Desalination 528 (2022) 115608

Contents lists available at ScienceDirect

Desalination

journal homepage: www.elsevier.com/locate/desal

Utilization of membrane separation processes for reclamation and reuse of geothermal water in agricultural irrigation of tomato plants-pilot membrane tests and economic analysis

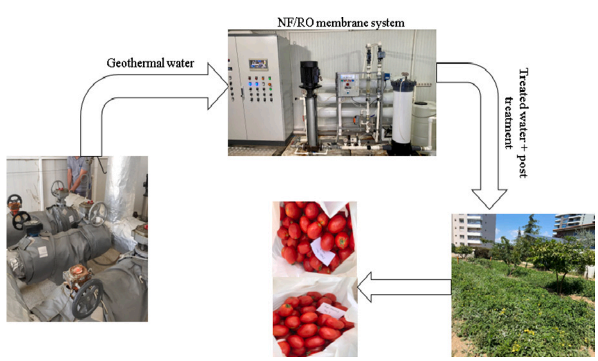
Yakubu A. Jarma [a], Aslı Karaoğlu [a,b], Islam Rashad Ahmed Senan [a], Mehmet Kamil Meriç [c], Yasemin Senem Kukul [d], Emrah Özçakal [d], Neriman Tuba Barlas [e], Hakan Çakıcı [e], Alper Baba [f], Nalan Kabay [a,*]

[a] Ege University, Faculty of Engineering, Department of Chemical Engineering, 35100 Bornova, Izmir, Turkey
[b] Ege University, Graduate School of Sciences, Division of Environmental Sciences, 35100 Bornova, Izmir, Turkey
[c] Ege University, Bergama Vocational Training School, Bergama, Izmir, Turkey
[d] Ege University, Department of Farm Structures and Irrigation, Faculty of Agriculture, 35100 Bornova, Izmir, Turkey
[e] Ege University, Department of Soil Science and Plant Nutrition, Faculty of Agriculture, 35100 Bornova, Izmir, Turkey
[f] Izmir Institute of High Technology, Department of International Water Resources, 35430 Urla, Izmir, Turkey

HIGHLIGHTS

- The application of NF and RO membranes to treat the spent geothermal water for agricultural irrigation of tomato plants.
- Blending of product water after membrane treatment to get suitable water quality.
- A mixing using well water with the product water of NF (50%) and RO (60%) to obtain Quality II water.
- The produced water obtained can be utilized for irrigating low-boron-sensitive crops.
- The total cost of water production using NF membrane was \$0.76/m^3 while that of RO process was \$1.56/m^3.

GRAPHICAL ABSTRACT



ABSTRACT

The quality of irrigation water is critical for enhancing agricultural productivity. As a result, this research was carried out with the aim of treating spent geothermal water before it is used for agricultural irrigation. While doing that, cost analysis of the system was taken into consideration as well. The product water was targeted to suit irrigation water standards for tomato plants. Two commercially available pressure driven membranes (NF8040-70 as NF membrane and TM720D-400 as RO membrane) were employed for this task. A constant applied pressure of 15 bar and 60% of water recovery were kept constant during the product water production while mode of operation for the membrane system was continuous. According to Turkish Ministry of Environment and Urbanization irrigation water standards and the results obtained from this study, it was clearly seen that both NF and RO product waters meet the quality I class irrigation water standards with respect total dissolved substances (TDS), electrical conductivity (EC), concentrations of Na^+ and Cl^- ions. Quality 1 means that the produced water will not cause any environmental effect when employed for irrigation purpose. Nevertheless, the produced water was found not to obey the irrigation standards with respect to sodium adsorption ratio (SAR) and boron concentration (quality III class). Quality III explains that the water will cause soil infiltration problems when employed for

* Corresponding author.
E-mail address: nalan.kabay@ege.edu.tr (N. Kabay).

https://doi.org/10.1016/j.desal.2022.115608
Received 10 December 2021; Received in revised form 25 January 2022; Accepted 26 January 2022
Available online 8 February 2022

irrigation purpose. Since most of the minerals needed for plant growth were rejected by NF and RO membranes, an appropriate mixing ratio of the product water with well water for remineralization was determined. Mixing 50 and 60% of well water with the product waters of NF (50%) and RO (40%) membranes, respectively was found to be the optimum mixing ratios to produce the requested water quality for tomato irrigation. Quality II class irrigation water which can be applied with caution was targeted in terms of SAR as well as boron concentration (2–4 and 4–6 mg/L) while determining the mixing ratios. The cost of the product water was found as 0.76 and 1.56$/m^3 for NF and RO processes, respectively.

1. Introduction

Water is used in all aspect of our daily activities. At the same time, water scarcity has been an issue in many nations in recent decades, particularly in developing countries. Among sectors where water is being used, the agricultural industry consumes a lot of water, mostly for irrigation. Agriculture requires a lot of freshwaters, especially in dry and semi-arid countries where rain fall is limited. About 70% of the world's freshwater resources are being utilized for the purpose of agriculture [1], meeting 45% of global food demand [2]. Irrigation and water management, according to Steduto et al. [2] have played a critical role in enabling countries to grow food crops even when there is no rain fall (dry season) and improve lives during the previous 50 years. The UN's Food and Agricultural Organization (FAO) projects that yearly grain output will rise by 140% by 2050, while overall world food production would rise by 70% [3]. For this reason, the total amount of water withdrawn due to irrigation activities is expected to rise by 11% [2]. However, water shortage and its impact on agricultural growth are becoming a major issue in many countries nowadays [4]. From 2030 to 2040, a projected irrigation water demand growth of 4% was estimated by Caldere and Breyer [5]. While desalination requirement for irrigation is estimated to be 8.32×10^8 m^3/day in 2030. Iran, China, and Pakistan alone contribute for over 55% of total irrigation water demand [5]. Water-saving irrigation and highly efficient water use have been adopted to reduce water use, but they are still far from meeting the growing need of water in agricultural expansion [6]. Salty water or seawater is being considered for irrigation by the implementation of new crops and water management practices to combat freshwater scarcity and at the same time maintain agricultural sustainability [7,8]. Surely, the use of seawater for irrigation can significantly reduce the scarcity of water in agricultural systems [9]. However, using saline seawater for irrigation has numerous drawbacks, including the accumulation of salts in the soil [10] as well as the plant stress caused by increase in osmotic pressure, which has a negative impact on crop growth and crop productivity [11]. Therefore, it is of vital importance to explore other sustainable water sources such as wastewater reclamation and reuse as well as valorization of the spent geothermal water among others.

Large volumes of water are being used by geothermal power plants for generation of electricity [12]. Using some portion of the spent geothermal water after the reclamation rather than consuming fresh water (from rivers or aquifer) can be utilized for industrial applications such as cooling applications or drying purposes to avoid excessive water consumption from the aquifer [13]. After the harvesting energy from geothermal fluids, the spent geothermal water can, therefore, be reasonably considered as a potential solution for industrial and agricultural irrigation water problems.

Exploring alternative water sources would undoubtedly relieve the load on currently available freshwater supplies. Utilization of the spent geothermal water for irrigation purpose is not possible without studying the physicochemical properties of that water. Physicochemical parameters for geothermal waters vary based on the depth upon which resources are found, the geological properties of the rocks involved, and indeed the source of water supply. Anions and cations, as well as neutral molecules, are abundant in geothermal waters. It was reported that high boron and arsenic concentrations in the spent geothermal water are the major problems in the Aegean region of Turkey, making it inappropriate for agricultural use [14]. With such high concentrations of boron and arsenic, geothermal waters are not suitable for agriculture. Because, the spent geothermal water contains boron and arsenic at even higher concentrations than those found in seawater and other brackish water sources [14]. Therefore, direct application of spent geothermal water as agricultural irrigation water will surely cause some damages to both plants and other living organisms. On the other hand, boron is an essential micronutrient element for plants and living beings at some concentrations. However, its presence in either drinking or irrigation water at a high concentration will endanger plant growth as well as cause health problems for humans [15]. Therefore, the spent geothermal water can be categorized as not environmentally friendly when is utilized for the agricultural irrigation in the area [16]. Boron toxicity has been observed to impact root growth in wheat, barley, and maize. Hence, excessive boron may harm wheat grown with geothermal water as an irrigation water source [17].

Electrocoagulation [18], ion exchange with clays [19], co-precipitation [20], continuous electrodeionization (CEDI) [21], ion exchange with polymeric chelating ion exchange resins [22,23], capacitive deionization (CDI) [24], adsorption-membrane filtration hybrid process [25], direct contact membrane distillation [26], membrane distillation process [27,28], and pressure-driven membrane processes are some of the methods presented in the literature for the treatment of either fresh or spent geothermal water. Thermal-driven desalination technologies account for about 31% of present worldwide desalination market, while pressure-driven membrane technologies like nanofiltration (NF) and reverse osmosis (RO) account for roughly 66% [28,29]. The RO technique, which dates to 1960s, is a membrane separation technology with an applied pressure as the main driven force for the separation. When compared to thermal technologies, the RO technologies require less energy input in the context of worldwide water scarcity and rising water pollution. Furthermore, ion rejection is excellent with modern RO membranes, with a rejection rate of not less than 99.9% in well-operated plants [30].

Numerous researchers have made a lot of efforts to treat the geothermal water and bring the water quality to agricultural irrigation standards [28–32]. Nonetheless, most of these studies were carried out either in a mini-pilot or laboratory scale test systems. Research about the real application of the obtained results for agricultural irrigation seems to be scarce, if any.

The present work aimed to apply commercially available NF and RO membranes to treat the spent geothermal water discharged at the geothermal heating center located in Izmir, Turkey. The spiral wound NF and RO membranes (NF8040-70 as NF membrane and TM720D-400 as RO membrane) were employed for this task. The irrigation water criteria given by Turkish Ministry of Environment and Urbanization were used to evaluate the produced water quality. Furthermore, the economic assessment of the membrane operation with each membrane was carried out as well.

2. Materials and method

A large pilot-scale NF/RO membrane system was installed in the geothermal heating center, Izmir, Turkey for reclamation of the spent geothermal water with a purpose of agricultural irrigation water production. After the energy has been harvested for domestic heating, the spent geothermal water used in this study was obtained from the reinjection line of the heating center. The treated spent geothermal water was intended to be used as agricultural irrigation water in the future. Because the membranes to be utilized for the treatment of spent geothermal water are made of polymeric materials, they can only withstand temperatures up to 45 °C as prescribed by the membrane producers. Thus, cooling the spent geothermal water becomes necessary before subjecting it to the membrane treatment in a pilot-scale membrane system. The spent geothermal water, which has a temperature of 50–55 °C was, therefore, first cooled in two containers of 5 m^3 before being treated in the pilot-scale membrane system. After the spent geothermal water was cooled down to the ambient temperature, the spent geothermal water was first pumped to sand and carbon filters as pretreatment for the removal of large particles and H_2S respectively. Activated carbon was reported to be effective in the removal of H_2S by adsorption [32–35]. The pilot-scale membrane system is equipped with cartridge filters (5 μm) for removal of particles that might possibly pass through sand and carbon filters. The spent geothermal water contains some inorganic species such as silica, Ca^{2+} and Mg^{2+} ions which can cause scaling on the active layer of the membrane, thereby threatening the productivity of the overall membrane system. As a result of that, the system was equipped with an antiscalant dosage pump feeding Ropur (PRI-3000 A) antiscalant at a concentration of 5 g antiscalant/m^3-spent geothermal water to be treated. Furthermore, parameters such as permeate and concentrate flow rates, pressure at inlet and exit (permeate and concentrate sides) of the membranes are monitored through a control panel in the pilot-scale membrane system. The automation system is equipped with a PID controller, making it easy to set the desired water recovery and operational pressure without disturbance. Details of the pilot-scale membrane system employed in this study are given in Fig. 1. Two commercially available membranes, NF8040–70 (NF membrane) and TM720D-400 (RO membrane) purchased from Toray Chemical Korea Inc. were employed for this task. Details of the membrane properties used in this study are given in Table 1. The mode of operation during the production of irrigation water was continuous. Water recovery and the applied pressure were kept constant at 60% and 15 bar, respectively throughout the study. Samples taken from feed and permeate streams, well water used for remineralization and mixtures of NF/RO permeates and well water were used for the quality analyses. Properties of the spent geothermal used in this study are given in Table 2.

To calculate the sodium hazards on soil penetration, the sodium adsorption ratio (SAR), a dimensionless parameter that relates sodium concentration in irrigation water to the total of magnesium and calcium concentrations can be calculated using Eq. (1). Irrigation water quality is categorized into three groups: quality I, quality II, and quality III. Quality I water explains that the water would not harm crops or soil. Quality II water would have some negative impacts and should be utilized with caution, while quality III water will have significant infiltration effects on the soil.

$$SAR = \frac{[Na^+]}{\sqrt{\frac{[Ca^{2+}]+[Mg^{2+}]}{2}}} \quad (1)$$

where SAR is the sodium adsorption ratio, $[Na^+]$, $[Ca^{2+}]$ and $[Mg^{2+}]$ are the concentrations as mg/L, respectively.

The Mg^{2+} hazard (MH) was estimated using Eq. (2) as proposed by Szaboles and Darab [36]. According to the literature, water is considered unsuitable for irrigation when MH is higher than 50%.

$$MH\ (\%) = \frac{Mg^{2+}}{Mg^{2+} + Ca^{2+}} \times 100 \quad (2)$$

where Mg^{2+} and Ca^{2+} concentrations are expressed in mmol/L.

Permeability index (PI) is another important parameter used for the evaluation of irrigation water quality. PI is categorized into three classes i.e., quality I (75%), quality II (25–75%) and quality III (25%, not suitable for irrigation). Eq. (3) is used to calculate PI as described by Dinka [37], Dinka and Tadesse [38].

$$PI(\%) = \frac{Na^+ + \sqrt{HCO_3^-}}{Na^+ + Ca^{2+} + Mg^{2+}} \times 100 \quad (3)$$

where Na^+, Ca^{2+}, Mg^{2+}, HCO_3^- ion concentrations are all in mmol/L.

The Hach-Lange HQ14D model multimeter was employed for measuring electrical conductivity (EC), pH, total dissolved substances (TDS), and salinity during each test. Curcumine method by means of JascoSSE-343 V-530 UV/vis model spectrophotometer was used for determination of the boron concentrations in water samples. The arsenic concentration in water samples was measured using ICP-OES (SM 3120 B) method. Concentrations of Cl^-, SO_4^{2-} and F^- ions were determined

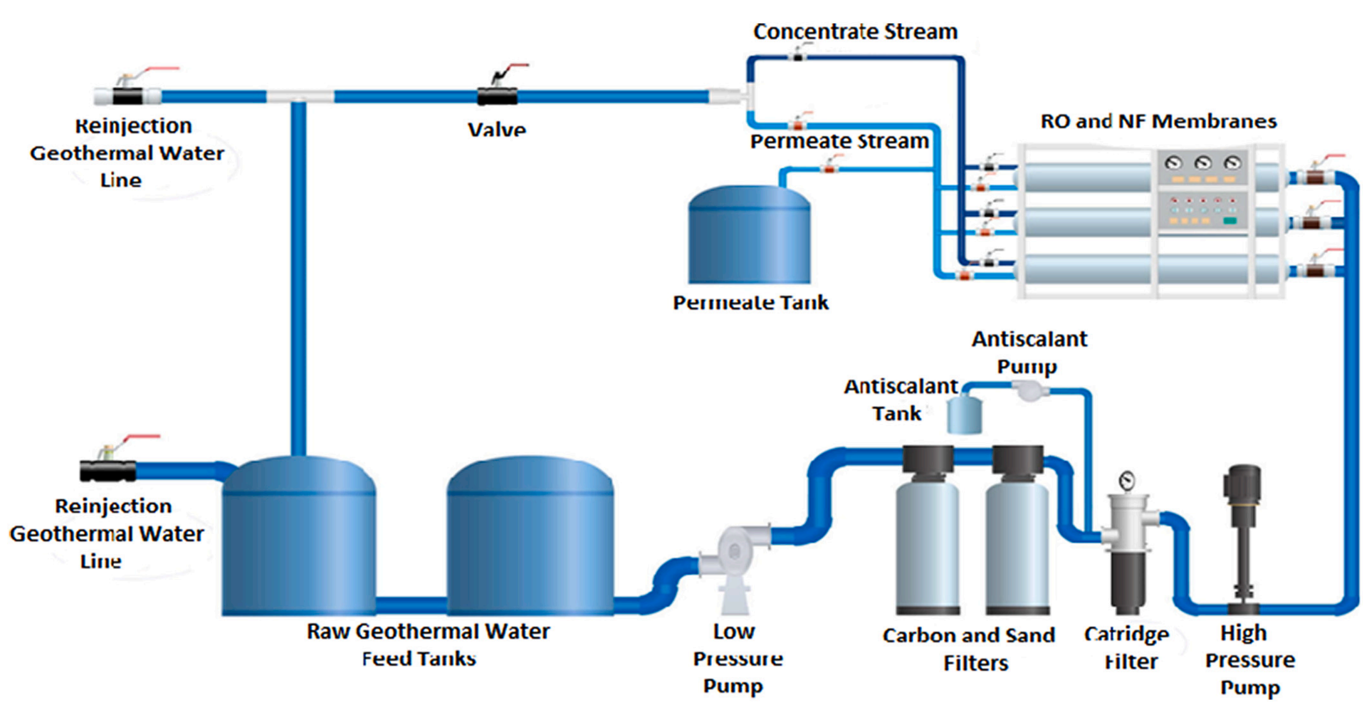


Fig. 1. Pilot-scale membrane treatment system.

Table 1
Properties of membranes employed in pilot-scale treatment system [39,40].

Membrane	Producer	pH range	Active membranearea (m^2)	Maximum pressure (bar)	Maximum temperature (°C)	Ion removal (%)
NF	Toray	2–11	37.2	41.4	45	97[a], 40–70[b]
RO	Toray	2–11	37.0	41.4	45	99.8[c]

[a] $MgSO_4$ removal.
[b] Monovalent ion removal (NaCl).
[c] Minimum salt removal.

Table 2
The characteristics of the spent geothermal water and well water.

Parameter	The spent geothermal water
pH	8.52
Conductivity (mS/cm)	1.8
TDS (mg/L)	1230
Cl^- (mg/L)	199
SO_4^{2-} (mg/L)	164
F^- (mg/L)	7.0
Na^+ (mg/L)	411
K^+ (mg/L)	32
Mg^{2+} (mg/L)	7.7
Ca^{2+} (mg/L)	25
B (mg/L)	12
Si (mg/L)	55
SiO_2 (mg/L)	118
As (μg/L)	170

using ion chromatography (Shimadzu IC 10 Ai Model) while Shimadzu AA-7000 model AAS was employed to measure the concentrations of Na^+, Mg^{2+} and Ca^{2+} ions in water samples. The Hach Lange spectrophotometer (model DR 3900) was used for the determination of silica concentration.

3. Results and discussion

3.1. Preparation of irrigation water for tomato plants from the spent geothermal water

This study was conducted with the aim of producing agricultural irrigation water from the spent geothermal water by using membrane treatment processes. It is good to keep in mind that every plant requires a different quality of irrigation water. Therefore, it is of paramount importance to make sure that the produced water meets the quality of irrigation water required by the plant intended to be irrigated.

In this study, we aimed to produce water with respect to tomato plant irrigation water standard prior to its use in the field tests. For this, we planned to produce water having low boron concentration (2–4 mg/L) and high boron concentration (4–6 mg/L). Table 3 depicts EC, concentrations of boron and arsenic together with pH for the requested water qualities by the agricultural people to irrigate the tomato plants during their field tests to check the resistance of tomato plants.

The quality of irrigation water used in agriculture has a significant impact on crop yield, plant quality, as well as soil properties. According to the Turkish Ministry of Environment and Urbanization, the salinity, EC value, pH, ion toxicity (such as excessive amounts of boron, sodium, arsenic, etc.) and sodium hazards on soil infiltration are some of the water quality characteristics that should be considered when evaluating the irrigation water quality as shown in Table 4. Unfortunately, when the pressure-driven membrane technologies are used to produce irrigation water from wastewater or any other water source, some of the nutrients essential for plant growth are also eliminated. Nonetheless, certain quantity of each of these elements is required for plant growth and soil quality. In the review by Qadir et al. [41], emphasize of the relevance of Ca^{2+} to Mg^{2+} ratio in irrigation water was stated. It was implied that the ratio of Mg^{2+} to Ca^{2+} concentrations in irrigation waters and the exchangeable percentage of Mg^{2+} in soils as 25% is high enough to cause soil deterioration and have a significant influence on crop production. According to Xu et al. [42], the TDS level and concentrations of Na^+, Mg^{2+}, and Ca^{2+}ions in water are the most important characteristics for agricultural irrigation. For the irrigation of sensitive crops, the SAR value tolerance limit of about 4 is required by the plants [43]. However, for most crops this limit is mostly between 8 and 18 [43].

Table 3
Recommended water quality values for irrigation of tomato plants.

	Irrigation water quality requested for tomato plant			
	EC (mS/cm)	B (mg/L)	As (μg/L)	pH
High boron content	0.9–1.5	4–6	<10	>6
Low boron content		2–4		

Table 4
Agricultural irrigation water qualities [44].

Parameter	Unit	Degree of restriction on use: None (Quality I)	Slight to moderate (Quality II)	Severe (Quality III)
Salinity				
EC	mS/cm	<0.7	0.7–3.0	>3.0
TDS	mg/L	<500	500–2000	>2000
Permeability				
SAR 0–3	EC: mS/cm	EC ≥ 0.7	0.7–0.2	<0.2
3–6		≥1.2	1.2–0.3	<0.3
6–12		≥1.9	1.9–0.5	<0.5
12–20		≥2.9	2.9–1.3	<1.3
20–40		≥5.0	5.0–2.9	<2.9
Specific ion toxicity				
Na^+	mg/L	<69	>69	
Cl^-	mg/L	<106.5	>106.5	
Boron	mg/L	<0.7	0.7–3.0	>3.0
Other				
pH		6.0–9.0		
Arsenic	μg/L	<10		

As stated in Table 4, other parameters such as SAR value, ion toxicity as well as EC of water must be taken into account before water can be utilized for agricultural irrigation. Table 5 shows details of the product water obtained from our study. Based on these results, it was clearly seen that both NF and RO product waters are suitable for irrigation with respect to the concentrations of Na^+ and Cl^- ions, EC as well as TDS. The pH value of the NF product water has complied with irrigation water standards while pH of RO membrane was found to be lower (5.5) than the standards (6.0–9.0). Nevertheless, the product water qualities obtained from both NF and RO membranes was found not to be suitable for irrigation with respect to boron concentration and SAR values. The product water of NF membrane in the preliminary study showed that boron concentration was found to be higher (8.7 mg/L) than the requested values (2–4 and 4–6 mg/L). The EC and pH of NF permeate were within the recommended range (EC:0.9–1.5 mS/cm and pH: 6.0–9.0), but both arsenic and boron concentrations in the NF permeate was above the recommended limits (As:10 μg/L and B: >6.0 mg/L). The EC values of the RO permeate in the preliminary study was found to be far away from the requested irrigation water quality. Therefore, the

Table 5
Evaluation of the NF and RO permeate waters for agricultural irrigation.

Parameter	Unit	NF	RO
Salinity			
EC	mS/cm	0.856*	0.0234*
TDS	mg/L	346.0*	8.8*
Permeability			
SAR	–	254.6***	16.7***
Specific ion toxicity			
Na^+	mg/L	180.0*	11.8*
Cl^-	mg/L	129.0*	0.00*
Boron	mg/L	8.7***	5.5***
Other parameters			
pH	–	6.9*	5.3***
Arsenic	μg/L	<23.0***	<10.0*
SO_4^{2-}	mg/L	2.6^{ns}	0.8^{ns}
F^-	mg/L	2.4^{ns}	0.1^{ns}
SiO_2	mg/L	93.8^{ns}	3.5^{ns}
Ca^{2+}	mg/L	0.5^{ns}	0.5^{ns}
Mg^{2+}	mg/L	0.5^{ns}	0.5^{ns}
MH	%	50.5^{ns}	50.5^{ns}
PI	%	99^{ns}	99^{ns}

*Quality I, ***Quality III, ^{ns} No standard.

product water must be tailored according to the water quality requested for tomato irrigation.

The arsenic concentration of the RO membrane has complied with irrigation water while arsenic concentration in NF membrane product water was found to be above the standard (>10.0 μg/L). The produced waters of NF and RO membranes have SAR values of 254.0 and 16.8, respectively (Table 5). These SAR values of the product waters are quite high, especially in case of the NF permeate making it not suitable for irrigation purpose. The NF and RO membranes eliminate more than 97% of divalent ions during the desalination process while NF membrane removes only 40–70% of monovalent ions. That is the reason why the product water obtained by the pressure driven membrane processes is generally not suitable for agricultural irrigation directly. Furthermore, the product water obtained by NF and RO membranes could be hazardous to the soil in terms of the MH value when they are employed directly for irrigation purpose. The MH values of both NF and RO permeates were found as higher than 50%. The MH value should be lower than 50% for it to be appropriate for agricultural irrigation as mentioned by Szaboles and Darab [36]. The product water obtained by using both NF and RO membranes was found to be not suitable with respect to the PI value as well. Irrigation water should have a PI value of 25–75% for it to be suitable for irrigation purposes as mentioned by Dinka and Tadesse [37] while the irrigation water with PI value of less than 25% is considered not suitable for agricultural purpose. Therefore, the product water of NF and RO membranes must by tailored to fit specification for the irrigation water standards.

There are numerous options for tailoring the irrigation water produced by the pressure driven processes for maximum agricultural output which includes;

i. adding CO_2 or lime for pH adjustment of the treated wastewater [45],
ii. injecting missing elements into the treated wastewater by utilizing dolomite mineral as Mg^{2+} and Ca^{2+} ions source in water,
iii. using the NF concentrate stream after appropriate treatment as a supplier of divalent ions [46],
iv. blending the product water obtained by the NF or RO membranes with water sources that contained those missing elements such as well water or seawater for re-mineralization [47].

Blending the produced water of NF and RO membranes with well water was considered to be a good option for re-mineralizing the produced water. The characteristics of well water employed for remineralization of NF and RO permeates are given in Table 6. As can be seen, boron concentration in well water was negligible while the arsenic concentration was also below the maximum allowable limit for drinking water (<10 μg/L). Therefore, blending the permeate water of NF and RO membranes with well water at a certain ratio will be suitable to prepare the irrigation water with respect to tomato plants in the future.

Theoretical blending of the product water obtained from NF and RO membranes with well water was calculated first prior to tomato irrigation. The agricultural group's recommendations and the irrigation water standards were taken into consideration for the determination of theoretical irrigation water quality. Generally, boron and arsenic concentrations, SAR value together with EC are among the major factors considered for the determination of the theoretical blending of NF and RO permeates with well water.

Figs. 2 and 3 show the theoretical mixtures of NF and RO permeates with well water versus EC values. The red line in Figs. 2 and 3 represent the mixture of NF or RO permeate with well water. The top axis is the percentage of well water mixed with NF or RO permeate and varies from 0 to 100% (from left to right). Above grey line is the quality III category, between grey and blue line is the quality II category while below blue line represent quality I category. When only NF or RO product water is considered, that is 0% of well water in the product water, the water quality clearly falls into quality III region according to the EC vs SAR plot. Keeping in mind that, quality II water was targeted for the mixture of NF or RO permeate and well water. Average water quality values for the theoretical mixture are shown in Table 7. Table 8 shows the measured and average recommended water quality values to be used for the irrigation of tomatoes at the farmer field of the geothermal heating center.

Figs. 2 and 3 show also the SAR values with respect to EC from the calculations of theoretical blending. Based on these plots, it is clearly seen that 45% of well water as minimum amount must be blended with the NF permeate in terms of infiltration problems (SAR value). Because water infiltration occurs when irrigation water has a high sodium content in comparison to calcium and magnesium concentrations [38]. Excessive salt build-up in the soil causes a phenomenon called sodicity. It causes soil clays to swell, disperse, crusting and pore blockage in agricultural soils [48]. Hence, sodicity reduces the downward passage of water into and through the soil. Consequently, actively growing plant roots may not receive enough water, despite water accumulating on the soil surface following watering. On the other hand, 28% of well water as minimum amount must be blended with the RO permeate to eliminate the risk of soil infiltration. An optimum 50% of well water mixed with 50% of the NF permeate was selected for irrigation water with high boron content while 60% of well water blended with 40% of the RO permeate was chosen as the optimum mixture for irrigation water with low boron content. It was clearly seen that the water quality of both NF

Table 6
The characteristics of well water.

Parameter	Value
pH	7.16
Conductivity (mS/cm)	1.769
TDS (mg/L)	1366
Cl^- (mg/L)	276
SO_4^{2-} (mg/L)	180
F^- (mg/L)	ND
Na^+ (mg/L)	105
K^+ (mg/L)	2.0
Mg^{2+} (mg/L)	42
Ca^{2+} (mg/L)	212
B (mg/L)	0.21
Si (mg/L)	12
SiO_2 (mg/L)	ND
As (μg/L)	<10

ND: Not determined.

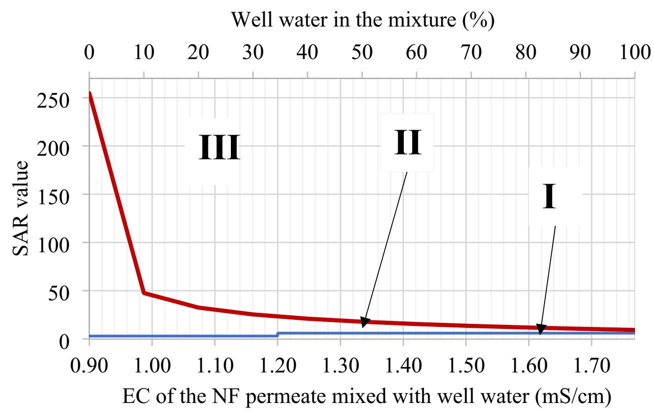


Fig. 2. SAR vs EC plot for NF permeate.

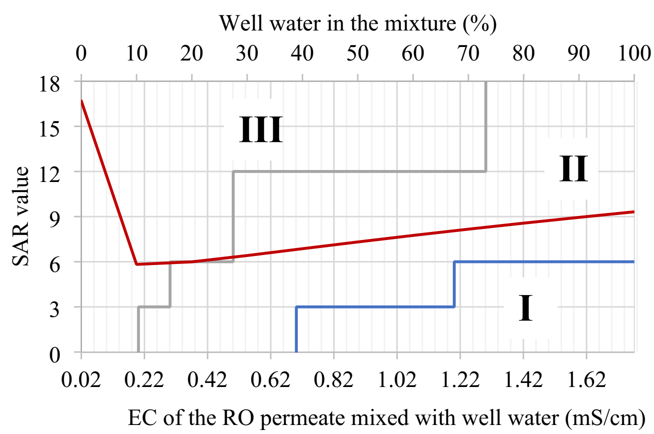


Fig. 3. SAR vs EC plot for RO permeate.

Table 7
Evaluation of NF and RO permeates blended with well water theoretically for agricultural irrigation.

Parameter	Unit	NF permeate (mixed with 50% well water)	RO permeate (mixed with 60% well water)
Salinity			
EC	mS/cm	1.313*	0.722*
TDS	mg/L	893.0*	553.0*
Permeability			
SAR		17.9**	6.9**
Specific ion toxicity			
Na^+	mg/L	142.5*	49.1*
Cl^-	mg/L	202.5*	110.4*
Boron	mg/L	4.5***	3.4***
Other parameters			
pH	–	7.0*	6.0*
Arsenic	μg/L	11.5***	<10*
SO_4^{2-}	mg/L	91.3^{ns}	72.5^{ns}
F^-	mg/L	1.2^{ns}	0.05^{ns}
Ca^{2+}	mg/L	106.3 ^{ns}	85.1 ^{ns}
Mg^{2+}	mg/L	21.3 ^{ns}	17.1 ^{ns}
SiO_2	mg/L	46.9^{ns}	2.1^{ns}
MH	%	24.77 ^{ns}	24.86 ^{ns}
PI	%	86 ^{ns}	89 ^{ns}

*Quality I, **Quality II, ***Quality III, ^{ns}No standard.

and RO permeates blended with well water at the selected mixing ratios fell into the quality II category (in terms of SAR value). The blended water quality falls into the quality I category with respect to pH, EC, TDS, concentrations of Na^+ and Cl^- ions.

Another important issue to be considered when evaluating irrigation water quality is the negative impact of high magnesium concentration on soil permeability. High magnesium concentration tends to make the soil more alkaline, particularly in saline-rich or sodic conditions, which could lead to a loss in agricultural yield [44]. Waters having an estimated MH of >50% are considered inappropriate for agricultural irrigation and this will result in lower crop yields as explained by Szabolcs and Darab [37]. Therefore, the irrigation water having MH ≤50% is considered to be suitable and will surely increase the farm product output. The MH values of the NF and RO permeates blended with well water were found to be 24.77 and 24.86%, respectively. Indicating that this water will not cause any MH problem if they are employed for irrigation purpose. The product waters blended with well water was found to be appropriate for agricultural purposes in terms of PI values also. The PI values of NF (50%) and RO (40%) permeates blended with well water were found to be 86 and 89%, respectively.

Table 8 shows the measured quality analysis of the NF and RO permeates blended at the optimum mixing ratio (50 and 40% for NF and RO permeates, respectively) with well water to be used for tomato irrigation in the future. The results showed clearly that the irrigation water to be used for tomato plants complied with the irrigation water standards. The product water was found to be in the quality II category with respect to SAR versus EC plot. Apart from boron (quality III), all other parameters fall under the quality I category according to irrigation water standards. Though the product water of both NF and RO membranes was found to be in quality III category with respect to boron concentration (meaning not suitable for irrigation), the threshold level of boron to be applied for growing tomatoes in the future irrigation tests is 6 mg/L. According to Regis et al. [49], tomato plant can tolerate up to 6 mg/L of boron in irrigation water. Therefore, the NF and RO permeates blended with well water will be utilized for the irrigation of tomatoes in the future. These mixtures were found to be suitable for irrigation purposes in terms of MH with a value of 25.9 and 16.0% for the mixtures of NF permeate-well water and RO permeate-well water, respectively as well. They were also suitable in terms of PI with a value of 95 and 66% for NF and RO permeates mixed with well water, respectively.

3.2. *Economic analysis of membrane processes for production of irrigation water from the spent geothermal water*

Various public and private institutions are tasked with developing efficient, reliable water and wastewater treatment methods. Wastewater treatment processes have been studied from a technological, economic, social, and environmental stand points by researchers [50,51]. It was also argued that the price of the product water should reflect on its scarcity value in the local area [52].

In this study, an economic analysis of the NF/RO membrane separation process for production of the agricultural irrigation water for tomato plant from the spent geothermal water was carried out. The life span of the project was designed as 15 years. The recommendations of the membrane producer were considered for membrane replacement and its maintenance time. The cost of power was taken as the commercial electricity cost in Izmir city, which is 0.13$/kWh after taxes (in 2021). The monthly operator income is equivalent to 447.23$ after taxes, which was Turkey's subsistence wage as of February–June 2021. The average permeate flow rates of NF and RO membranes were 44.80 and 20.40 m^3/day, respectively, while pump efficiency (for both low and high pressure pumps) was taken as 85%. The electric consumption of low and high-pressure pumps was considered when calculating the power consumption of the NF and RO membranes, carbon, sand and cartridge filters. The costs of membranes were taken into consideration for calculation of the fixed cost (Table 9). The monthly wage of the operator, periodic maintenance cost, membrane cleaning cost, and cost of antiscalant were taken into consideration for calculation of the operational cost. Table 9 shows all parameters taken into consideration

Table 8
Average characteristics of NF/RO permeates blended with well water and the recommended quality of irrigation water for tomato plant.

		EC (ms/cm)	TDS (mg/L)	Boron (mg/L)	pH	Na^{+} (mg/L)	Mg^{2+} (mg/L)	Ca^{2+} (mg/L)	F^{-} (mg/L)	Cl^{-} (mg/L)	SAR	Arsenic (μg/L)	SO_4^{2-} (mg/L)
Mixture of the RO permeate (40%) and the well water (60%)		1.069	528	3.0	6.8	53.2	20.4	106.8	0.3	154.8	4.9	<10	4.9
Mixture of the NF permeate (50%) and the well water (50%)		1.333	704	5.6	7.0	148.3	22.0	62.8	4.1	169.0	16.3		16.3
Well water		1.790	900	0.2	6.8	101.9	7.7	51.1	7.0	199	7.0		7.0
Irrigation water to be used for growing tomato plant	With high boron content	0.9–1.5	NS	4–6	>6	NS	NS	NS	NS	NS	NS		NS
	With low boron content		NS	2–4		NS	NS	NS	NS	NS	NS		NS
Water qualities of NF and RO permeates blended with well water[a]	III	I	I	III	I	I	NS	NS	NS	NS	II	I	NS

NS: Not specified.
[a] Water qualities of NF (50%) permeate and well water (50%) along with RO permeate (40%) and well water (60%) mixtures were evaluated according to agricultural irrigation water standards.

Table 9
Parameters used for techno-economic calculations.

Parameter	NF	RO
	Values	
Plant capacity (m^3/day)	44.8	20.2
Membrane area of module (m^2)	37.4	37.0
Module length (m)	1	
Number of modules per pressure vessel	1	
Energy cost ($/kWh)	0.13	
Membrane cost ($)	690	513
Operation time (h/year)	6000	
High pressure power consumption (kW)	5.5	
Low pressure power consumption (kW)	2.2	
Catridge filter cost ($/unit)	8.6	
Carbon filter cost ($/unit)	935.7	
Sand filter cost ($/unit)	792.5	
Pump efficiency (η_{pump}) [45]	0.85	

during techno-economic calculations while Table 10 shows the cost distribution of the NF and RO membrane processes to produce the irrigation water for tomato plants. The total cost of water production using the NF membrane was found to be 0.76 $/m^3$ while that of the RO process was found to be 1.56 $/m^3$. Studies with higher flow rates will have the lowest cost because the cost calculation findings were reported as per unit volume of the product water. Due to this fact, the cost of the RO process was found to be higher than that of the NF process. Because the permeate flux of the NF membrane was 60.23 $Lm^{-2}h^{-1}$ while that of the RO membrane was calculated as 27.35 $Lm^{-2}h^{-1}$. Nevertheless, the process costs of NF and RO processes will surely decrease when the plant capacity is increased. The product water produced from the RO membrane has a better quality compared with that of the NF membrane. Therefore, some compromise must be done between quality of the product water and the process cost. Costa and Pinho [53] reported the cost of water production using an NF membrane as 0.26 $/m^3$ while Greenlee et al. [54] informed as 0.62 $/m^3$ as the cost of the RO membrane for brackish water treatment.

Table 10
Unit costs for NF and RO processes.

	Unit	NF	RO
Sand filter	$/ m^3	0.041	0.091
Carbon filter		0.051	0.112
Monthly service		0.031	0.068
Cartridge filters		0.057	0.126
Antiscalant cost		0.058	0.058
Membrane cost		0.013	0.021
Utility cost (tanks, pumps etc.)		0.132	0.292
Operator salary		0.013	0.029
Power consumption cost		0.36 (48%)	0.76 (49%)
Total fixed cost		0.29 (38%)	0.64 (41%)
Total operational cost		0.10 (14%)	0.16 (10%)
Total		0.76	1.56

The costs of the NF and RO processes found in this study are higher than the findings in the literature. Actually, the plant capacity plays a vital role in the final cost of the produced water. It was mentioned in the study conducted by Loutatidou et al. [55] and Pan et al. [56] that the desalination plants can be categorized into i) large-scale with an average capacity of >20,000 m^3 per day, ii) medium-scale (average capacity of 5000–20,000 m^3 per day), iii) small-scale (average capacity of <500 m^3 per day). The cost of product water is inversely proportional to the plant capacity, meaning as the plant capacity increases the cost of product water decreases. The cost of the water produced by the NF process was found to be 0.42–0.53 $/m^3$ when the plant capacity was 3780 m^3day^{-1} and 0.11–0.14 $/m^3$ for a plant capacity of 56,700 m^3/day [57]. It is also good to keep in mind that as the TDS value of the water to be treated increases, the cost of the whole process will increase as well [58]. The cost of water production was found as 0.29–0.63$/m^3$ for a plant capacity of 4500–104,000 m^3/day [58] and 0.26–0.54 $/m^3$ for 40,000–46,000 m^3/day plant capacity [59] for RO membrane while 0.26 $/m^3$ for NF membrane [52]. Regis et al. [49] found the cost of fresh water from river to be 0.88 and 1.06 $/m^3$ for brackish water RO and NF membranes, respectively. Bhojwani et al. [60] reported the cost of water production by using the brackish water RO membrane as 0.712 $/m^3$ when the plant capacity was 3785 m^3/day. Price of the product water was found in the range of 5.66–12.98 $/m^3$ [57] and 12.99 $/m^3$ [61] for small plants operating at a capacity of <20 m^3/day.

Based on the findings in this research, it was found that power consumption takes the highest share with 48 and 49% for NF and RO processes, respectively. Fixed and operational costs were found to be 38 and 14% for the NF process while 42 and 10% for the RO process, respectively as shown in Figs. 4 and 5. Power consumption can be reduced by improving the energy management of both the NF and RO systems during the desalination process. To make the RO process cost-effective, energy should be collected from the high-pressure brine [62]. Energy recovery devices, for example pelton wheel, energy recovery booster pump (ERBP), turbo charger, and others can be used to recover the energy in the brine and re-direct it to increase the feed pressure to the membrane system [63]. As reported by Timur et al. [64], energy was recovered from the existing concentrate stream and circulated back to the feed side during seawater desalination in Bodrum,

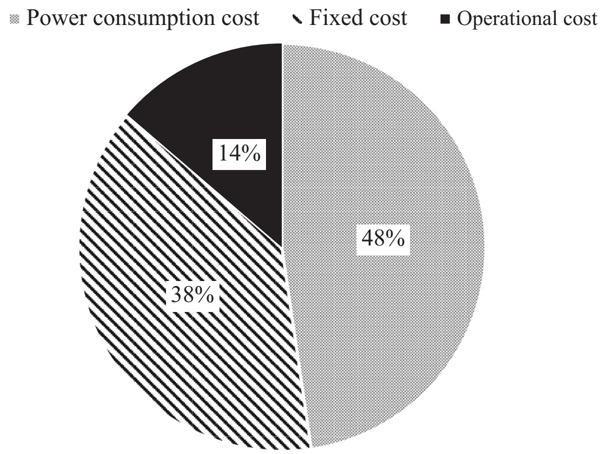


Fig. 4. Cost distribution of treatment of the spent geothermal water by NF process.

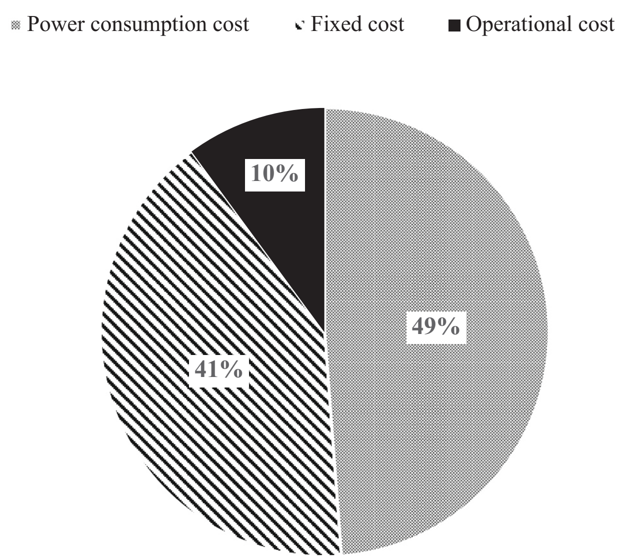


Fig. 5. Cost distribution of treatment of the spent geothermal water by RO process.

Turkey. The ERBP ERI PX model was employed in their study, where the RO system capacity was 100 m^3/day. According to their findings, energy and cost comparison between a system that consist of energy recovery system and the one without energy recovery demonstrated a 54% of reduction in power consumption as well as the cost of the water produced [64]. The cost of product water was also found to be 0.57 $/$m^3$ when the ERBP system was incorporated with RO systems, while the cost of the product water was about 0.43 $/$m^3$ when the turbine systems were incorporated with the RO system [64].

4. Conclusions

With the goal of producing irrigation water for tomato plant, successful treatment of the spent geothermal water was conducted utilizing the pressure-driven membranes in a pilot-scale system. According to the results obtained from this study, it was clearly seen that the direct application of the produced water from the pressure-driven membrane processes is not appropriate for both irrigation of the tomato plants and the soil stability. Hence, a post-treatment or polishing step must be added to the pressure-driven membrane process. An optimum of 50 and 60% of well water could be blended with the NF and RO permeates, respectively to re-mineralize the product water as well as to decrease the boron concentrations in the produced water. The results of the quality analysis of the product water used for irrigating tomato plants agreed well with the theoretical calculations. After blending the permeates of NF and RO membranes with well water, apart from boron concentration all other irrigation water quality results complied with the irrigation standards (EC, SAR, TDS, pH, arsenic and specific ion toxicity). Nevertheless, the produced water in this study can be utilized for crops including alfalfa, sugar beet and sorghum cabbage, oats, bluegrass turnip, bluegrass, barley, cowpea, and cauliflower. From the economical point of view, it is clearly seen that the pressure driven membrane processes can be utilized for reclamation of the spent geothermal water for agricultural irrigation purposes. Although the costs of the product water treated with the pressure driven membranes (with NF 0.56 $/$m^3$ and with RO 1.56 $/$m^3$) were a bit high, the cost will surely decrease when considered these processes in a full scale application.

Novelty statement

In this manuscript, assessment of nanofiltration and reverse osmosis membranes for treatment spent geothermal water in order to produce agricultural irrigation water for tomato plants was investigated for the first time using a pilot membrane treatment system installed in the geothermal heating center. An economical analysis for such treatment was also performed.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgement

A research grant from TUBITAK was used to provide financial assistance and scholarships to students working on this research project under the TÜBITAK-NCBR international research project (Project No: 118Y490-POLTUR3/Geo4Food/4/2019). We acknowledge TUBITAK for financing this project. The Presidency for Turks Abroad and Related Communities (YTB) awarded Y.A. Jarma for a PhD fellowship. We would like to express our gratitude to the Izmir Geothermal Energy Co. for allowing us to install our pilot system at the geothermal heating center. We also thank K. Bostancı for his assistance with several of the ICP-OES instrumental analyses.

References

[1] World Bank Group-Water in agriculture https://www.worldbank.org/en/topic/water-in-agriculture (2021) (accessed August 12, 2021).
[2] P. Steduto, B. Schultz, O. Unver, S. Ota, D. Vallee, S. Kulkarni, M.D.-J. Garcia, Food security by optimal use of water: synthesis of the 6th and 7th world water forums and developments since then, Irrig. Drain. 67 (2018) 327–344.
[3] http://www.fao.org/wsfs/forum2050/wsfs-background-documents/hlef-issues-briefs/en/, 2009.
[4] B. Rahimi, M. Afzali, F. Farhadi, A.A. Alamolhoda, Reverse osmosis desalination for irrigation in a pistachio orchard, Desalination 516 (2021), 115236.
[5] U. Caldera, C. Breyer, Assessing the potential for renewable energy powered desalination for the global irrigation sector, Sci. Total Environ. 694 (2019), 133598.
[6] N. Su, Y. Chang, Analysis of Beijing accommodation service based on gaode POIJ, Green Sci. Technol. (2019) 165–169, https://doi.org/10.16663/j.cnki.lskj.2019.06.062 (in Chinese with English abstract).
[7] J.E. Ayars, R.A. Schoneman, F. Dale, B. Meso, P. Shouse, Managing subsurface drip irrigation in the presence of shallow ground water, Agric. Water Manag. 47 (2001) 243–264.
[8] J.G. Pérez-Pérez, J.M. Robles, F. García-Sánchez, P. Botía, Comparison of deficit and saline irrigation strategies to confront water restriction in lemon trees grown in semi-arid regions, Agric. Water Manag. 164 (2016) 46–57.

[9] M. Cheng, H. Wang, J. Fan, X. Wang, X. Sun, L. Yang, S. Zhang, Y. Xiang, F. Zhang, Cropyield and water productivity under salty water irrigation: a global meta-analysis, Agric. Water Manag. 256 (2021), 107105.
[10] G.S. Baath, M.K. Shukla, P. Bosland, S.J. Walker, R.K. Shaw, R. Shaw, Wateruse and yield responses of Chile pepper cultivars irrigated with brackish groundwater and reverse osmosis concentrate, Horticulturae 6 (2020) 1–12.
[11] S. Singh, K. Grover, S.H. Begna, S. Angadi, M.K. Shukla, R. Steiner, D. Auld, Physiological response of diverse origins pring safflower genotypes to salinity, J. Arid Land Study 24 (2014) 169–174.
[12] EPAUS, Public Review Draft National Water Program Strategy: Response to Climate Change, Office of Water, 2008.
[13] J. Macknick, R. Newmark, G. Heath, K.C. Hallett, in: A Review of Operational Water Consumption and Withdrawal Factors for Electricity Generating Technologies, National Renewable Energy Laboratory, 2011, pp. 275–300.
[14] A.Y. Goren, H.E. Okten, Energy production from treatment of industrial wastewater and boron removal in aqueous solutions using microbial desalination cell, Chemosphere 285 (2021), 131370.
[15] Y. Tang, L. Luo, Z. Thong, T.S. Chung, Recent advances in membrane materials and technologies for boron removal, J. Membr. Sci. 541 (2017) 434–446.
[16] Q. Ramos, M.A. Armienta, A. Aguayo, O. Cruz, Evaluation of the interactions of arsenic (As), boron (B), and lead (Pb) from geothermal production wells with agricultural soils, Ecotoxicol. Environ. Saf. 211 (2021), 111843.
[17] N. Esim, D. Tiriaki, O. Karadagoglu, Toxiceffects of boron on growth and antioxidant system parameters of maize (Zeamays L.) roots, Toxicol. Ind. Health 29 (2013) 800–805.
[18] E.K. Mroczek, D. Graham, L. Bacon, Removal of arsenic and silica from geothermal fluid by electrocoagulation, J. Environ. Chem. Eng. 7 (2019), 103232.
[19] Y. Cao, Q. Guo, Y. Zhuang, Z. Yu, W. Guo, C. Zhang, M. Zhu, Q. Zhao, T. Ren, Removal of harmful constituents from geothermal water by selected anion clays, 15th Water-Rock Interaction International Symposium, WRI-15, Procedia Earth Planet. Sci. 17 (2017) 161–164.
[20] K. Sasaki, Y. Hayashi, K. Toshiyuki, B. Guo, Simultaneous immobilization of borate, arsenate, and silicate from geothermal water derived from mining activity by co-precipitation with hydroxyapatite, Chemosphere 207 (2018) 139–146.
[21] A. Ruiz-García, F.A. Leon, A. Ramos-Martín, Different boron rejection behavior in two RO membranes installed in the same full-scale SWRO desalination plant, Desalination 449 (2019) 131–138.
[22] S. Samatya, A. Tuncel, N. Kabay, Boron removal from RO permeate of geothermal water by monodisperse poly (vinylbenzyl chloride-co-divinylbenzene) beads containing N-methyl-D-glucamine, Desalination 364 (2015) 75–81.
[23] E. Kir, B. Gurler, A. Gulec, Boron removal from aqueous solution by using plasma-modified and unmodified anion-exchange membranes, Desalination 267 (2011) 114–117.
[24] A. Siekierka, B. Tomaszewska, M. Bryjak, Lithium capturing from geothermal water by hybrid capacitive deionization, Desalination 436 (2018) 8–14.
[25] E. Çermikli, F. Şen, E. Altıok, J. Wolska, P. Cyganowski, N. Kabay, M. Bryjak, M. Arda, M. Yüksel, Performances of novel chelating ion exchange resins for boron and arsenic removal from saline geothermal water using adsorption-membrane filtration hybrid process, Desalination 491 (2020), 114504.
[26] X. Zhu, Y. Liu, F. Du, J. Han, G. Hao, L. Li, Q. Ma, Geothermal direct contact membrane distillation system for purifying brackish water, Desalination 500 (2021), 114887.
[27] B. Ozbey-Unal, E. Gezmis-Yavuz, B. Eryildiz, Y. Derya, K. Imer, B. Keskinler, I. Koyuncu, Boron removal from geothermal water by nanofiber-based membrane distillation membranes with significantly improved surface hydrophobicity, J. Environ. Chem. Eng. 8 (2020), 104113.
[28] B. Tomaszewska, J. Bundschuh, L. Pająk, M. Dendys, V.D. Quezada, M. Bodzek, M. A. Armienta, M.O. Muñoz, A. Kasztelewicz, Use of low-enthalpy and waste geothermal energy sources to solve arsenic problems in freshwater production in selected regions of Latin America using a process membrane distillation–research into model solutions, Sci. Total Environ. 714 (2020), 136853.
[29] M. Tagliabue, A.P. Reverberi, R. Bagatin, Boron removal from water: needs, challenges and perspectives, J. Clean. Prod. 77 (2014) 56–64.
[30] Y.A. Jarma, A. Karaoglu, O. Tekin, A. Baba, H.E. Okten, B. Tomaszewska, K. Bostancı, M. Arda, N. Kabay, Assessment of different nanofiltration and reverse osmosis membranes for simultaneous removal of arsenic and boron from spent geothermal water, J. Hazard. Mater. 405 (2021), 124129.
[31] Y.A. Jarma, A. Karaoglu, O. Tekin, I.A. Senan, A. Baba, N. Kabay, The use of integrated pressure-driven membrane separation processes for the production of agricultural irrigation water from spent geothermal water-mini-pilot tests at geothermal heating center, Desalination 523 (2022), 115428.
[32] B. Jung, C.Y. Kim, S. Jiao, U. Rao, A.V. Dudchenko, J. Tester, D. Jassby, Enhancing boron rejection on electrically conducting reverse osmosis membranes through local electrochemical pH modification, Desalination 476 (2020), 114212.
[33] D.V. Gonçalves, M.A.G. Paiva, J.C.A. Oliveira, M. Bastos-Neto, S.M.P. Lucena, Prediction of the mo, nocomponent adsorption of H2S and mixtures with CO2 and CH4 on activated carbons, Colloids Surf. A Physicochem. Eng. Asp. 559 (2018) 342–350.
[34] S. Chen, Y. Guo, Y. Zhang, Y. Guo, X. Liang, CuFe2O4/activated carbon adsorbents enhance H2S adsorption and catalytic oxidation from humidified air at room temperature, Chem. Eng. J. 431 (2022), 134097.
[35] H. Moradi, H. Azizpour, H. Bahmanyar, M. Mohammadi, Molecular dynamics simulation of H2S adsorption behavior on the surface of activated carbon, Inorg. Chem. Commun. 118 (2020), 108048.
[36] I. Szabolcs, C. Darab, The influence of irrigation water of high sodium carbonate content of soils, in: Proceedings of 8th International Congress of ISSS, Transmission 2, 1964, pp. 803–812.
[37] M.O. Dinka, Quality composition and irrigation suitability of various surface water and ground water sources at Matahara Plain, Water Resour. 43 (2016) 677–689.
[38] M.O. Dinka, K.B. Tadesse, Suitability of shallow groundwater for irrigation: the case of the Wonji Shoasugare state (Ethiopia), Irrig. Drain. 68 (2019) 857–866.
[39] Lenntech: water treatment and purification https://www.lenntech.com/products/membrane/toray.htm (Accessed 23, June, 2021).
[40] Lenntech, water treatment and purification, https://www.lenntech.com/Data-sheets/CSM-NE8040-70-L.pdf/ (Accessed 23, June 2021).
[41] M. Qadir, S. Schubert, J.D. Oster, G. Sposito, P.S. Minhas, S.A.M. Cheraghi, G. Murtaza, A. Mirzabaev, M. Saqib, High-magnesium waters and soils: emerging environmental and food security constraints, Sci. Total Environ. 642 (2018) 1108–1117.
[42] P. Xu, J.E. Drewes, D. Heil, Beneficial use of co-produced water through membrane treatment: technical-economic assessment, Desalination 225 (2008) 139–155.
[43] N.J. Falizi, M.C. Hacıfazlıoğlu, I. Parlar, N. Kabay, T.O. Pek, M. Yüksel, Evaluation of MBR treated industrial wastewater quality before and after desalination by NF and RO processes for agricultural reuse, journal of waterProcess. Eng. 22 (2018) 103–108.
[44] Technical Procedure Declaration for Wastewater Treatment Plants, in: Ministry of Environment and Urbanization, Republic of Turkey, 2010, pp. 91–93.
[45] A.J. Karabelas, C.P. Koutsou, M. Kostoglou, D.C. Sioutopoulos, Analysis of specific energy consumption in reverse osmosis desalination processes, Desalination 431 (2018) 15–21.
[46] D. Hasson, L. Fine, A.ABraham Sagiv, R. Semiat, H. Shemer, Modeling remineralization of desalinated water by micronized calcite dissolution, Environmental Science and Technology 51 (2017) 12481–12488.
[47] L. Birnhack, O. Lahav, Chapter 8- post-treatment of desalinated water chemistry, design, engineering, and implementation, in: Sustainable Desalination Handbook, 2018, pp. 305–350.
[48] S.C.N. Tang, L. Birnhack, P. Nativ, O. Lahav, Highly-selective separation of divalent ions from seawater and seawater RO retentate, Sep. Purif. Technol. 175 (2017) 460–468.
[49] A.O. Regis, J. Vanneste, S. Acker, G. Martínez, J. Ticona, V. García, F.D. Alejo, J. Zea, R. Krahenbuhl, G. Vanzin, J.O. Sharp, Pressure-driven membrane processes for boron and arsenic removal: pH and synergistic effects, Desalination 522 (2022), 115441.
[50] M. Anim-Gyampo, G.K. Anornu, E.K. Appiah-Adjei, S.K. Agodzo, Quality and health risk assessment of shallow ground water aquifers with in the a tank widi basin of Ghana, Groundw. Sustain. Dev. 9 (2019), 100217.
[51] J. Xie, A. Liebenthal, J.J. Warford, J.A. Dixon, M. Wang, S. Gao, S. Wang, Y. Jiang, Z. Ma, Addressing China's Water Scarcity: Recommendations for Selected Water Resource Management Issues, The World Washington, DC, 2009.
[52] M. Ilyas, F.M. Kassa, M.R. Darun, Life cycle cost analysis of wastewater treatment: a systematic review of literature, J. Clean. Prod. 310 (2021), 127549.
[53] A.R. Costa, M.N.d. Pinho, Performance and cost estimation of nanofiltration for surface water treatment in drinking water production, Desalination 196 (2006) 55–65.
[54] L.F. Greenlee, D.F. Lawler, B.D. Freeman, B. Marrot, P. Moulin, Reverse osmosis desalination: water sources, technology, and today's challenges, Water Res. 43 (2009) 2317–2348.
[55] S. Loutatidou, B. Chalermthai, P.R. Marpu, H.A. Arafat, Capital cost estimation of RO plants: GCC countries versus southern Europe, Desalination 347 (2014) (2014) 103–111.
[56] S.-Y. Pan, A.Z. Haddad, A. Kumar, S.-W. Wang, Brackish water desalination using reverse osmosis and capacitive deionization at the water-energy nexus, Water Res. 183 (2020), 116064.
[57] R. Clayton, Desalination for Water Supply, Foundation for Water Research, Bucks, 2011.
[58] I.C. Karagiannis, P.G. Soldatos, Water desalination cost literature: review and assessment, Desalination 223 (2008) 448–456.
[59] I.S. Jaber, M.R. Ahmed, Technical and economic evaluation of brackish groundwater desalination by reverse osmosis (RO) process, Desalination 165 (2004) 209–213.
[60] S. Bhojwani, K. Topolski, R. Mukherjee, D. Sengupta, M.M. El-Halwagi, Technology review and data analysis for cost assessment of water treatment systems, Sci. Total Environ. 651 (2019) 2749–2761.
[61] A. Al-Karaghouli, L.L. Kazmerski, Energy consumption and water production cost of conventional and renewable-energy-powered desalination processes, Renew. Sust. Energ. Rev. 24 (2013) 343–356.
[62] K.A. Plappally, H. John, V. Lienhard, Costs for water supply, treatment, end-use and reclamation, Desalin. Water Treat. 51 (2013) 200–232.
[63] L. Malaeb, G.M. Ayoub, Reverse osmosis technology for water treatment: state of the art review, Desalination 267 (2011) 1–8.
[64] R.S. Timur, G. Demir, A. Coban, A. Corum, T. Bozbura, Decreasing water resources and a comprehensive approach to seawater reverse osmosis (SWRO): case study–cost analysis of a sample SWRO system, Desalin. Water Treat. 26 (2011) 145–151.