



Arsenic removal from drinking water by reverse osmosis: Minimization of costs and energy consumption



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ABSTRACT

Arsenic is one of the most serious inorganic contaminants in drinking water on a worldwide scale. To comply with the MCL (maximum contaminant level, 10 µg/l arsenic in drinking water) established by the World Health Organization, numerous techniques have been studied, such as ion exchange, coagulation and flocculation, precipitation, adsorption and membrane technologies. Among the available technologies applicable to water treatment, membrane filtration has been identified as a promising technology to remove arsenic from water.

The goal of this study is to demonstrate the technical and economic viability of removing arsenic (V) using an optimized reverse osmosis process, with minimization of the total cost as the objective of the optimization strategy. The optimization results showed that the total costs of a two-stage membrane cascade used for the removal of arsenic (V) from drinking water for a population of 20,000 inhabitants were 1041 \$/d and 0.52 \$/m³ of drinking water produced. Energy consumption was the most relevant cost, corresponding to 35% of the total cost. Sensitivity analysis was performed to determine the total costs of the installation for different scenarios in terms of drinking water production: (i) 0.44–0.56 \$/m³ for electricity prices of 0.05–0.10 \$/KW h; (ii) 0.88–0.45 \$/m³ for populations ranging from 5000 to 50,000 inhabitants; and (iii) 0.52–0.61 \$/m³ when the membrane lifetime was reduced from 3 to 1.5 years. The multiobjective optimization solutions, which consider the best compromises among the quality and cost objectives, indicated that the concentration of As (V) in the permeate water can be reduced to 0.5 µg/l at a feasible cost.

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1. Introduction

Arsenic, which typically exists in natural waters in oxidation states of As(III) and As (V), is currently recognized as one of the most serious inorganic contaminants in drinking water on a worldwide scale. A long-term intake of arsenic causes serious chronic symptoms; therefore, the World Health Organization (WHO) has established a maximum contaminant level (MCL) of 10 µg/l [18].

Arsenic is released from a variety of natural and anthropogenic sources. Arsenic occurs naturally in over 200 different mineral forms, of which approximately 60% are arsenates, 20% are sulphides and sulphosalts, and the remaining 20% includes arsenides, arsenites, oxides, silicates and elemental arsenic [7]. The primary anthropogenic sources of arsenic compounds are the mining industry, the pharmaceutical sector, enterprises producing glass and ceramics, pesticides, herbicides, dyes, woodworking enterprises,

oil refineries and the metal smelting and melted alloy industries [10].

Note that for humans, exposure to arsenic through food or drink is more important than through the skin; the latter can be considered non-existent. The symptoms of arsenic poisoning caused by the consumption of drinking water are typically revealed over a period of 5–20 years, and certain consequences of arsenic exposure are irreversible [10]. The only solution to arsenic poisoning is to stop drinking the contaminated water. Diseases related to arsenic contamination are broad, ranging from a dry throat to cancer of the skin, lungs, urinary bladder, liver and kidney [5]. Therefore, arsenic is classified as a Group 1 carcinogenic substance to humans.

Currently, to comply with the maximum contaminant level, numerous techniques have been studied, such as ion exchange, coagulation and flocculation, precipitation, adsorption and membrane technologies [5]. Among the available technologies applicable to water treatment, membrane filtration has been identified as a promising technology to remove arsenic from water [15]. In addition, this technology can eliminate other types of ions or molecules. Membrane separation is addressed as a pressure-driven process, and

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Nomenclature

$A_{(i)}$	membrane area of the i stage (m^2)	OC_{en}	energy costs ($\$/d$)
AC	capital costs attributable to analysis ($\$/d$)	OC_{lab}	labour costs ($\$/d$)
CC	capital costs ($\$/d$)	OC_m	maintenance costs ($\$/d$)
CC_{inst}	capital costs attributable to installation ($\$/d$)	OC_{pt}	pretreatment costs ($\$/d$)
CC_{memb}	capital costs attributable to membranes ($\$/d$)	P	permeate flow of the final stage (m^3/d)
C_F	concentration of arsenic in the feed stream (ppb)	$P(i)$	permeate flow of the i stage (m^3/d)
C_P	concentration of arsenic in the permeate stream (ppb)	R	rejection coefficient
$C_{F(i)}$	concentration of arsenic in the i feed stream (ppb)	$R_{(i)}^{As}$	rejection coefficient of arsenic in the i stage
$C_{P(i)}$	concentration of arsenic in the i permeate stream (ppb)	$R(i)$	retentate flow of the i stage (m^3/d)
$C_{R(i)}$	concentration of the arsenic in the i retentate stream (ppb)	$Rec_{(i)}$	recovery rate of the i stage
$(C_s)_{ln}$	logarithmic average solute concentration across the membrane (mol/m^3), defined by $\Delta C_s / \Delta(\ln C_s)$	SF	safety factor
C_{WHO}	maximum allowed concentration of arsenic by the World Health Organization (ppb)	TC	total costs ($\$/d$)
F	initial feed flow (m^3/d)	Y_{elec}	electricity price ($\$/kW h$)
$F(i)$	feed flow of the i stage (m^3/d)	Y_{lab}	salary ($\$/h$)
J_V	permeate flux (m/s)	Y_{memb}	price of reverse osmosis membranes ($\$/m^2$)
$J_{V(i)}$	permeate flux of the i stage (m/d)		
J_s	flux of the solute due to the gradient of chemical potential ($mol/m^2 s$)	<i>Greek symbols</i>	
K_{memb}	ratio of the membrane capital costs to total capital costs	ΔP	pressure difference across the membrane (bar)
L_p	hydraulic permeability coefficient ($m/s bar$)	$\Delta P_{(i)}$	pressure difference across the membrane in the i stage (bar)
LT_{memb}	membrane lifetime (d)	$\Delta \Pi$	osmotic pressure difference across the membrane (bar)
LT_{inst}	installation lifetime (d)	η	pump efficiency
OC	operation costs ($\$/d$)	σ	reflection coefficient
		ω	coefficient of solute permeability (m/s)
		ω'	modified coefficient of solute permeability (m/s)

it is classified into four categories: microfiltration (MF), ultrafiltration (UF), nanofiltration (NF) and reverse osmosis (RO) [17]. Among these categories, the applications of the latter two have proven to be reliable in removing arsenic from water [16].

In recent years, substantial research efforts have been conducted to identify arsenic removal technologies that can be applied in rural areas. Membrane technologies are considered the best option for application in point-of-use filters or household filters to evaluate the arsenic levels in drinking water to ensure that they meet the MCL in rural areas or in certain arsenic-contaminated areas. Oh et al. [11] developed the concept of passing the fluid through RO and NF membranes using a bicycle pumping system, which is ideal for rural areas without electricity.

Different commercial membranes for nanofiltration and reverse osmosis systems have been reported in the literature, and the following studies are noted:

- Fang et al. [6] evaluated the removal of arsenate using nanofiltration with DK and DL (GE Osmonics) membranes.
- Chang et al. [4] employed a nanofiltration membrane (Desal HL for General Electric Co.) and a low-pressure reverse osmosis membrane (Desal AK for General Electric Co.).
- Akin et al. [3] studied the removal of arsenic using a reverse osmosis technique with SWHR and BW-30 (Filmtec DOW) membranes.
- Uddin et al. [15] investigated the removal of arsenic from drinking water by the nanofiltration membranes NF-90 and NF-200 (Filmtec Dow).
- Saitúa et al. [12] studied arsenic removal from synthetic waters and surface water using the nanofiltration membrane 192-NF300 (Osmonics).
- Kosutic et al. [9] investigated the removal of arsenic and pesticides from natural groundwater by nanofiltration membranes NF270 and NFc (Filmtec DOW) and a reverse osmosis membrane CPA2 (Hydranautics); and

- Oh et al. [11] tested the membrane HR3155 (Toyobo) for reverse osmosis and the membranes ES-10 (Nitro Denko) and HS5110 (Toyobo) for nanofiltration.

The effects of pH and arsenic concentration in the feed water, as well as the ionic strength and operating pressure on the rejection of arsenate and arsenite, were examined in these studies. Certain points to highlight include the following: (i) high pressure, high pH and low temperature favoured a more efficient removal of arsenic, whereas an increase in ionic strength reduced the removal of arsenate; (ii) the removal of arsenate is more complete than the removal of arsenite because at the pH that is typically used, arsenate exists in an anionic form, whereas arsenite is present in a neutral molecular form in aqueous solution, which complicates its rejection; and (iii) for the nanofiltration process, pre-oxidation of arsenite to arsenate can be required to obtain drinking water because the removal of arsenic is low, whereas better results were obtained with the reverse osmosis process, in which the pre-oxidation step was not required.

The use of an oxidizing agent, such as chlorine, was indicated for the improvement of the arsenic removal rate when arsenic in the source water is primarily present as As(III). However, oxidation is not a simple method to improve the efficiency because the oxidant could damage the membrane. Certain microorganisms can transform the arsenic oxidation state without the addition of an oxidant, providing a possible method to improve the efficiency of arsenite removal by combining membrane processes and biooxidation [13].

Considering that the referenced literature does not address the optimization of the membrane system for arsenic removal, the goal of this study is to use the process system engineering approach for the removal of arsenic (V) in aqueous solution by reverse osmosis to design and optimize the operation of this system under specific conditions. Experimental data for arsenic rejection and water permeate flux were obtained for a set of selected membranes to calculate the transport parameters. The transport equations

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