^3/\text{h}$, 35 bar for $Q_d = 0.520 \text{ m}^3/\text{h}$, and 38 bar for $Q_d = 0.625 \text{ m}^3/\text{h}$.

In Figure 4.58, Figure 4.59 and Figure 4.60, water productivity is illustrated at draw flow rates of 0.416, 0.520, and 0.625 m^3/h , respectively. At 0.416 m^3/h , the last configuration demonstrated the highest water productivity among the six configurations, as discussed in section 4.3.1. Interestingly, as the draw flow rate increased to 0.520 and 0.625 m^3/h , the first five configurations achieved high water productivity, illustrated in section 4.3.1 as well.

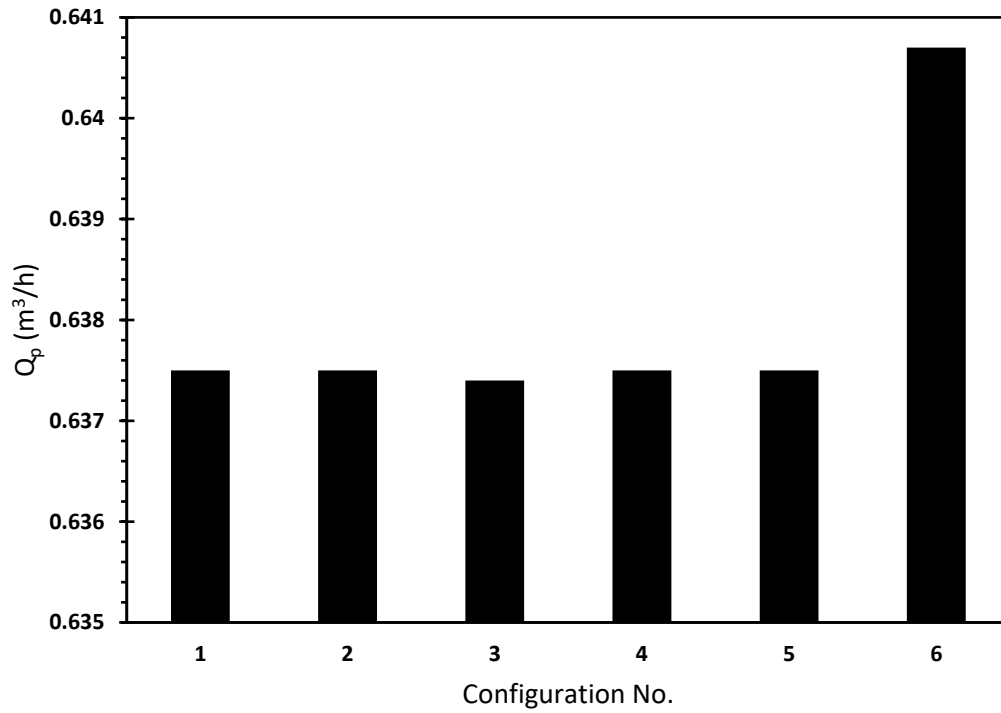


Figure 4.58: Water productivity FO-RO system for six configurations at draw flow rates of $Q_d = 0.416 \text{ m}^3/\text{h}$, $P = 31 \text{ bar}$.

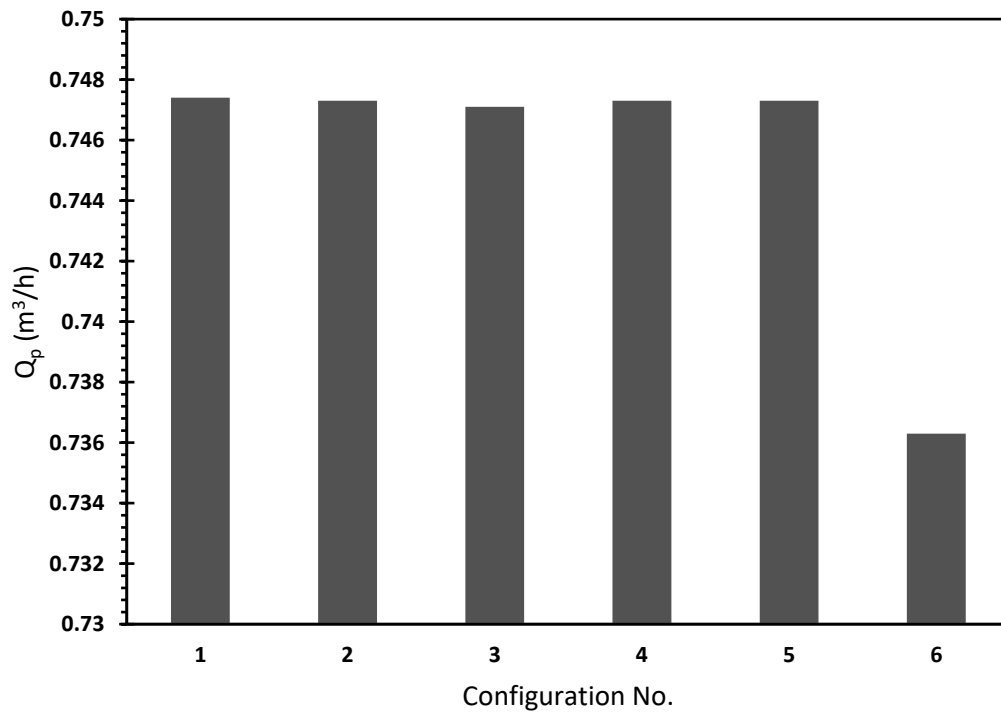


Figure 4.59: Water productivity FO-RO system for six configurations at draw flow rates of $Q_d = 0.520 \text{ m}^3/\text{h}$, $P = 35 \text{ bar}$.

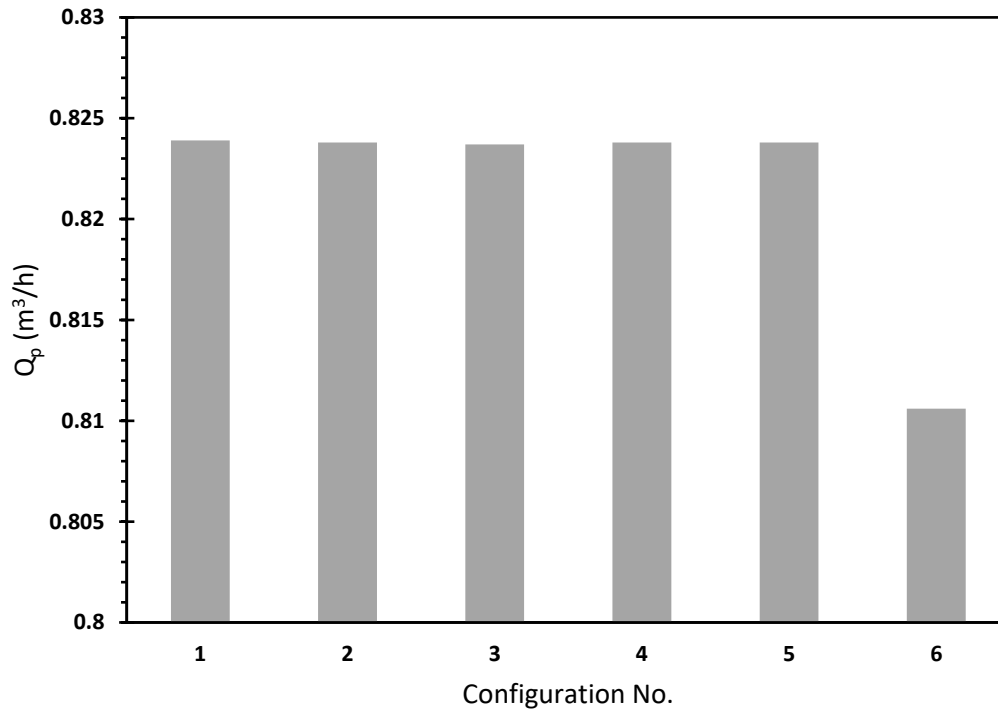


Figure 4.60: Water productivity FO-RO system for six configurations at draw flow rates of $Q_d = 0.625 \text{ m}^3/\text{h}$, $P = 38 \text{ bar}$.

The SEC for all six configurations is illustrated in Figure 4.61. It's noticeable that the draw flow rate doesn't exert a substantial influence on the SEC. Despite the elevated energy demands associated with high flow rates driven by pumps, the compensatory effect of high-water productivity mitigates the impact on SEC. Furthermore, the inclusion of ERD leads to significant variations, resulting in an approximate 25-28% reduction in SEC. This emphasizes the noteworthy impact of ERD in achieving substantial savings in SEC within the considered system configurations.

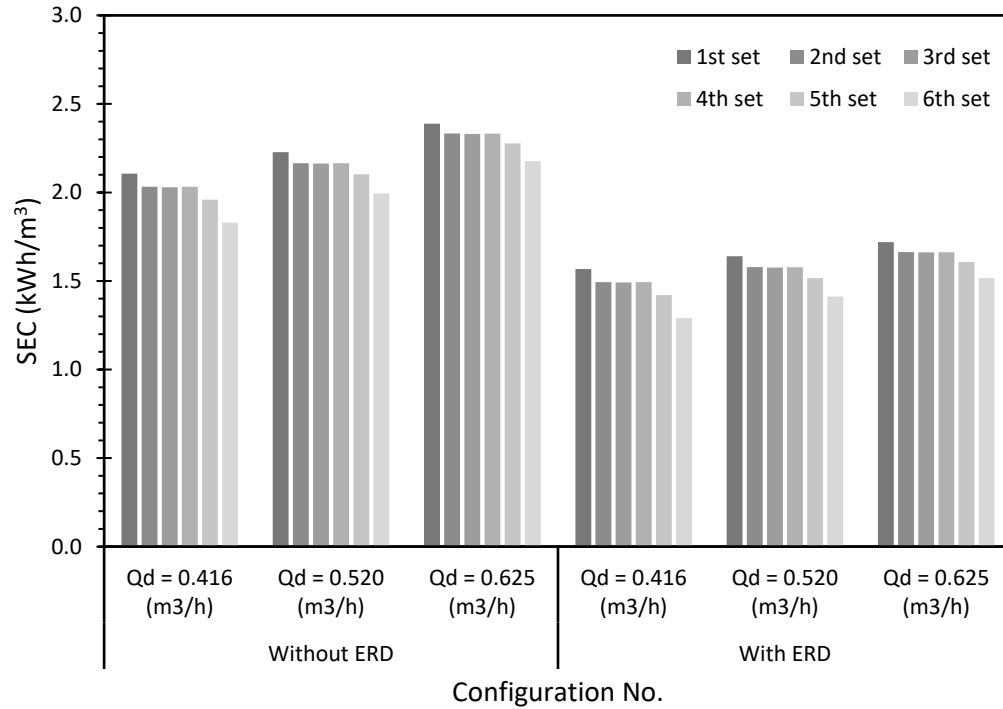


Figure 4.61: Pressure effect on SEC of FO-RO system with & without ERD for six configurations at different draw flow rates: 31 bar for $Q_d = 0.416 \text{ m}^3/\text{h}$, 35 bar for $Q_d = 0.520 \text{ m}^3/\text{h}$, and 38 bar for $Q_d = 0.625 \text{ m}^3/\text{h}$.

Figure 4.62 depicts the SWC for three distinct draw flow rates, considering SEC both with and without the incorporation of ERD. Clearly, as the flow rate increased, SWC showed a corresponding decrease. This relationship is attributed to the heightened water productivity associated with pressure compensation, which is inversely linked to SWC. Notably, the first configuration emerged as the costliest across all draw flow rates in both scenarios, regardless of whether ERD was considered or not.

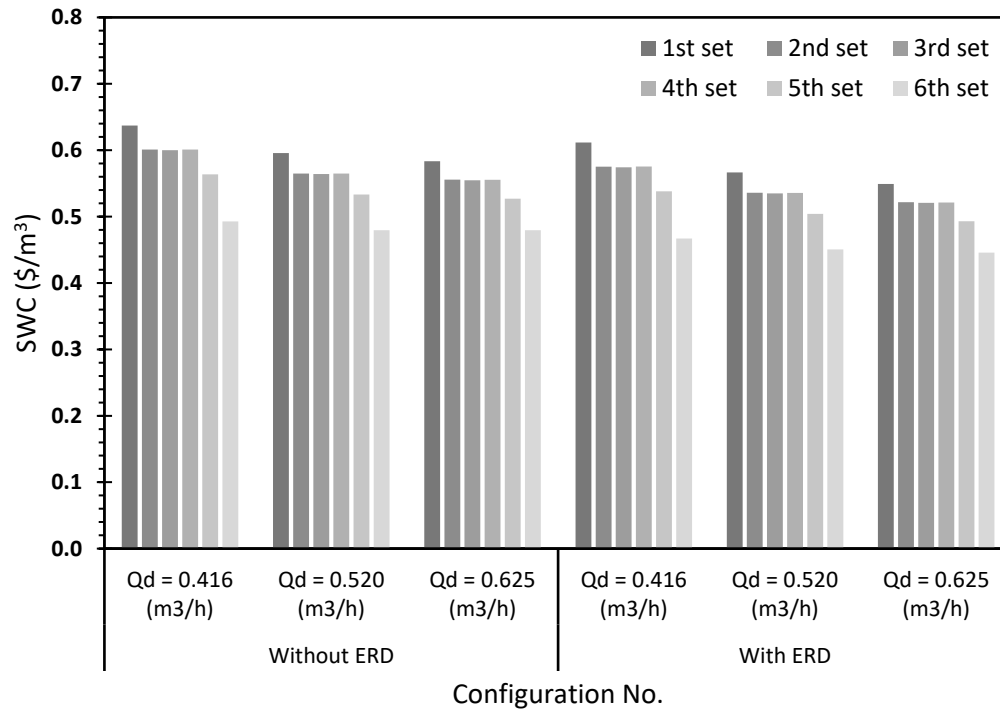


Figure 4.62: Pressure effect on SWC of FO-RO system with & without ERD for six configurations at different draw flow rates: 31 bar for $Q_d = 0.416 \text{ m}^3/\text{h}$, 35 bar for $Q_d = 0.520 \text{ m}^3/\text{h}$, and 38 bar for $Q_d = 0.625 \text{ m}^3/\text{h}$.

CHAPTER 5

CONCLUSION

In this study, the performance assessment of novel configuration of FO-RO system was conducted using a computational model, and membranes are utilized are similar to those developed by commercial membrane manufacturing companies.

The first configuration stated FO units connected in serial with RO for water purification. FO-RO system's configuration began with a single FO unit integrated with an RO unit, with subsequent scenarios increasing the number of units. The feed side of FO units utilized a brackish water and fed in equally in parallel, where draw side used an Arabian Gulf Sea. The system exhibited notable improvements at six FO units, demonstrating a high water productivity in contrast to one FO unit was considered. Furthermore, the SEC exhibited a decreasing trend as more FO units were integrated into the system. At six FO units, the SEC was recorded with difference of 26% less when ERD incorporated. Within the scope of this study, a comprehensive economic evaluation has been conducted, and the findings indicate that the system demonstrates economic feasibility falling within the range of 0.4 to 0.6 \$/m³. This signifies not only the financial viability but also the cost-effectiveness of the system in providing water treatment solutions.

An alternative arrangement is suggested where the effluents from FO units are looped back as inputs to the initial FO units. The recirculation process limited the utilization of a backup as a feed solution to the FO process. The system attained a reasonable water productivity,

specific energy consumption and cost effectiveness. Nevertheless, the former system that integrated six FO units connected in serial exhibited superior performance compared to the latter configuration.

The second configuration, RO unit located prior to last FO unit, is designed to be environmentally conscious by implementing a recirculation approach for the discharged effluents. This environmentally friendly feature minimizes the impact on the environment by constraining the release of high salinity effluents and, consequently, reduces potential hazards. This environmentally friendly aspect enhances the overall eco-efficiency of the configuration, contributing to a more sustainable water purification process.

REFERENCES

- [1] “Water Scarcity and Humanitarian Action: Key Emerging Trends and Challenges | OCHA.” <https://www.unocha.org/es/publication/policy-briefs-studies/water-scarcity-and-humanitarian-action-key-emerging-trends-and> (accessed Jan. 02, 2022).
- [2] R. Saeed, A. H. Konsowa, M. S. Shalaby, M. S. Mansour, and M. G. Eloffy, “Optimization of Integrated Forward – Reverse Osmosis Desalination Processes for Brackish Water,” *Alexandria Eng. J.*, vol. 63, pp. 89–102, Feb. 2023, doi: 10.1016/J.AEJ.2022.07.054.
- [3] J. Seo, Y. M. Kim, S. H. Chae, S. J. Lim, H. Park, and J. H. Kim, “An optimization strategy for a forward osmosis-reverse osmosis hybrid process for wastewater reuse and seawater desalination: A modeling study,” *Desalination*, vol. 463, pp. 40–49, Aug. 2019, doi: 10.1016/J.DESAL.2019.03.012.
- [4] S. Manju and N. Sagar, “Renewable energy integrated desalination: A sustainable solution to overcome future fresh-water scarcity in India,” *Renew. Sustain. Energy Rev.*, vol. 73, pp. 594–609, Jun. 2017, doi: 10.1016/J.RSER.2017.01.164.
- [5] “Water, sanitation and hygiene links to health: facts and figures.” <https://apps.who.int/iris/handle/10665/69489> (accessed May 05, 2023).
- [6] “Ras Al Khair Desalination Plant, Saudi Arabia.” <https://www.water->

- technology.net/projects/ras-al-khair-desalination-plant/ (accessed Jan. 31, 2023).
- [7] E. J. Okampo and N. Nwulu, “Optimisation of renewable energy powered reverse osmosis desalination systems: A state-of-the-art review,” *Renew. Sustain. Energy Rev.*, vol. 140, p. 110712, Apr. 2021, doi: 10.1016/J.RSER.2021.110712.
 - [8] A. Al-Karaghoul and L. L. Kazmerski, “Energy consumption and water production cost of conventional and renewable-energy-powered desalination processes,” *Renew. Sustain. Energy Rev.*, vol. 24, pp. 343–356, Aug. 2013, doi: 10.1016/J.RSER.2012.12.064.
 - [9] J. Miller, “Review of water resources and desalination technologies,” 2003, Accessed: Oct. 24, 2023. [Online]. Available: <https://www.osti.gov/biblio/809106>.
 - [10] L. F. Greenlee, D. F. Lawler, B. D. Freeman, B. Marrot, and P. Moulin, “Reverse osmosis desalination: Water sources, technology, and today’s challenges,” *Water Res.*, vol. 43, no. 9, pp. 2317–2348, May 2009, doi: 10.1016/J.WATRES.2009.03.010.
 - [11] K. Tarnacki, M. Meneses, T. Melin, J. van Medevoort, and A. Jansen, “Environmental assessment of desalination processes: Reverse osmosis and Memstill®,” *Desalination*, vol. 296, pp. 69–80, Jun. 2012, doi: 10.1016/J.DESAL.2012.04.009.
 - [12] X. Xiang, S. Zou, and Z. He, “Energy consumption of water recovery from wastewater in a submerged forward osmosis system using commercial liquid

- fertilizer as a draw solute,” *Sep. Purif. Technol.*, vol. 174, pp. 432–438, 2017, doi: 10.1016/j.seppur.2016.10.052.
- [13] W. L. Ang, A. Wahab Mohammad, D. Johnson, and N. Hilal, “Forward osmosis research trends in desalination and wastewater treatment: A review of research trends over the past decade,” *J. Water Process Eng.*, vol. 31, p. 100886, Oct. 2019, doi: 10.1016/J.JWPE.2019.100886.
- [14] D. L. Shaffer, J. R. Werber, H. Jaramillo, S. Lin, and M. Elimelech, “Forward osmosis: Where are we now?,” *Desalination*, vol. 356, pp. 271–284, Jan. 2015, doi: 10.1016/J.DESAL.2014.10.031.
- [15] M. Qasim, M. Badrelzaman, N. N. N. A. N. A. N. N. Darwish, N. N. N. A. N. A. N. N. Darwish, and N. Hilal, “Reverse osmosis desalination: A state-of-the-art review,” *Desalination*, vol. 459, pp. 59–104, Jun. 2019, doi: 10.1016/j.desal.2019.02.008.
- [16] M. Mohammadifakhr, J. de Grooth, H. D. W. Roesink, and A. J. B. Kemperman, “Forward Osmosis: A Critical Review,” *Process. 2020, Vol. 8, Page 404*, vol. 8, no. 4, p. 404, Mar. 2020, doi: 10.3390/PR8040404.
- [17] D. Dsilva Winfred Rufuss, V. Kapoor, S. Arulvel, and P. A. Davies, “Advances in forward osmosis (FO) technology for enhanced efficiency and output: A critical review,” *J. Clean. Prod.*, vol. 356, no. May 2021, p. 131769, Jul. 2022, doi: 10.1016/j.jclepro.2022.131769.
- [18] D. L. Shaffer, N. Y. Yip, J. Gilron, and M. Elimelech, “Seawater desalination for

- agriculture by integrated forward and reverse osmosis: Improved product water quality for potentially less energy,” *J. Memb. Sci.*, vol. 415–416, pp. 1–8, Oct. 2012, doi: 10.1016/J.MEMSCI.2012.05.016.
- [19] G. Q. Chen, S. L. Gras, and S. E. Kentish, “The application of forward osmosis to dairy processing,” *Sep. Purif. Technol.*, vol. 246, no. March, p. 116900, Sep. 2020, doi: 10.1016/j.seppur.2020.116900.
- [20] J. Jeon, J. Jung, S. Lee, J. Y. Choi, and S. Kim, “A simple modeling approach for a forward osmosis system with a spiral wound module,” *Desalination*, vol. 433, no. January, pp. 120–131, 2018, doi: 10.1016/j.desal.2018.01.004.
- [21] J. Su, S. Zhang, M. M. Ling, and T. S. Chung, “Forward osmosis: An emerging technology for sustainable supply of clean water,” *Clean Technol. Environ. Policy*, vol. 14, no. 4, pp. 507–511, May 2012, doi: 10.1007/S10098-012-0486-1/FIGURES/1.
- [22] Z. M. Binger and A. Achilli, “Forward osmosis and pressure retarded osmosis process modeling for integration with seawater reverse osmosis desalination,” *Desalination*, vol. 491, p. 114583, Oct. 2020, doi: 10.1016/j.desal.2020.114583.
- [23] A. Altaee, G. Zaragoza, and H. R. van Tonningen, “Comparison between Forward Osmosis-Reverse Osmosis and Reverse Osmosis processes for seawater desalination,” *Desalination*, vol. 336, no. 1, pp. 50–57, Mar. 2014, doi: 10.1016/J.DESAL.2014.01.002.

- [24] M. A. Abdelkareem, M. El Haj Assad, E. T. Sayed, and B. Soudan, "Recent progress in the use of renewable energy sources to power water desalination plants," *Desalination*, vol. 435, pp. 97–113, Jun. 2018, doi: 10.1016/J.DESAL.2017.11.018.
- [25] M. T. Vu, W. E. Price, T. He, X. Zhang, and L. D. Nghiem, "Seawater-driven forward osmosis for pre-concentrating nutrients in digested sludge centrate," *J. Environ. Manage.*, vol. 247, pp. 135–139, Oct. 2019, doi: 10.1016/J.JENVMAN.2019.06.082.
- [26] W. Suwaileh, D. Johnson, D. Jones, and N. Hilal, "An integrated fertilizer driven forward osmosis- renewables powered membrane distillation system for brackish water desalination: A combined experimental and theoretical approach," *Desalination*, vol. 471, p. 114126, Dec. 2019, doi: 10.1016/J.DESAL.2019.114126.
- [27] P. K. Park, S. Lee, J. S. Cho, and J. H. Kim, "Full-scale simulation of seawater reverse osmosis desalination processes for boron removal: Effect of membrane fouling," *Water Res.*, vol. 46, no. 12, pp. 3796–3804, Aug. 2012, doi: 10.1016/J.WATRES.2012.04.021.
- [28] M. Sarai Atab, A. J. Smallbone, and A. P. Roskilly, "An operational and economic study of a reverse osmosis desalination system for potable water and land irrigation," *Desalination*, vol. 397, pp. 174–184, Nov. 2016, doi: 10.1016/j.desal.2016.06.020.
- [29] P. S. Goh, W. J. Lau, M. H. D. Othman, and A. F. Ismail, "Membrane fouling in desalination and its mitigation strategies," *Desalination*, vol. 425, pp. 130–155, Jan. 2018, doi: 10.1016/J.DESAL.2017.10.018.

- [30] W. L. Ang, A. W. Mohammad, D. Johnson, and N. Hilal, “Unlocking the application potential of forward osmosis through integrated/hybrid process,” *Sci. Total Environ.*, vol. 706, p. 136047, Mar. 2020, doi: 10.1016/J.SCITOTENV.2019.136047.
- [31] N. M. Mazlan, D. Peshev, and A. G. Livingston, “Energy consumption for desalination - A comparison of forward osmosis with reverse osmosis, and the potential for perfect membranes,” *Desalination*, vol. 377, pp. 138–151, 2016, doi: 10.1016/j.desal.2015.08.011.
- [32] M. Xie, L. D. Nghiem, W. E. Price, and M. Elimelech, “A forward osmosis-membrane distillation hybrid process for direct sewer mining: System performance and limitations,” *Environ. Sci. Technol.*, vol. 47, no. 23, pp. 13486–13493, Dec. 2013, doi: 10.1021/ES404056E/SUPPL_FILE/ES404056E_SI_001.PDF.
- [33] R. Valladares Linares, Z. Li, S. Sarp, S. S. Bucs, G. Amy, and J. S. Vrouwenvelder, “Forward osmosis niches in seawater desalination and wastewater reuse,” *Water Res.*, vol. 66, pp. 122–139, Dec. 2014, doi: 10.1016/J.WATRES.2014.08.021.
- [34] P. Pazouki, R. A. Stewart, E. Bertone, F. Helfer, and N. Ghaffour, “Life cycle cost of dilution desalination in off-grid locations: A study of water reuse integrated with seawater desalination technology,” *Desalination*, vol. 491, p. 114584, Oct. 2020, doi: 10.1016/J.DESAL.2020.114584.
- [35] O. A. Bamaga, A. Yokochi, B. Zabara, and A. S. Babaqi, “Hybrid FO/RO desalination system: Preliminary assessment of osmotic energy recovery and

- designs of new FO membrane module configurations,” *Desalination*, vol. 268, no. 1–3, pp. 163–169, Mar. 2011, doi: 10.1016/J.DESAL.2010.10.013.
- [36] A. Altaee, G. J. Millar, G. Zaragoza, and A. Sharif, “Energy efficiency of RO and FO–RO system for high-salinity seawater treatment,” *Clean Technol. Environ. Policy*, vol. 19, no. 1, pp. 77–91, Jan. 2017, doi: 10.1007/S10098-016-1190-3/FIGURES/8.
- [37] K. Park, H. Heo, D. Y. Kim, and D. R. Yang, “Feasibility study of a forward osmosis/crystallization/reverse osmosis hybrid process with high-temperature operation: Modeling, experiments, and energy consumption,” *J. Memb. Sci.*, vol. 555, pp. 206–219, Jun. 2018, doi: 10.1016/J.MEMSCI.2018.03.031.
- [38] V. Yangali-Quintanilla, Z. Li, R. Valladares, Q. Li, and G. Amy, “Indirect desalination of Red Sea water with forward osmosis and low pressure reverse osmosis for water reuse,” *Desalination*, vol. 280, no. 1–3, pp. 160–166, Oct. 2011, doi: 10.1016/j.desal.2011.06.066.
- [39] B. G. Choi, M. Zhan, K. Shin, S. Lee, and S. Hong, “Pilot-scale evaluation of FO–RO osmotic dilution process for treating wastewater from coal-fired power plant integrated with seawater desalination,” *J. Memb. Sci.*, vol. 540, pp. 78–87, Oct. 2017, doi: 10.1016/j.memsci.2017.06.036.
- [40] S. Kook, C. Lee, T. T. Nguyen, J. Lee, H. K. Shon, and I. S. Kim, “Serially connected forward osmosis membrane elements of pressure-assisted forward osmosis-reverse osmosis hybrid system: Process performance and economic

- analysis,” *Desalination*, vol. 448, pp. 1–12, Dec. 2018, doi: 10.1016/J.DESAL.2018.09.019.
- [41] Y. Choi, H. Cho, Y. Shin, Y. Jang, S. L.- Membranes, and undefined 2016, “Economic evaluation of a hybrid desalination system combining forward and reverse osmosis,” *mdpi.com*, Accessed: Dec. 30, 2021. [Online]. Available: <https://www.mdpi.com/122852>.
- [42] R. Valladares Linares *et al.*, “Life cycle cost of a hybrid forward osmosis – low pressure reverse osmosis system for seawater desalination and wastewater recovery,” *Water Res.*, vol. 88, pp. 225–234, Jan. 2016, doi: 10.1016/J.WATRES.2015.10.017.
- [43] D. Zhao, P. Wang, Q. Zhao, N. Chen, and X. Lu, “Thermoresponsive copolymer-based draw solution for seawater desalination in a combined process of forward osmosis and membrane distillation,” *Desalination*, vol. 348, pp. 26–32, Sep. 2014, doi: 10.1016/J.DESAL.2014.06.009.
- [44] H. Wang *et al.*, “Comprehensive analysis of a hybrid FO-NF-RO process for seawater desalination: With an NF-like FO membrane,” *Desalination*, vol. 515, p. 115203, Nov. 2021, doi: 10.1016/J.DESAL.2021.115203.
- [45] S. H. Park, B. Park, H. K. Shon, and S. Kim, “Modeling full-scale osmotic membrane bioreactor systems with high sludge retention and low salt concentration factor for wastewater reclamation,” *Bioresour. Technol.*, vol. 190, pp. 508–515, Aug. 2015, doi: 10.1016/J.BIORTECH.2015.03.094.

- [46] S. Kim, “Scale-up of osmotic membrane bioreactors by modeling salt accumulation and draw solution dilution using hollow-fiber membrane characteristics and operation conditions,” *Bioresour. Technol.*, vol. 165, pp. 88–95, Aug. 2014, doi: 10.1016/J.BIORTECH.2014.03.101.
- [47] S. Loeb, L. Titelman, E. Korngold, and J. Freiman, “Effect of porous support fabric on osmosis through a Loeb-Sourirajan type asymmetric membrane,” *J. Memb. Sci.*, vol. 129, no. 2, pp. 243–249, Jul. 1997, doi: 10.1016/S0376-7388(96)00354-7.
- [48] M. A. Al-Obaidi, A. A. Alsarayreh, A. M. Al-Hroub, S. Alsadaie, and I. M. Mujtaba, “Performance analysis of a medium-sized industrial reverse osmosis brackish water desalination plant,” *Desalination*, vol. 443, pp. 272–284, Oct. 2018, doi: 10.1016/J.DESAL.2018.06.010.
- [49] Y. Y. Lu, Y. D. Hu, X. L. Zhang, L. Y. Wu, and Q. Z. Liu, “Optimum design of reverse osmosis system under different feed concentration and product specification,” *J. Memb. Sci.*, vol. 287, no. 2, pp. 219–229, Jan. 2007, doi: 10.1016/J.MEMSCI.2006.10.037.
- [50] S. U. U. Sayyad, N. K. K. Kamthe, and S. M. M. Sarvade, “Design and simulation of reverse osmosis process in a hybrid forward osmosis-reverse osmosis system,” *Chem. Eng. Res. Des.*, vol. 183, pp. 210–220, May 2022, doi: 10.1016/J.CHERD.2022.05.002.
- [51] K. M. Sassi and I. M. Mujtaba, “MINLP based superstructure optimization for boron removal during desalination by reverse osmosis,” *J. Memb. Sci.*, vol. 440, pp. 29–

- 39, Aug. 2013, doi: 10.1016/J.MEMSCI.2013.03.012.
- [52] J. Kim and S. Hong, “A novel single-pass reverse osmosis configuration for high-purity water production and low energy consumption in seawater desalination,” *Desalination*, vol. 429, pp. 142–154, Mar. 2018, doi: 10.1016/J.DESAL.2017.12.026.
- [53] S. H. Aladwani, M. A. Al-Obaidi, and I. M. Mujtaba, “Performance of reverse osmosis based desalination process using spiral wound membrane: Sensitivity study of operating parameters under variable seawater conditions,” *Clean. Eng. Technol.*, vol. 5, p. 100284, Dec. 2021, doi: 10.1016/J.CLET.2021.100284.
- [54] A. Altaee, “Computational model for estimating reverse osmosis system design and performance: Part-one binary feed solution,” *Desalination*, vol. 291, pp. 101–105, Apr. 2012, doi: 10.1016/J.DESAL.2012.01.028.
- [55] M. I. Soomro and W. S. Kim, “Performance and economic investigations of solar power tower plant integrated with direct contact membrane distillation system,” *Energy Convers. Manag.*, vol. 174, pp. 626–638, Oct. 2018, doi: 10.1016/J.ENCONMAN.2018.08.056.
- [56] A. Luo and N. Lior, “Critical review of membrane distillation performance criteria,” *Desalin. Water Treat.*, vol. 57, no. 43, pp. 20093–20140, Sep. 2016, doi: 10.1080/19443994.2016.1152637.
- [57] C. P. Koutsou, E. Kritikos, A. J. Karabelas, and M. Kostoglou, “Analysis of

- temperature effects on the specific energy consumption in reverse osmosis desalination processes,” *Desalination*, vol. 476, p. 114213, Feb. 2020, doi: 10.1016/J.DESAL.2019.114213.
- [58] K. G. Nayar *et al.*, “Feasibility study of an electrodialysis system for in-home water desalination in urban India,” *Dev. Eng.*, vol. 2, pp. 38–46, Jan. 2017, doi: 10.1016/J.DEVENG.2016.12.001.
- [59] “Ion-Exchange Membrane Separation Processes - H Strathmann - Google Books.” https://books.google.com.sa/books?hl=en&lr=&id=pcNF7HWbFPIC&oi=fnd&pg=PP1&ots=SNS0V1ZxYx&sig=UwUdfrqY2d2KefF8jAQqjBXIYYA&redir_esc=y#v=onepage&q&f=false (accessed Dec. 08, 2023).
- [60] H. T. El-Dessouky and H. M. Ettouney, *Appendix B - Thermodynamic Losses*. 2002.
- [61] “Consumption Tariffs.” <https://www.se.com.sa/en/OurServices/ColumnC/Bills-and-Consumption/ConsumptionTariffs> (accessed Dec. 06, 2023).
- [62] A. Zarebska-Mølgaard *et al.*, “Techno-economic assessment of a hybrid forward osmosis and membrane distillation system for agricultural water recovery,” *Sep. Purif. Technol.*, vol. 283, p. 120196, Jan. 2022, doi: 10.1016/J.SEPPUR.2021.120196.
- [63] E. Cardona, A. Piacentino, and F. Marchese, “Energy saving in two-stage reverse osmosis systems coupled with ultrafiltration processes,” *Desalination*, vol. 184, no. 1–3, pp. 125–137, Nov. 2005, doi: 10.1016/J.DESAL.2005.03.063.

- [64] K. Park, D. Y. Kim, Y. H. Jang, M. gyu Kim, D. R. Yang, and S. Hong, “1eco-Comprehensive analysis of a hybrid FO/crystallization/RO process for improving its economic feasibility to seawater desalination,” *Water Res.*, vol. 171, p. 115426, Mar. 2020, doi: 10.1016/j.watres.2019.115426.
- [65] D. Patel, A. Mudgal, V. Patel, and J. Patel, “Techno-economic analysis of forward osmosis system for domestic wastewater treatment,” *Mater. Today Proc.*, vol. 77, pp. 69–74, Jan. 2023, doi: 10.1016/J.MATPR.2022.08.560.
- [66] C. F. Wan and T. S. Chung, “Techno-economic evaluation of various RO+PRO and RO+FO integrated processes,” *Appl. Energy*, vol. 212, pp. 1038–1050, Feb. 2018, doi: 10.1016/J.APENERGY.2017.12.124.
- [67] K. Park, D. Y. Kim, and D. R. Yang, “Cost-based feasibility study and sensitivity analysis of a new draw solution assisted reverse osmosis (DSARO) process for seawater desalination,” *Desalination*, vol. 422, pp. 182–193, Nov. 2017, doi: 10.1016/J.DESAL.2017.08.026.
- [68] M. M. Generous, N. A. A. Qasem, U. A. Akbar, and S. M. Zubair, “Techno-economic assessment of electrodialysis and reverse osmosis desalination plants,” *Sep. Purif. Technol.*, vol. 272, p. 118875, Oct. 2021, doi: 10.1016/J.SEPPUR.2021.118875.
- [69] V. Romero-Ternero, L. García-Rodríguez, and C. Gómez-Camacho, “Thermoeconomic analysis of a seawater reverse osmosis plant,” *Desalination*, vol. 181, no. 1–3, pp. 43–59, Sep. 2005, doi: 10.1016/J.DESAL.2005.02.012.

- [70] “EES: Engineering Equation Solver | F-Chart Software : Engineering Software.” <https://fchartsoftware.com/ees/> (accessed May 21, 2023).
- [71] F. E. Ahmed, A. Khalil, and N. Hilal, “Emerging desalination technologies: Current status, challenges and future trends,” *Desalination*, vol. 517, p. 115183, Dec. 2021, doi: 10.1016/J.DESAL.2021.115183.
- [72] N. Y. Yip, A. Tiraferri, W. A. Phillip, J. D. Schiffman, and M. Elimelech, “High performance thin-film composite forward osmosis membrane,” *Environ. Sci. Technol.*, vol. 44, no. 10, pp. 3812–3818, May 2010, doi: 10.1021/ES1002555/SUPPL_FILE/ES1002555_SI_001.PDF.
- [73] S. J. Im, G. W. Go, S. H. Lee, G. H. Park, and A. Jang, “Performance evaluation of two-stage spiral wound forward osmosis elements at various operation conditions,” *New pub Balaban*, vol. 57, no. 51, pp. 24583–24594, Nov. 2016, doi: 10.1080/19443994.2016.1157989.
- [74] S. J. Im, S. Jeong, and A. Jang, “Feasibility evaluation of element scale forward osmosis for direct connection with reverse osmosis,” *J. Memb. Sci.*, vol. 549, pp. 366–376, Mar. 2018, doi: 10.1016/J.MEMSCI.2017.12.027.
- [75] S. J. Im, S. S. Jeong, S. S. Jeong, and A. Jang, “Techno-economic evaluation of an element-scale forward osmosis-reverse osmosis hybrid process for seawater desalination,” *Desalination*, vol. 476, no. November 2019, p. 114240, Feb. 2020, doi: 10.1016/j.desal.2019.114240.

- [76] Z. Yang, Y. Zhou, Z. Feng, X. Rui, T. Zhang, and Z. Zhang, “A review on reverse osmosis and nanofiltration membranes for water purification,” *Polymers (Basel)*., vol. 11, no. 8, 2019, doi: 10.3390/polym11081252.
- [77] T. M. Mansour, T. M. Ismail, K. Ramzy, and M. Abd El-Salam, “Energy recovery system in small reverse osmosis desalination plant: Experimental and theoretical investigations,” *Alexandria Eng. J.*, vol. 59, no. 5, pp. 3741–3753, 2020, doi: 10.1016/j.aej.2020.06.030.

VITAE

Name : Mohammed Hasan Ahmed Al-Baiti

Nationality : Yemeni

Date of Birth : 09/15/1993

Email : m.albaiti111@gmail.com

Address : Mukalla-Hadhramaut-Yemen

Academic Background : B.Sc. of Mechanical Engineering
KFUPM, Dhahran, Saudi Arabia.

M.Sc. of Mechanical Engineering
KFUPM, Dhahran, Saudi Arabia.