ENVIRONMENTAL IMPACTS OF REVERSE OSMOSIS IN WASTEWATER TREATMENT VERSUS DESALINATION TO MEND THE WATER CYCLE: A LIFE CYCLE ASSESSMENT

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ABSTRACT

Sustainable water production is one of the top five challenges facing humanity within the upcoming decade; for arid regions, this challenge is aggravated. In this research, we evaluate the fastest growing technology in water treatment, reverse osmosis (RO), for both municipal wastewater treatment and seawater desalination to combat the challenges of water scarcity and climate change. We conduct a life cycle assessment (LCA) to evaluate the environmental impacts of municipal wastewater treatment and seawater desalination for a consistent functional unit using ISO 14040/44 standards. The modeling concept adopts a cradle-to-gate consequential paradigm. The life cycle inventory is based on field data collection from one of the largest wastewater RO plants worldwide, as well as reports, literature and ecoinvent database processes. The life cycle impact assessment is conducted on both the characterized and normalized levels using the ReCiPe method. The results are intended to assist policy-makers in better managing water resources. The study is applied to Kuwait but has wider repercussions.
Keywords: reverse osmosis, desalination, wastewater, life cycle assessment (LCA), Gulf Cooperation Council (GCC), Kuwait.

1 INTRODUCTION

The UN water report [1] has shown that the Gulf Cooperation Council (GCC) states are the top countries worldwide in terms of the water scarcity index (Fig. 1). The increasing population, changing lifestyles and warmer weather due to climate change have resulted in a sixfold growth in global water demand over the past century [1]. For Kuwait, although the country's commitment to the Sustainable Development Goal (SDG) No. 6 of clean water and sanitation is commendable, the price for this achievement has affected other SDGs. To name one, SDG No. 13 of climate action, as potable water is mainly produced through thermal desalination, an energy-intensive process. In the GCC, a staggering 30%–50% of oil production is consumed by the cogeneration of electricity and desalination. The COP21 in Glasgow, UK and the figures of The 2019 UN Environment Programme's Emissions Gap Report indicate that not enough action is taken worldwide to mitigate carbon emissions [2]. The report concludes that to abide by the Paris Agreement, emissions need to drop by 7.6% annually by 2030 for the 1.5°C target. For this seemingly "impossible" task, the European Union (EU) launched a new world-challenging mission to reach the objectives of the Paris Agreement to reduce global warming to preindustrial era levels, the "Mission possible". For the same urgent cause, the United Nations has also launched the "Decade of Change" mission to mobilize everyone everywhere to increase momentum and take immediate action and gather forces to deliver the 2030 promise [3]. It has long been agreed that energy efficiency at the end-use stage is the fastest and most cost-effective solution for reducing greenhouse emissions [4]. Countries worldwide have established targets to achieve sustainable water and energy systems, consistent with the SDGs [5].

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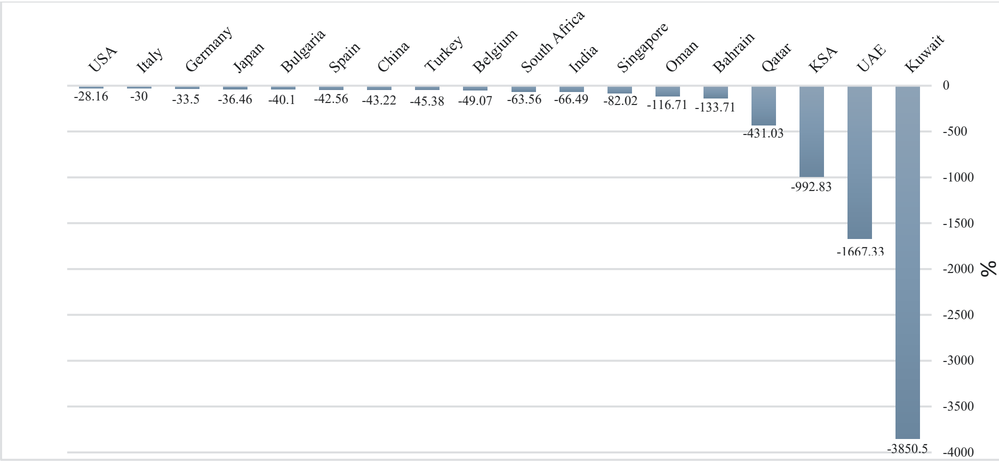

Figure 1: Water stress (%) for GCC countries: Bahrain, Kuwait, Oman, Qatar, the Kingdom of Saudi Arabia (KSA) and the United Arab Emirates (UAE) in comparison with selected countries [6].

Our area of focus is the most arid area worldwide, the GCC [7]. The GCC presents an intricate paradox of severe water scarcity coupled with staggered water consumption, which is a result of rentierism and socioeconomic situations. The GCC regions have long relied on costly thermal seawater desalination, followed by the high abstraction of nonrenewable groundwater resources, to satisfy their demand for water [8]–[10]. The availability of fossil fuels at low extraction costs has slowed the conversion to energy-efficient desalination in the GCC, such as multistage flash distillation (MSF) [10], [11]. Currently, desalination megaprojects in the GCC are transitioning to membrane-based desalination plants (DPs) [12]–[14]. For instance, the Yanbu seawater reverse osmosis (SWRO) DP in the Kingdom of Saudi Arabia (KSA) is one of the largest SWRO plants in the Middle East. The plant started its operation in 2020 with a total capacity of 450K m^3/day [15]. Similarly, the Taweelah SWRO DP is expected to start its operation in 2022 with a capacity of 450,000 m^3/day [15].

Kuwait has three SWRO DPs: the Shuwaikh SWRO DP and the Al-Zour South SWRO DP, which commenced in 2013 and 2014, respectively, and the Doha SWRO DP, which was recently inaugurated but was not included and has not yet reached its design capacity. The total installed capacity of each of the aforementioned operating SWRO DPs is 30 million imperial gallons per day (MIGPD) [11]. This number is expected to increase when the Doha SWRO DP reaches its full operation capacity. The Shuwaikh and Al-Zour South SWRO DPs combined contribute only 12% of the total freshwater production in the country (see Fig. 2), while the rest is produced using MSF and the newly inaugurated multieffect distillation (MED) DP [9].

Wastewater reuse is now considered indispensable for meeting the increasing water demand, particularly under conditions of alarming water scarcity, which are now already affecting every continent [16]. The GCC has already embarked on constructing mega wastewater treatment plants (WWTPs) and projects. The overall capacity of WWTPs in the GCC is approximately 2,800 Mm^3/yr (million cubic meters per year). The total number of WWTPs is 241; these stations primarily use secondary and tertiary methods [8]. One

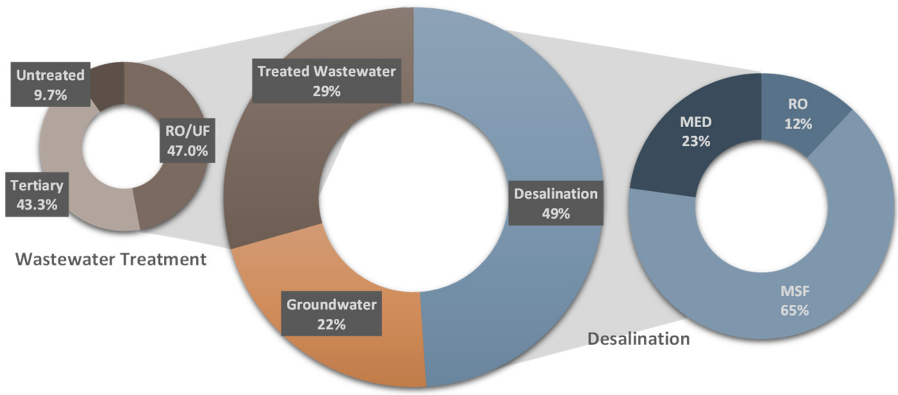

Figure 2: Water sources in Kuwait.

exception to this is in Kuwait, which vastly uses RO to treat wastewater (WWRO). Over 90% of Kuwait municipal wastewater is treated, of which 47% is treated through ultrafiltration (UF) and RO, and the remaining is treated through tertiary and advanced tertiary treatment (see Fig. 2). There are seven WWTPs in Kuwait: Alriqqa, Um Alhayman, Sulaibiya, Kabd, Wafra, Sabah Alhamed and Alkhiran (pilot plant). All WWTPs treat wastewater to the tertiary level, except for the Sulaibiya WWTP, which uses UF/RO to achieve potable water quality for nonpotable use [17].

This study conducts a life cycle assessment (LCA) on state-of-the-art RO treatment used for both seawater desalination and domestic wastewater treatment. The results are intended to assist policy-makers in better utilizing conventional water resources in Kuwait. The study is applied to Kuwait but has wider repercussions.

2 ASSESSING RO FOR WATER DESALINATION AND WASTEWATER TREATMENT USING LCA

LCA has been implemented to assess the environmental impacts of DPs with different plant characteristics [9], [18]. Al-Shayji and Aleisa [11] investigated the environmental impacts of all operating DPs in Kuwait. Mannan et al. [19] highlighted the regional impact on the environmental impact of a DP. Aljuwaisseri et al. [9] investigated the impacts of intake water salinity and turbidity on the environmental impact. Researchers have addressed varying desalination process scenarios, including different gain ratios [19], multiple energy sources [10], [20], [21] and different capacities [22]. The effects of using renewable energy sources in DPs and their associated impacts on environmental loads have also been addressed within LCAs [19], [20], [23]. A literature review on SWRO LCAs can be found in Aljuwaisseri et al. [9].

For wastewater treatment assessment using LCAs, to date, more than 100 research papers have been published in this field [24]. Detailed literature reviews comparing different LCA objectives, challenges, methodological choices and results related to wastewater treatment and sludge management can be found in Corominas et al. [24], Yoshida et al. [25], Pradel et al. [26], and Gallego-Schmid and Tarpani [27]. In addition, LCA has been used to analyze environmental impacts in the field of storm-water management [28], to determine appropriate solutions in the field of the urban water cycle [29], to control emitted greenhouse gases [30], and to identify the environmental impacts of wastewater sludge treatment [31].

3 MATERIALS AND METHODS

The goal of this study is to evaluate the environmental burden of RO treatment on two main water production processes, SWRO and WWRO, using LCA. Both analyses adhere to the four stages outlined by ISO 14044 [32]. The analysis is conducted using open-loop consequential modeling. The UF used is 1 Mm^3 of permeate to potable quality per the requirements of the World Health Organization (WHO). The two system boundaries are described next.

3.1 System scope and boundary

The system boundaries are the cradle-to-gate impacts of all processes, materials, energy requirements and chemicals through operation and are calculated through field visits, reports and literary analysis. Water delivery and disposal are excluded. The construction and decommissioning phases were excluded from the LCA due to their insignificant contributions to the total environmental impact [20], [33]–[35]. For instance, Raluy et al. [36] found that the construction phase only contributed 5% to the total environmental impact. Furthermore, brine disposal was also excluded from the study due to its relatively negligible environmental impact [34], [36].

3.1.1 SWRO system description

The process of producing desalinated water using SWRO is based on Aljuwaisseri et al. [9] and is shown in Fig. 3. Ferric chloride is injected to coagulate the particles, improving the removal of suspended material through gravity filters. Sodium bisulfate is injected to remove the residual chlorine to protect the membranes from oxidization. An antiscalant is also

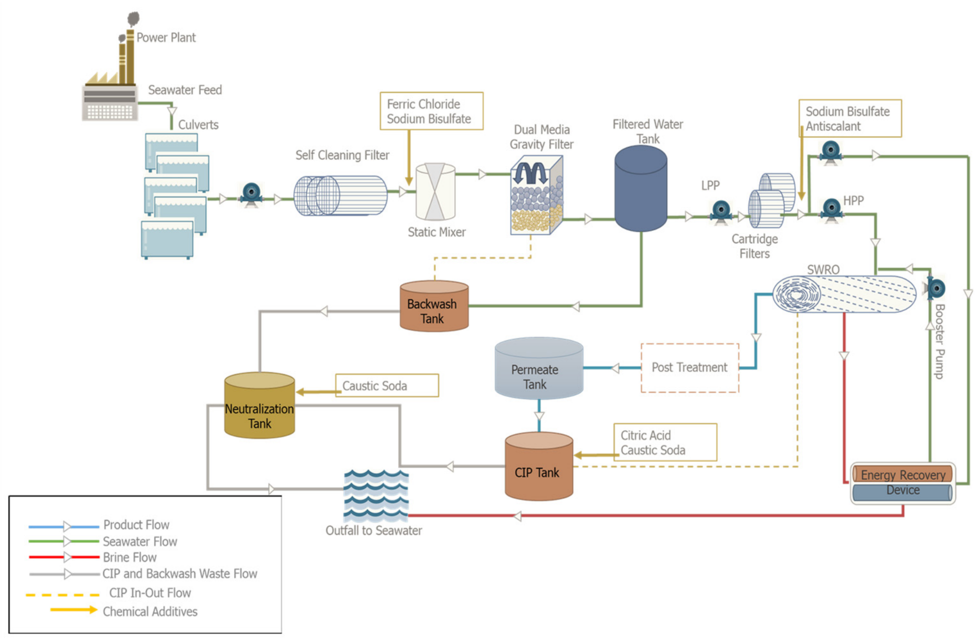

Figure 3: Process flowchart for the SWRO DP. *(Source: Adapted from [9].)*

injected into the filtered seawater before it enters the SWRO unit. The SWRO system is a single-pass system with energy-recovery device units supplied with filtered seawater by a low-pressure pump. The concentrated brine rejection line is located at the outlet of the membrane array to feed the energy-recovery device. Finally, the permeate is mixed with the distilled water produced at a nearby plant before it is sent to the distribution network. Clean-in-place (CIP) is the main cleaning process applied to remove scaling and biofouling. Citric acid and caustic soda are the chemicals used in CIP.

3.1.2 UF/RO system description

Wastewater first undergoes a primary treatment that is a physical/mechanical process that removes suspended and floating particles from the wastewater entering the WWTP. Primary treatment includes screening to screen grit and other suspended solids. Secondary treatment uses biological processes to digest and dissolve organic pollutants to produce settleable solids. The process is followed by aeration basins or settling tanks to clarify the influent by removing approximately 85% of its suspended solids and BOD [37], [38]. The biological treatment stage uses a vertical loop reactor (VLR) [39]. The wastewater is then moved by gravity to secondary wastewater treatment equipment, which consists of aeration chambers and primary clarifiers. The type of clarifier used is a rim flow clarifier. The resultant active sludge is continuously recycled to the aeration tank. The surplus activated sludge (SAS) is used for sludge treatment [31]. The effluent undergoes a tertiary treatment, which eliminates over 95% of all impurities from the sewage. It consists of rotating disc filters and an ultraviolet (UV) system. Advanced treatment uses UF/RO as the membrane process to remove the residual solids, inorganics, organics and microorganisms remaining in the tertiary effluent. The UF/RO treatment is built based on the Sualibiayh WWTP. The UF system consists of 8.7 K UF membranes, and the RO trains consist of 21 K membranes. Eventually, 85% of the tertiary effluent is reclaimed, and the remaining 15% is discharged as brine into the sea [40].

Excess sludge is thickened to reduce its volume. A polymer preparation unit (PPU) is used for additional thickening and flocculation [39]. Aerobic digesters use gravity belts that carry sludge for dewatering to form a sludge cake, which is then landfilled [31].

The chemical and microbiological characteristics of the wastewater RO permeate (ROP) in Kuwait exceed the WHO standards [17], [41], [42] of potable quality and the Kuwait standards as published by the Kuwait Environmental Public Authority (KEPA) and the Ministry of Public Works (MPW) (see Table 1).

Table 1: Specifications of the effluent per cubic meter [43].

Specification	**Unit**	**ROP**	**Potable water**	**Specification**	**Unit**	**ROP**
pH	–	6–8	6.8–7.5	Chloride	mg/L	
Conductivity			515	Ammonia	mg/L	< 1
TSS	mg/L	< 1	–	Nitrite	mg/L	< 1
VSS	mg/L	< 1	–	Total count	Colony/100 mL	Nil
COD	mg/L		–	T. Coli	Colony/100 mL	Nil
BOD	mg/L	< 1	–	F. Coli	Colony/100 mL	Nil
Grease and oil	mg/L	< 0.05	–	Salmonella	Colony/100 mL	Nil
TDS	mg/L	< 100	400	Streptococci	Colony/100 mL	Nil

Note: BOD = biochemical oxygen demand; COD = chemical oxygen demand; TSS = total suspended solids; VSS = volatile suspended solids; T. Coli = total coliforms; F. Coli = fecal coliforms.

3.2 Life cycle inventories

The life cycle inventory (LCI) foreground data, including energy consumption, chemical dosage, and membrane data, were collected from field visits and reports. The background data comprising the production of chemicals, energy and membranes were obtained from [44] and the ecoinvent database v.3.0. For SWRO, the LCI is provided in Table 2. The tertiary wastewater treatment LCI is provided in Table 3. The UF/RO LCI was obtained from the Sulaibiya WWTP in Kuwait [40]. The energy calculations were obtained from Aleisa and Heijungs [10] and Aleisa and Al-Shayji [21]. The electrical energy required for SWRO is 5.2 kWh/m^3 [9]. The electrical energy required for tertiary wastewater treatment is 3.95×10^{-1} kWh/m^3, and that required for UF/RO (excluding tertiary) is 3.14×10^{-1} kWh/m^3 [40].

Table 2: LCI of the SWRO DP. *(Source: Adapted from [9], [44].)*

Input data	Formula	Unit	Amount	Ecoinvent process
Antiscalant hydrex	$CH_2 = CHCOOH$	g/m^3	15.857	Acrylic acid [9]
Caustic soda	$NaOH$	g/m^3	56.2	Sodium hydroxide 50% in solution [44]
Ferric chloride	$FeCL_3$	g/m^3	45.31	Iron (III) chloride 40% in solution [44]
Sodium bisulfate	$NaHSO_3$	g/m^3	0.906	Sodium hydrogen sulfite [9]
Citric acid	$C_6H_8O_7$	g/m^3	0.906	Citric acid [9]
SWRO membrane		g/m^3	0.898	Glass fiber-reinforced plastic, polyamide [9]

Table 3: Chemical additives per cubic meter of tertiary treated wastewater [40].

Chemicals	Formula	Amount (g)
Sodium hydroxide 50%	*NaOH*	1.096
Sodium hypochlorite 12.5%	*NaOCl*	2.740
Activated carbon	*C*	3.044×10^{-2}
Cationic polymer	–	1.461
Chlorine liquid	*Cl*	3.288

The landfilling facility is designed for biogenic waste from the ecoinvent database version 3.0. It has a design capacity of 1.8 million m^3 with a 30-year lifetime. It is equipped with a leachate and landfill gas collection system [31], [45].

3.3 Life cycle impact assessment

The life cycle impact assessment (LCIA) was calculated using the ReCiPe midpoint (H) V1.10. Table 4 lists the midpoint impact categories.

4 RESULTS

Figs 4 and 5 illustrate the characterized and normalized LCIA results, respectively. The LCIA shows a significant difference in the environmental impacts between SWRO and WWRO. Using the characterized results (see Fig. 4), SWRO scores higher (worse) in terms of CC, OD, PMF and FD. This was mainly due to the high energy consumption of SWRO. Over

Table 4: Midpoint impact categories investigated in the LCIA phase (ReCiPe V1.10).

Midpoint impact category	**Unit**
Climate change (CC)	kg (CO_2 to air)
Ozone depletion (OD)	kg (CFC-11 to air)
Fossil depletion (FD)	kg (oil)
Metal depletion (MD)	kg (Fe)
Particulate matter formation (PMF)	kg (PM_{10} to air)
Human toxicity (HT)	kg (14-DCB to urban air)
Marine ecotoxicity (MET)	kg (14-DCB to marine water)

92% of the environmental burden is attributed to the electricity use required by SWRO. Ferric chloride followed by the antiscalant contributed 3% and 1%, respectively, to the environmental impact of the SWRO DP. The process contribution analysis revealed that petroleum and gas production were the highest contributors to FD (95% contribution). The main contributor to CC was the CO_2 resulting from high-voltage electricity production. On the other hand, WWRO scores higher (worse) in characterized values in terms of MET and MD. This is due to the extensive use of ferric chloride and hydrochloric acid in WWRO. The results are similar in terms of HT at 52.7% and 53.3% for WWRO and SWRO, respectively. The first is due to ferric chloride, and the second is due to energy. The normalized results (see Fig. 5) indicate that FD is the impact category with the largest effect, followed by CC, MD and then PMF.

The single score results (see Fig. 6) indicate that the WWRO impact is only 31% of that of the SWRO impact. Regulations exclude all amenity uses of WWRO and restrict its uses to the irrigation of crops and some industrial applications [17]. 19% of all water consumed in the agricultural sector is recycled water. WWRO treatment is regulated by KEPA standards [46], [47], which are on several parameters more conservative than those of the WHO [41]. No outbreaks of infectious disease have occurred since 2005, when the first utilization of

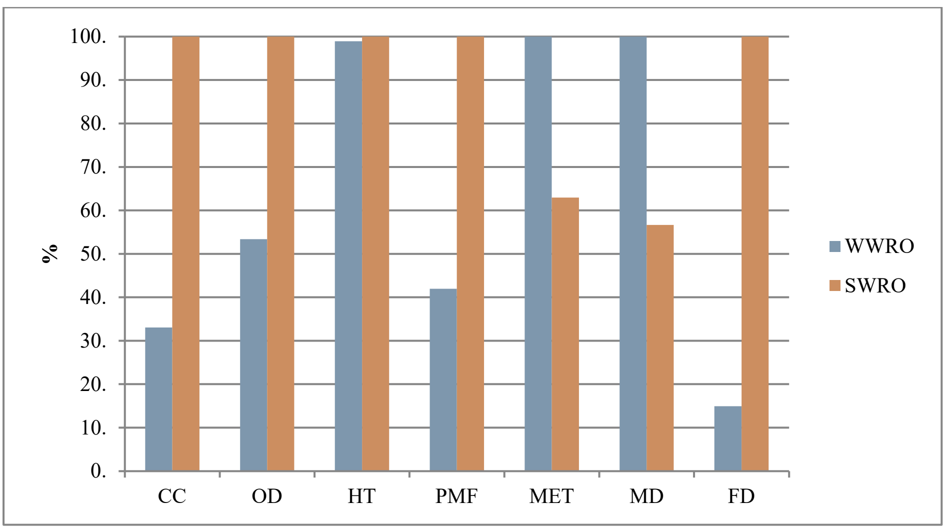

Figure 4: Characterized results for WWRO versus SWRO production using ReCiPe Midpoint (H) V1.10.

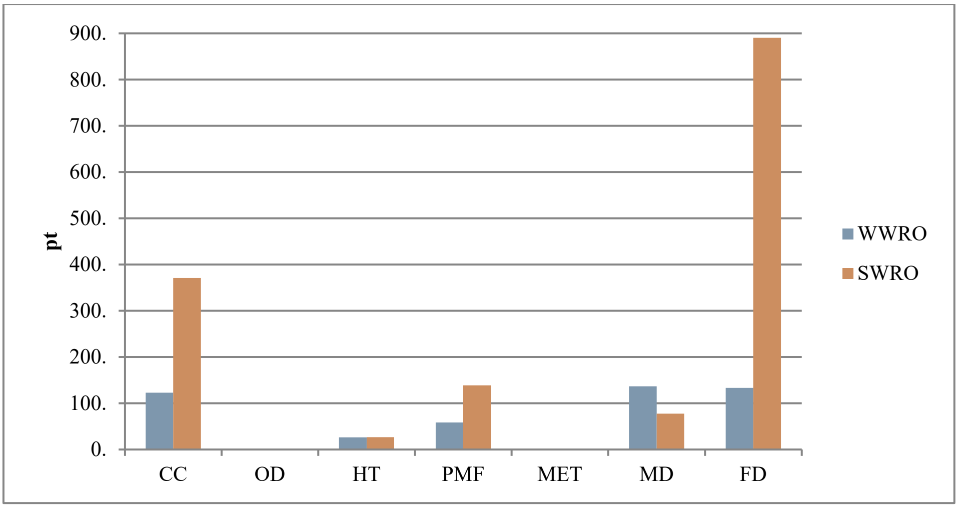

Figure 5: Normalized results for WWRO versus SWRO production using ReCiPe Midpoint (H) V1.10.

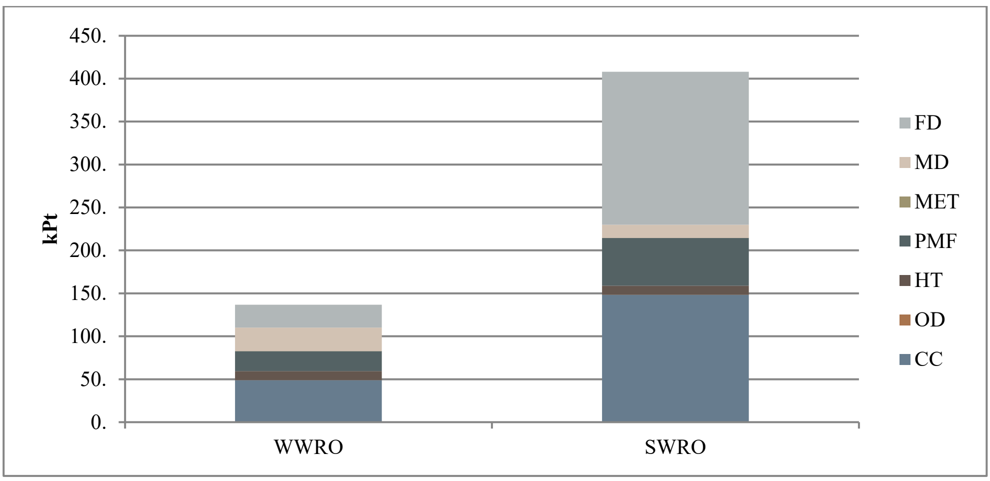

Figure 6: Single score results for WWRO versus SWRO production using ReCiPe Midpoint (H) V1.10.

ROP water took place. This clearly indicates a great opportunity that could significantly contribute to balancing SDG No. 6 (clean water and sanitation) and SDG No. 7 (affordable and clean energy) to contribute to SDG No. 13 (climate action).

5 CONCLUSIONS

This study provides an LCA that compares the environmental impacts of WWRO versus SWRO. SWRO has three times the environmental impact of WWRO. This result was most significant in terms of CC, OD, PMF and FD. This was mainly due to the high energy consumption of SWRO. Over 92% of the environmental burden is attributed to the electricity use required by SWRO.

On the other hand, WWRO scores higher (worse) in characterized values in terms of MET and MD. This is due to the extensive use of ferric chloride and hydrochloric acid in WWRO. The local regulations exclude all amenity uses of WWRO and restrict its uses to the irrigation of crops and some industrial applications. Relaxing some of these regulations could significantly and safely contribute to a circular economy and promote a better balance between achieving SDG No. 6 (clean water and sanitation) and SDG No. 13 (climate action).

REFERENCES

[1] UN Water, *United Nations World Water Development Report 2020: Water and Climate Change*, ed. R. Connor, UN Water: Paris, 2020.
[2] UNEP, Emissions Gap Report 2019. United Nations Environment Programme: Nairobi, 108 pp., 2019.
[3] UN.org, Decade of change. 2020. https://www.un.org/sustainabledevelopment/decade-of-action/. Accessed on 16 Sep. 2020.
[4] Rezessy, S., Bertoldi, P. & Voogt, M., Mission possible: Bringing end-use energy efficiency to the European Emissions Trading scheme. Summer study of the European Council for Energy Efficient Economy. ECEEE: La Colle Sur Loup, 2007.
[5] Nock, D. & Baker, E., Holistic multi-criteria decision analysis evaluation of sustainable electric generation portfolios: New England case study. *Applied Energy*, **242**, pp. 655–673, 2019.
[6] Mateo-Sagasta, J. et al., *Safe Use of Wastewater in Agriculture*, eds J. Liebe & R. Ardakanian, Food and Agriculture Organization (FAO) of the United Nations and United Nations Water: Bonn, 2016.
[7] GCC Secretariat General, Development of a Unified Water Sector Strategy for Gulf Cooperation Council of Arab Member States (DRAFT) (English). King Abdullah Institute for Research and Consulting Studies: Riyadh, 2015.
[8] Aleisa, E. & Al-Zubari, W., Wastewater reuse in the countries of the Gulf Cooperation Council (GCC): The lost opportunity. *Environmental Monitoring and Assessment*, **189**(11), pp. 553–568, 2017.
[9] Aljuwaisseri, A., Aleisa, E. & Alshayji, K., Environmental and economic analysis for desalinating seawater of high salinity using reverse osmosis: A life cycle assessment approach. *Environment, Development and Sustainability*, 2022.
[10] Aleisa, E. & Heijungs, R., Leveraging life cycle assessment and simplex lattice design in optimizing fossil fuel blends for sustainable desalination. *The International Journal of Life Cycle Assessment*, **25**(4), pp. 744–759, 2020.
[11] Al-Shayji, K. & Aleisa, E., Characterizing the fossil fuel impacts in water desalination plants in Kuwait: A life cycle assessment approach. *Energy*, **158**, pp. 681–692, 2018.
[12] IRENA, *Renewable Energy Market Analysis*, IRENA: Abu Dhabi, UAE, 154, pp., 2019.
[13] Kaya, A., Tok, M.E. & Koc, M., A levelized cost analysis for solar-energy-powered sea water desalination in the Emirate of Abu Dhabi. *Sustainability*, **11**(6), pp. 1691, 2019.
[14] Mena desalination market, Ventures ONSITE, 2019. menadesal.com.
[15] Project, B.f.M.D., Major Desalination Plants in MENA, p. 4, 2019.
[16] UN Water, Water scarcity, 2020. https://www.unwater.org/water-facts/scarcity/.
[17] Aleisa, E. & Alshayji, K., Analysis on reclamation and reuse of wastewater in Kuwait. *Journal of Engineering Research*, **7**(1), pp. 1–13, 2019.

[18] Aziz, N. & Hanafiah, M.M., Application of life cycle assessment for desalination: Progress, challenges and future directions. *Environ. Pollut.*, **268**(Pt B), 115948, 2021.
[19] Mannan, M. et al., Examining the life-cycle environmental impacts of desalination: A case study in the State of Qatar. *Desalination*, **452**, pp. 238–246, 2019.
[20] Shahabi, M.P. et al., Environmental life cycle assessment of seawater reverse osmosis desalination plant, powered by renewable energy. *Renewable Energy*, **67**, pp. 53–58, 2014.
[21] Aleisa, E. & Al-Shayji, K., Ecological–economic modeling to optimize a desalination policy: Case study of an arid rentier state. *Desalination*, **430**, pp. 64–73, 2018.
[22] Bhakar, V. et al., Life cycle assessment of filtration systems of reverse osmosis units: A case study of a university campus. *13th Global Conference on Sustainable Manufacturing: Decoupling Growth from Resource Use*, eds G. Seliger, H. Kohl & J. Mallon, pp. 268–273, 2016.
[23] Al-Kaabi, A.H. & Mackey, H.R., Environmental assessment of intake alternatives for seawater reverse osmosis in the Arabian Gulf. *Journal of Environmental Management*, **242**, pp. 22–30, 2019.
[24] Corominas, L. et al., Life cycle assessment applied to wastewater treatment: State of the art. *Water Research*, **47**(15), pp. 5480–5492, 2013.
[25] Yoshida, H., Christensen, T.H. & Scheutz, C., Life cycle assessment of sewage sludge management: A review. *Waste Manag. Res.*, **31**(11), pp. 1083–101, 2013.
[26] Pradel, M. et al., From waste to added value product: Towards a paradigm shift in life cycle assessment applied to wastewater sludge: A review. *Journal of Cleaner Production*, **131**, pp. 60–75, 2016.
[27] Gallego-Schmid, A. & Tarpani, R.R.Z., Life cycle assessment of wastewater treatment in developing countries: A review. *Water Research*, **153**, pp. 63–79, 2019.
[28] Tavakol-Davani, H. et al., Combining hydrologic analysis and life cycle assessment approaches to evaluate sustainability of water infrastructure. *Journal of Irrigation and Drainage Engineering*, **144**(11), 2018.
[29] Petit-Boix, A. et al., Addressing the life cycle of sewers in contrasting cities through an eco-efficiency approach. *Journal of Industrial Ecology*, **22**(5), pp. 1092–1104, 2018.
[30] Raghuvanshi, S. et al., Comparative study using life cycle approach for the biodiesel production from microalgae grown in wastewater and fresh water. *Procedia CIRP*, **69**(1), pp. 568–572, 2018.
[31] Aleisa, E., Alsulaili, A. & Almuzaini, Y., Recirculating treated sewage sludge for agricultural use: Life cycle assessment for a circular economy. *Waste Management*, **135**, pp. 79–89, 2021.
[32] ISO 14044, Environmental Management – Life Cycle Assessment – Requirements and Guidelines. The International Organization for Standardization (ISO): Geneva, 2006.
[33] Garfi, M. et al., Life cycle assessment of drinking water: Comparing conventional water treatment, reverse osmosis and mineral water in glass and plastic bottles. *Journal of Cleaner Production*, **137**, pp. 997–1003, 2016.
[34] Tarnacki, et al., Comparison of environmental impact and energy efficiency of desalination processes by LCA. *Water Science and Technology-Water Supply*, **11**(2), pp. 246–251, 2011.
[35] Zhou, J., Chang, V.W.C. & Fane, A.G., Life cycle assessment for desalination: A review on methodology feasibility and reliability. *Water Research*, **61**, pp. 210–223, 2014.

[36] Raluy, G., Serra, L. & Uche, J., Life cycle assessment of MSF, MED and RO desalination technologies. *Energy*, **31**(13), pp. 2361–2372, 2006.
[37] Hamoda, M., Advances in wastewater treatment technology for water reuse. *Journal of Engineering Research*, **1**(1), pp. 1–27, 2013.
[38] Hsu, A. et al., Environmental Performance Index: Full Report and Analysis. Yale Center for Environmental Law and Policy, Yale University: New Haven, CT, 2014.
[39] MPW, Kabd WWTP, S.E. sector, Department of Operation and Maintenance of Plants (North Zone): Kuwait, 2019.
[40] Aleisa, E., Al-Mutairi, A. & Hamoda, M.F., Reconciling water circularity through reverse osmosis for wastewater treatment for a hyper-arid climate: A life cycle assessment. *Sustainable Water Resources Management*, 2022.
[41] WHO, A compendium of standards for wastewater reuse in the Eastern Mediterranean Region C.f.E.H.A. (CEHA), 2006.
[42] FAO, Wastewater treatment and human exposure control: Kuwait. Wastewater use case studies, 1992.
[43] MPW, Reports from the sanitary engineering sector in Kuwait. Ministry of Public Work: Kuwait, 2018.
[44] Vince, F. et al., LCA tool for the environmental evaluation of potable water production. *Desalination*, **220**(1–3), pp. 37–56, 2008.
[45] Aleisa, E. & Heijungs, R., Leveraging life cycle assessment to better promote the circular economy: A first step using the concept of opportunity cost. *Sustainability*, **14**(6), 2022.
[46] KEPA, Kuwait Environmental Law 42/2014 emended by law 99/2015. K.E.P. Authority, Kuwait Al Youm: Kuwait, 2014.
[47] KEPA, Decree No. 12 of 2017 issuing the Executive Regulations for the Protection of the Aquatic and Coastal Environment from Pollution (Articles 88, 90, 92 and 94–99 of Law No. 42/2014), K.E.P. Authority, Kuwait Al-Youm: Kuwait, 2017.