



Water treatment in a new flux-enhancing, continuous forward osmosis design: Transport modelling and economic evaluation towards scale up



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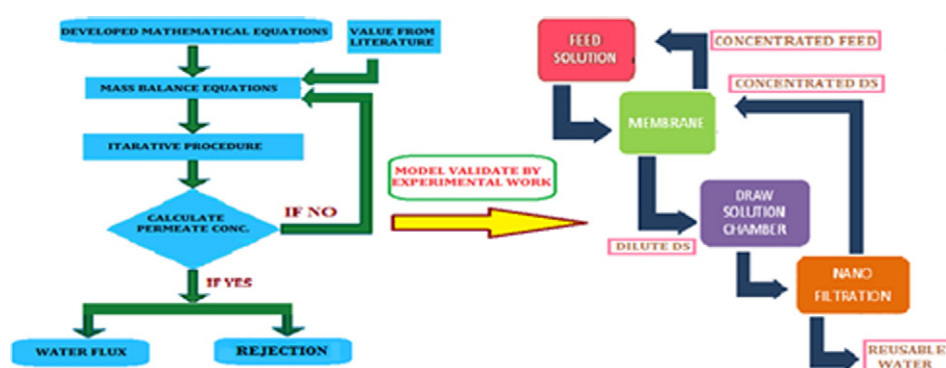
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HIGHLIGHTS

- A novel forward osmosis–nanofiltration system developed for purification of water
- The new system characterized by sustained high flux and high degree of separation
- Dynamic modelling and economic evaluation paves the way for scale-up.
- The developed model successfully predicted system performance.

GRAPHICAL ABSTRACT



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ABSTRACT

A forward osmosis–nanofiltration integrated system was designed for experimental investigation and mathematical modelling for purification of contaminated water in steady state and continuous mode. Unlike the conventional module of a FO scheme, this new design provided different hydrodynamic regimes that very significantly reduced concentration polarization. Dynamic modelling encompassing the effects of pressure, cross flow rate, draw solution, run time and overall hydrodynamics on the efficiency of separation as well as yield of pure water flux was done to capture the most significant transport phenomena during forward osmosis and nanofiltration. The system applied in purification of arsenic-contaminated water produced encouraging results in terms of 99% purification of water at reasonably high flux of 58–60 L/(m²·h) (LMH). Recovery of draw solute could be done efficiently at the rate of 60 LMH in a steady state continuous operation. The developed model successfully predicted system performance as reflected in the high values of the overall correlation coefficient ($R^2 > 0.98$), Willmott d-index (> 0.95) and low relative error (< 0.1). Economic evaluation indicated that such FO–NF system in the proposed new configuration could be quite promising in purifying arsenic-contaminated groundwater at a low cost of \$ 1.57 m⁻³.

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1. Introduction

In the backdrop of ever-increasing demand for safe potable water, contamination of groundwater by leached out arsenic, fluoride, iron and chromium in several parts across the world has thrown a challenge

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to the scientific community in finding efficient, low cost treatment systems for removal of such contaminants from water. Over the decades, extensive research has established adsorption, ion-exchange, chemical coagulation–precipitation, pressure-driven membrane separation, membrane distillation and photo-catalytic oxidation as the broad technology options [1–7] for water purification. However, till this day, 1.2 billion people across the world do not have access to safe drinking water. Search is still continuing for simple, low cost and easy to implement technologies for producing safe drinking water in the vast arsenic-affected areas of the world. In this context, forward osmosis (FO) assumes significance as a potential water purification system. This system of water purification has been studied [8–14] in treatment of seawater/brackish water, wastewater, and in liquid food processing. FO has progressed substantially towards establishing itself as a viable technology of water purification though the major hurdle of low flux persists. However, studies on arsenic or fluoride removal by FO remain scanty, though in several parts of the world from South-West USA to Taiwan, Vietnam, China, Thailand, Bangladesh, Nepal and India this problem of groundwater contamination by leached out arsenic is quite widespread [15]. In the limited studies on synthetic solution [16,17], reported pure water flux is extremely low ($5\text{--}15 \text{ Lm}^{-2} \text{ h}^{-1}$) and all the different forms of arsenic that are normally present in contaminated groundwater have not been investigated. For example, Butler et al. [18] reported 88.3% rejection of only As(V) from a model solution

while Jin et al. [16] achieved only 60% rejection of As(III). Moreover, studies on a total scheme of FO representing a continuous and steady state operation for removal of target contaminant and for efficient recovery and recycle of the draw solute are quite scanty. High concentration polarization (external as well as internal), back diffusion of solute and low flux stand in the way of effective use of conventional FO system [19–22]. FO has mostly been investigated in flat sheet or tubular modules [23–25] where major problem of tubular module is fouling. Studies on a total scheme that includes upstream removal of target contaminant along with downstream recovery of draw solute in a continuous steady state operation have hardly been reported. Modelling of such a system also needs to be done along with economic evaluation to raise scale up confidence in the backdrop of extremely limited implementation of membrane-based technology in arsenic-affected areas.

This study adopts a novel approach in addressing these issues in the context purification of arsenic-contaminated water. The proposed system is expected to be applicable to other water purification cases also. This study for the first time investigates a complete scheme consisting of an upstream arsenic separation loop by forward osmosis and a downstream nanofiltration loop for recovery and recycle of draw solute. To our knowledge, no modelling, simulation and economic feasibility study have been reported on such a scheme despite its potential of offering largely fouling-free operation in a very simple module and at a relatively low price.

2. Model development of the hybrid (FO–NF) system

In pressure retarded forward osmosis, the principal solute flux is an assortment of two transport mechanisms namely, diffusion and convection. In addition to this, dilutive and concentrative external concentration polarization (ECP) is always encountered although here as these are relatively small in magnitude and predominantly reversible in nature.

2.1. Model assumptions

- i. Ratio of osmotic pressures of the feed side and draw solution side is same as the ratio of bulk solution concentration to the active membrane surface concentration during forward osmosis.
- ii. In the hydrodynamic conditions maintained during forward osmosis, back diffusion of feed solute from the membrane interface to the bulk feed solution is negligible.
- iii. Change of osmotic pressure ($\Delta\pi$) may be assumed to be negligible compared to applied pressure during nanofiltration because of low level of concentration of arsenic in groundwater.
- iv. The effective membrane charge density (X_{mc}) is controlled by concentration and pH of the solution and persists uniformly throughout the membrane. This is justified in view of small membrane surface involved in the separation process under uniform hydrodynamic conditions.

2.2. Transport model of arsenic separation by forward osmosis process

Based on the assumptions, transport of arsenic ions from the feed side to the draw solution side may be described as [26]:

$$J_{As} = (F_p \times \Delta\Pi_{eff}) + [(1 - \sigma_r) J_{exp} C_{eff}] \quad (1)$$

where, J_{As} and F_p are the solute flux and permeability of the feed solute through the membrane respectively and σ_r is the reflection coefficient which characterizes the degree of solute passage allowed by the membrane. With an assumed value of permeate concentration, permeability of feed solute may be calculated by the following equation:

$$F_p = J_{exp} \left(\frac{C_{FB} - C_{p,As}}{C_{p,As}} \right) e^{\left(-\frac{J_{exp}}{K} \right)} \quad (2)$$

where J_{exp} is the experimental water flux as defined by the following equation:

$$J_{exp} = A_w \times \Delta P_{eff} \quad (3)$$

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