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Research Proposal

On

Assessing Solar-Powered FO-RO Hybrid Systems for Sustainable Drinking Water in Bangladesh

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Introduction

Bangladesh faces acute drinking water stress due to coastal salinity intrusion, depleting groundwater resources and industrial effluents that cause serious environmental pollution [1]; this compromises its traditional drinking water sources. Conventional reverse osmosis (RO) plants have been deployed in coastal districts but remain resource-intensive, with high operational expenditure (OPEX) and environmentally unsustainable due to high brine discharge. However, when integrated with Forward Osmosis (FO) powered by solar energy, a new system can emerge, enhancing water recovery, reducing energy usage and fouling. Previous techno-economic studies indicate that FO-RO hybrids can lower operating costs by 56% compared to standalone seawater RO, despite slightly higher capital costs [2]. Prior research has been conducted on solar-powered RO systems [3], but little research has been carried out on their FO-RO hybrid counterparts. Existing studies primarily focus on seawater desalination in high-income or pilot-scale contexts, with limited evaluation of the hybrids for drinking water in the context of a developing country with such complex geomorphology as Bangladesh. Moreover, few studies focus on assessing the encompassing facets of implementing a water filtration system in an environmentally, technologically, and economically sustainable manner - this is the gap that the research aims to fill. This study will combine laboratory-scale experiments with synthetic brine solutions and system modelling, including capital expenditures (CAPEX) and operating and maintenance (OPEX) analysis. Furthermore, a primary data survey on household water demand and ability and willingness to pay will help to contextualise the monetary practicality. An environmental assessment based on energy use and brine discharge will evaluate the role of solar power in reducing its impacts. These methods will aim to assess whether solar-powered FO-RO hybrids can offer a more sustainable and cost-effective alternative to the current grid-powered reverse osmosis system for safe drinking water in Bangladesh.

Research Questions:

1. *How does a solar-powered FO–RO hybrid system perform in terms of water flux, salt rejection, and fouling resistance compared to conventional grid-powered RO under synthetic saline water conditions relevant to Bangladesh?*
2. *To what extent does integrating solar power with FO–RO reduce specific energy consumption, lifecycle carbon emissions, and brine discharge compared to grid-powered RO systems?*
3. *What is the levelized cost of water (LCOW) for solar-powered FO–RO hybrids compared to grid-powered RO, and how do household willingness-to-pay levels in Bangladesh align with this cost?*

Literature Review

1. *Technical Performance of FO–RO vs Conventional RO*

Reverse osmosis (RO) accounts for the majority of desalination plants worldwide but it is constrained by high operating pressures, brine discharge and membrane fouling which increases with higher local salinity [4]. Forward-osmosis (FO) causes lower fouling potential and has reduced energy requirements as it is a spontaneous process, using osmotic gradient rather than hydraulic pressure [5]. Studies which have implemented the hybrid system have demonstrated much lower energy requirements, due to improved double dense membrane barrier protection as well Water flux increased by up to 10 times in comparison with the stand-alone RO membranes at high osmotic pressure [6].

2. *Energy Intensity & Environmental Sustainability*

Conventional seawater RO desalination plants consume between C3 and 4 kWh/m3 and emit between 1.4 and 1.8 kg CO_2 per cubic meter of produced water depending on feedwater salinity and recovery rate [7]. Brackish water desalination requires less energy, typically in the range of 0.5–2.5 kWh/m3 , making it more applicable in areas affected by salinity intrusion such as Bangladesh [8]. In prior studies, FO-RO hybridization had reduced the specific energy consumption (SEC) of the RO process to 1.5 kWh/m3 and almost doubled the increased final product volume [9]. Pilot-scale trials further reported that chemical cleaning became ineffectual as physical cleaning proved to be sufficient [6]. From an environmental perspective, desalination contributes significantly to greenhouse gas emission when powered by fossil fuel grids and pose risks from brine disposal due to lower water recovery. Solar-driven desalination has been shown to cut carbon emissions, yet FO-RO systems powered by the largest renewable energy source globally, is vastly unexplored [10]

3. *Economic Feasibility of Solar-Powered FO–RO*

The economic viability of desalination depends on both capital expenditure (CAPEX) and operating expenditure (OPEX), with energy costs being the dominant factor.Conventional RO systems typically involve high OPEX due to pressure and electricity requirements, whereas the hybrid systems can manage the costs between higher CAPEX , but lower OPEX , which over the lifetime of the plant saves constant expenditure on upkeep [5],[6] . Long-term costs can further be reduced when coupled with renewable energy, an example of a study which showed that hybrid desalination powered by solar energy could achieve lower levelised costs of water, comparable to fossil-fuel powered systems under volatile energy markets [11]. However, there is scarce evidence on FO-RO cost modelling in developing countries, and ability and willingness-to- pay assessments seem to be nonexistent.

4. *Gaps in Current Research*

While FO-RO systems have been studied for their technical and economic potential, the literature remains fragmented and context-specific. Most work is concentrated on seawater applications or pilot studies in developed countries which leaves limited evidence for resource constrained countries like Bangladesh. Comprehensive studies that combine technical performance with economic feasibility are rare, and studies considering local affordability coupled with environmental factors are almost absent. Therefore, research on solar-powered FO-RO hybrids for drinking water provision in Bangladesh is still lacking.

Methodology

This study adopts a mixed methods approach, combining laboratory experiments, financial modelling, environmental life cycle assessment, and household surveys to evaluate the feasibility of a solar powered FO-RO hybrid system in Bangladesh.

Technical Performance

A small scale FO–RO hybrid system will be constructed using commercially available FO and RO membranes, determined by lowest fouling rate. Then a synthetic saline solution will be prepared at salinities of 2,000, 5,000, and 7,000 mg/L NaCl and other ions to represent the range of brackish water conditions found in coastal Bangladesh. Water flux (L/m²·h), salt rejection (%), and fouling rate (measured as percentage decline in flux over time) will be recorded using conductivity meters, turbidity analyzers, and pressure sensors. All the data will be logged digitally, and flux decline curves will be analyzed in MATLAB and Microsoft Excel. Differences in technical performance between solar-powered FO–RO and grid-powered RO will be tested for significance using independent-samples t-tests and two-way ANOVA at a 95% confidence level ($\alpha = 0.05$).

Energy and Environmental Assessment

Energy consumption will be measured as specific energy consumption (SEC, kWh/m³ of product water). For solar integration, system design can be modelled using HOMER Pro, using varying solar irradiance values for different parts of Bangladesh, PV panel efficiency and storage capacity. For comparison, values for a conventional grid-powered RO will be used as a benchmark. Environmental performance to calculate carbon emissions (kg CO_2/m^3) and brine discharge volumes (% of feedwater) will be done through programs like OpenLCA and applying the ReCiPe midpoint method. The results will be shown through scatter diagrams comparing solar FO-RO and grid-powered RO.

Economic Feasibility

Using programs such as Excel and Python to calculate the Levelised Cost of Water (LCOW, USD/m³) under different scenarios. A table comparing CAPEX inputs (membranes, pumps, PV modules, batteries) and OPEX inputs (maintenance, replacement, electricity cost) will be made from collected vendor quotes and published data. A sensitivity analysis will be conducted that varies the PV module prices by ±20% and membrane lifespans by ±2 years to test the total range of its abilities. Statistical regression models in R will be used to evaluate the relationship between LCOW, system size, and energy source.

Household Survey and Qualitative Contextualization

A structured household survey (N= 500-600 respondents) will be conducted in saline-prone coastal districts (e.g., Satkhira, Khulna, Barguna) to assess household water demand, willingness-to-pay, and perceptions of solar-powered water systems.

Timeline

The proposed research will be completed over a period of eight months. The first month will focus on finalising the research design and methodology as well as procuring the necessary materials. Months two through three will be devoted to laboratory experiments on the FO-RO hybrid system, followed by the techno-economic and environmental modelling in month four. In month five, household surveys will be conducted in saline-prone districts to assess the most critical regions with water stress and determine water demand and willingness-to-pay. Month six will integrate and validate findings from the laboratory, modelling and survey work. The final two months, (Months 6-8) will be dedicated to drafting, analysis and preparation of figures for the final research paper.

Conclusion

Bangladesh's drinking water crisis will only be exacerbated as climate change worsens, thus it demands solutions that can balance technical efficiency, affordability, and environmental responsibility. Conventional stand-alone systems like RO may be effective, but still remain energy intensive and environmentally unsustainable. This proposal introduces a solar-powered FO-RO desalination system as an alternative– designed to reduce energy consumption, minimize fouling and brine discharge, and lower long-term costs. By carrying out all these evaluations, the study will generate a holistic evaluation of the system's feasibility for Bangladesh, starting with its most vulnerable areas. The outcomes are expected to demonstrate that the hybrids can deliver safe and affordable drinking water by reducing greenhouse gas emissions and ultimately providing a flexible solution for all the climate-vulnerable regions of Bangladesh.

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