AI Framework on Reverse Osmosis Water Treatment for Maintenance Responses

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***Abstract*—Water scarcity is a growing global challenge, exacerbated by rapid industrialization, population growth, and climate change. Reverse osmosis (RO) has emerged as a key desalination technology to meet the increasing demand for freshwater. However, operational inefficiencies, such as membrane fouling and high maintenance costs, limit its widespread adoption. This research proposes an AI-driven framework to enhance the performance and maintenance of RO membranes. Literature review demonstrates the intial frame work design. Also, it concludes that using hybrid models such as particle swarm optimization (PSO) with artificial neural networks (ANNs) outperformed the use of single model.**

***Keywords—Framework, AI, RO, …etal** (key words)*

I. INTRODUCTION

Reverse osmosis (RO) is one of the promising techniques for water treatment and wastewater reuse. Membrane fouling is the major challenge that limits the adoption of RO applications due to the difficult control of its performance. With advancements in computation and big data, AI become an essential tool that contributes in solving the challenges and obstacles in various fields of science and engineering. Machine learning is also a subfield of computer science and developed from the study of pattern recognition. Therefore, both AI and ML algorithms have been used for the monitoring and management of membrane fouling. .

I.I. Background

Due to arid climate in the UAE, the UAE faces the shortage in drinking water. Therefore, the UAE built some of the largest desalination plants not only in GCC but also in the world to meet water demand. These plants convert seawater to drinking water. The UAE strategy focused on using Renewable energy sources such as solar power plants and reduce operational cost. The energy consumed by these plants in the stage to be shifted to sustainable energy sources (solar Power photovoltaic) (Black Ridge Research and Consulting, 2024).

Project Name	Location	Capacity
Jebel Ali Desalination Plant	Dubai	490 MIGD/day
Al Taweelah Desalination Plant	Abu Dhabi	200 MIGD/day
Umm Al Quwain Desalination Plant	Abu Dhabi	150 MIGD/day
Fujairah F1 Desalination Plant	Fujairah	71 MIGD/day
AL Layyah Desalination Plant	Sharjah	51 MIGD/day

Table 1: Top Five RO desalination plants in the UAE.

A. Reverse Osmosis and Configuration

In RO, the feed water is pre-treated, then a high pressure pump as shown in Figure 1c is used to flow the water through the permeable membrane separating salts from water. The pressure, the amount of salt in the input water, and the membrane' salt permeation constant all affect the quality of the water that is generated (Gul, Hruza, & Yalcinkaya, 2021).
The standard RO element configuration (spiral-wound type) is depicted in Figure 1a. One side of the RO element receives the pressurized feed water, which then flows through the feed-side gap between the RO membranes. Concentrate (brine) is released from the opposite side of the RO element, while the permeate water is collected via a middle pipe. As seen in Figure 1b, six to eight RO elements are typically mounted in series within a pressure vessel. The fundamental layout of a seawater desalination plant is one pass and one stage; numerous pressure vessels are placed in parallel according to the facility's capacity (Takabatake,Taniguchi, & Kurihara, 2021).

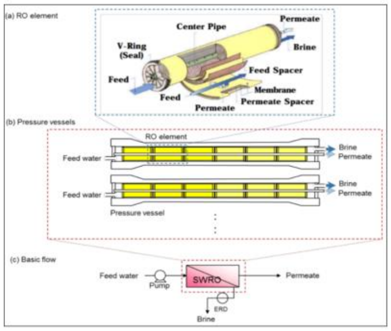

Figure 1: The basic configuration of the RO process. (**a**) Typical configuration of the RO element (spiral-wound type), (**b**) configuration of pressure vessels containing the RO elements, and (**c**) basic flow of single pass and single stage system.

B. Mechanisms of membrane fouling (Cake Formation & Pore Blocking

If the foul-ants (colloids) are smaller than the membrane pores (i.e., solutes), pore blockage and adsorption take place in the interior pore surfaces. On the other hand, a cake layer will typically form on the membrane's surface if the foul-ants (colloids and sludge flocs) are significantly bigger than the membrane holes. Actually, while cake layer can add another layer of resistance to permeation flow, pore blockage enhances the membrane resistance (Ladewig, & Al Shaeli, 2017).

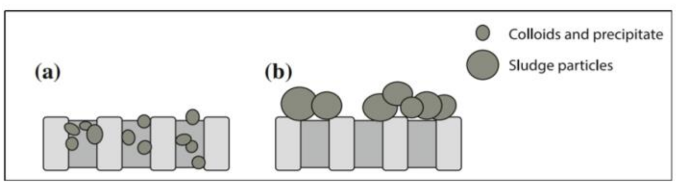

Figure 2: Membrane fouling process via; (a) Pore blocking; (b) Cake layer formation.

I.II. Motivation

Water scarcity is a major challenge that faced people on this planet and the global demand for freshwater has been increasing by just under 1% per year (Adda et al, 2022, UN-Water, 2024). Along with that, rapid industrialization, and climate change have placed more pressure on world to work more on insuring the existence of enough fresh water for sustaining human life. Along with that, rapid industrialization, and climate change have placed more pressure on world to work more on insuring the existence of enough fresh water for sustaining human life. Over the past half century, several advancements have emerged in the field of water desalination and wastewater treatment. Multistage flash (MSF) distillation, multi-effect evaporation (MEE) distillation, vapour compression (VC) and reverse osmosis (RO) are convenient membrane technologies used to meet the massive demand for freshwater (Al Aani et al, 2019).

I.III. Problem Statement

Ineffective membrane separation produce low quality water which has several consequences because of the adsorption of unwanted species in the feed water on membrane surface. These species affect membranes' performance in the separation process and produced low quality water that doesn't comply with regulatory standards and requires more additional treatment to make it potable and valid for drinking or other usage. Otherwise the permeate may contain harmful contaminants that pose serious health risk. Also, performing additional treatment to desalinate water will increase the cost because of high consumption of energy which is costly. In addition, customers will use potable water which is costly too till validation of freshwater that in compliance to water quality standards set by regulator based on the use of water.

Repeating unscheduled adhoc maintenance which will increase the cost of operations and need additional time to ensure quality of water, is becoming unbearable. Although periodic maintenance contributes to reduce the fouling issue in RO membranes, more control is required because feed water quality has a large impact on membrane fouling and affect membrane performance. Therefore, predictable membrane maintenance is required which depend on the type and severity of the fouling layer. The predictive maintenance allow performing maintenance work just in time before a failure occurs and shut down the plant. Therefore, predictive maintenance will help in extending the life time of membrane, reducing the downtime of the plant, improve safety, and enhance operational efficiency.

The operating cost of Reverse Osmosis (RO) is a significant barrier to its widespread adoption and popularization. Membrane maintenance and replacement contribute to the annual operating cost since membrane is prone to fouling of several types such as bio-fouling, inorganic, colloidal and organic. Membrane cost depends on the plant capacity and varies between $500 to $1000 per module, which have production rates of 50-100 m3 /d (Hasan, 2019).

IV. Research Objectives

The aim of this research is to propose an AI framework for controlling the effective performance of RO membrane.
The main objectives of this study are;

A. To investigate existing frameworks for effective water treatment

Finding the existing frameworks for water treatment will help in designing the proposed frame work for monitoring the performance of RO membrane. Also, investigating these frameworks will highlight the important information included within these frameworks and a comparison may be conducted (similarities and difference) to strengthen the proposed framework with valuable similarities and differences .

B. To investigate existing AI technologies can be used for effective control of RO membrane

Literature review provides the researcher a broad idea about what type of AI predicting models used and more than that. Also, input and output predictable features found in previous work with the hyper-parameters such as number of layers, number of neurons in each layer, activation function ..et al in case of using Artificial Neural Networks (ANNs) (Abuwatfa et al, 2023).

C. To propose an AI framework for controlling the effective performance of RO membrane

Several framework for water treatment plant can used to extract the proposed framework for the effective performance of RO membrane.

I. V. Research Questions

The research questions are;

A. What type of data can help in determining fouling issues in RO membrane?

B. Which AI tools (using AI technological devices and algorithms) can help in detecting the degree of fouling issue with RO membrane?

C. Which AI tools can be used for predicting the maintenance of RO membrane?

I. VI. Research Gap

This literature review revealed that the most successful employed methods for predicting the fouling is the hybrid methods consists of either ANN and ML or optimization methods such as PSO-ANN (Mahadeva et al, 2021). This is consistent with the review paper written by Bagheri et al, 2019. Furthermore, this review explores the need to more comprehensive AI frameworks in water treatment and waster reuse sector. It is appeared that not enough framework discussed in this review due to lack in references for the related topic. There are some review papers that includes information but not a framework with AI.

I. VII. Paper Structure

The paper comprises of the introduction which includes background, motivation, problem statement, research objectives, research questions, research gap, expected problem solution and literature review. The following sections will be Research ethics and methadology, results and discussion, conclusion and future work.

I. VIII. Literature review

The literature review is conducted to investigate the existing frameworks for effective water treatment and existing AI tools used for effective control of membrane fouling in RO.

A. Comparative analysis

In Table 2, flowchart in figure 2 and approach in figure 3 (Bagheri et al, 2019) emphasize the use of hybrid methods of Artificial intelligence models and optimization techniques in monitoringand controlling the RO membranes. On the other hand, a supervised learning algorithm (Random Forest) is used in framework in figure 4 (Niu et al, 2023). Therefore, the flow

Flow chart/frameworks

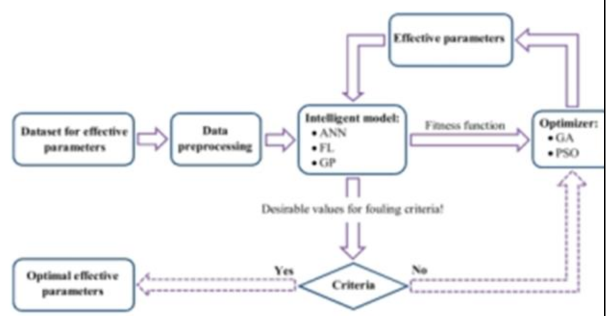

Figure 2: The typical flow chart for the optimization for the effective parameters for membrane mitigation (Bagheri et al, 2019).

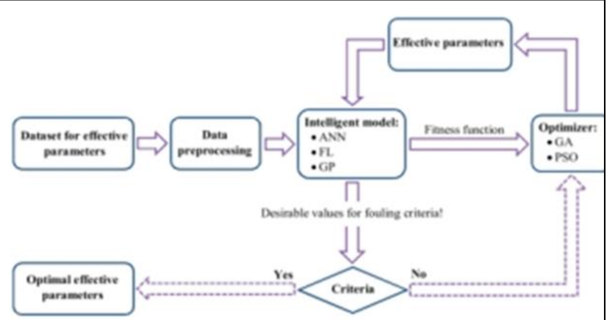

Figure 3: Proposed approach for the advanced control of membrane fouling using artificial intelligence and machine learning technologies (Bagheri et al, 2019).

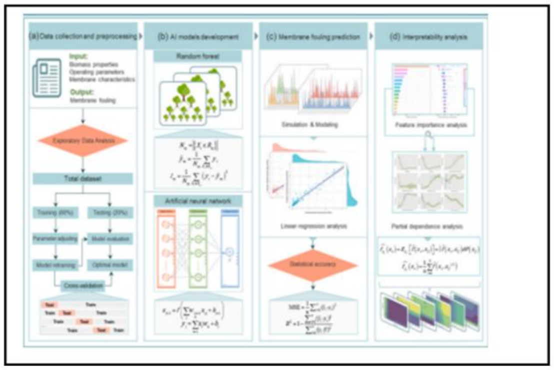

Figure 4: Schematic of AI based membrane fouling modeling framework (Niu et al, 2023).

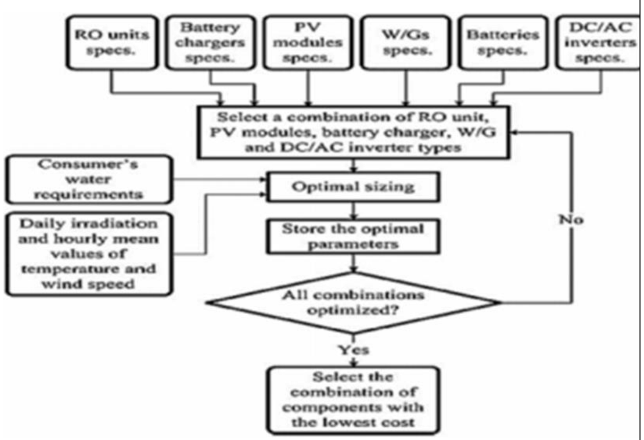

Figure 5: The proposed Optimization methadology (AlAani et al, 2019).

Table 2: Frameworks and flow charts from literature review which can contribute in the initial framework design step in methodology.

charts and frame works in figure 2, 3, and 4 promote the use of hybrid methods of AI and ML. Although, flowchart in figure 2 and 3 have the same process steps for analysis such as data prepossessing and intelligent models used, there are some differences in the used models for predicting membrane fouling. In addition, flow chart in figure 2 mentioned the optimization methods using genetic algorithm (GA) which is also used in figure 5 (Al Aani et al, 2019) to reduce the annual operating cost. On the other hand, approach in figure 3 provides bigger view than figure 2 because it includes the data mining step, feature selection, image recognition, and cluster analysis techniques such as K-means.

Moreover, flow chart in figure 2 shows that artificial neural network (ANN), genetic programming (GP), and fuzzy logic (FL) algorithms with optimization tools such as genetic algorithm (GA) or particle swarm optimization (PSO) are effective in predicting the membrane fouling. In contrast, approach in figure 3 revealed that by the combination of more than one simulation or AI models, severity of membrane fouling can be predicted because it contains image recognition so historical data can be stored for future usage and analysis/simulation.

Approach in figure 5 illustrates the process of optimizing the lowest cost for hybrid technology of RO with sustainable energy sources. In this approach the GA was used to implement and optimize a desalination plant's power supply system that uses sustainble sources of energy. For example, Manesh et al. used GA to do a whole site study and perform an exergoeconomic optimization in order to acquire the best integrated design of the site utility steam network with the hybrid desalination plant which is Multi-effect Distillation-Reverse Osmosis (MED-RO) desalination unit. This improvement's goal was to reduce overall expenses and raise the hybrid system's gain output ratio. In order to establish the global optimum for the Multi-Objective Optimization (MOO) problem, GA determined the Pareto set. With a gain output ratio of 9.1 and an increase in desalinated water production to 126,300 m3/d at a cost of $0.81/m3, the outcome showed the advantages of GA (Manesh et al, 2013).

Regarding the method, although fuzzy algorithm shows good performance in predicting the membrane fouling (Moumni et al, 2022; Galizia et al, 2021), the hybrid model of PSO_ANN outperformed it optimizing sea water reverse osmosis (SWRO) plant performance, reducing costs, and improving efficiency (Mahadeva et al, 2021). In addition, the hybrid models outperforms the single model. As a single model, the ANN out performed the Multi-linear regression model (MLR) in predicting permeate conducttivity, permeate flow rate, and recovery with R^2 of 0.969, 0.942, 0.963 respectively while the Multi Linear Regression (MLR) shows low accuracy where R^2 is around 0.6 (Adda et al, 2022).

In terms of input parameters, the literature review revealed that either all of feed pressure, feed temperature, feed flow rate, feed TDS, feed electrical conductivity or some of them are used as input parameter to AI model while one or two of the permeate flow rate, permeat flux, and recovery rate are the most used as output or predicted variable (Roehl et al, 2018; Adda et al, 2022; Moumni et al, 2022; Mahadeva et al, 2021; Galizia et al, 2021).

I. IX. Expected Problem Solution

A. Fouling types & Mitigation

Fouling can be classified as reversible or irreversible. The concentration polarization of materials at the membrane rejection surface or the cake layer cause reversible fouling, which includes both backwashable and non-backwashable fouling. While non-backwashable reversible fouling can only be eliminated by chemical cleaning, membranes with backwashable reversible fouling can be restored using the proper physical washing strategy, such as backwashing or hydrodynamic scouring (surface washing). Chemisorption and pore clogging processes cause irreversible fouling. The transmembrane flow loss in the event of irreversible fouling cannot be recovered chemically or hydrodynamically (Guo, NGO, & Li, 2012).

There are four foulant types which are;

1.Particulates: Either organic or inorganic colloids or particles function as filth that can physically blind the membrane surface, obstruct the pores, or prevent transfer to the surface by forming a cake layer;

2. Organic: dissolved substances and colloids that would adsorb to the membrane, such as proteins, hydrophilic and hydrophobic compounds, and humic and fulvic acids;

3. Inorganic: dissolved substances that have a tendency to precipitate onto the membrane surface as a result of oxidation (such as iron or manganese oxides) or pH change (scaling), such as iron, manganese, and silica. Inorganic foulants may also be present as coagulant/flocculant residues.

4. Microbiological organisms: this category includes bacteria and other microorganisms that can stick to membranes and produce biofouling, or the creation of biofilms, as well as vegetative matter like algae (Guo, NGO, & Li, 2012).

Therefore, AI tools used shall be able to detect each type of fouling and predict the degree of severity of this issue with the RO membrane. May be hybrid tool (AI and optimizer/ML) can be suggested. Furthermore, more than one AI tool can be used to detect the behaviour of fouling on RO membrane. Along with AI tools, sensors will supposed to be installed to collect data about temperature humidity, water quality (Salinity, pH, Feed flow rate, permeate flow rate).In addition, suppose that a high quality camera will be used to take high quality images at high magnification with high resolution on the side of the membranes for observing the deposited layer. All these strategies can help in identifying the severity and types of fouling, and notify the maintenance team about the issue of fouling in case maintenance is required.

II. Proposed Research Ethics and Methodology

A. Research Ethics

- Informed Consent: Individuals shall know what data will be collected or shared, how this data will be used, and who will have access to it. Also, any contribution from individuals is easily withdraw-able. ADSM committee approval for the experts shall be taken before conducting the survey.
- Transparency: Clearly show the purpose of data collection or sharing and make individuals know the purpose of providing their data. Any hidden practices must be avoided.
- Accuracy: ensure that data is accurate and up to date.
- Privacy and Security: apply secure techniques such as encryption or anonymize data for protecting collected or shared data from unauthorized access,or misuse.

B. Methodology

The research methodology processes is displayed in figure 6.

B.I Problem evaluation

Addressing the issue accurately help in finding the mitigation. Membrane fouling could results in decreasing the permeate flux but this can be occurred because of polarization concentration. In this case operating conditions can be optimized. But the issue is determining the severity of membrane fouling in order to take the proper action by maintenance team/management.

B.II Comparative analysis for existing research

Conducting a comparative analysis for the existing research for both existing frameworks and the existing AI tools for predicting the membrane fouling from the literature review in order to reveal the best ideas and methods from the existing frameworks and AI tools. Finding the proper frameworks where the researcher can extract ideas and proper AI tools for predicting the issue properly. On the other hand, frameworks and AI tools that does not match the topic specifically such as the membrane technology (RO) or not related to predict the issue was excluded.

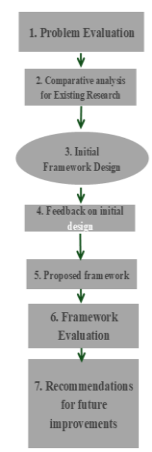

Figure 6: Research Methodology.

B.III Initial Framework Design

After conducting the comparative analysis, the process of collecting and arranging the ideas and tools that best fit the issue for mitigation starts. Developing themes for the framework based on the work and responsibilities. Also, management requirement has taken in consideration in designing the framework.

B.IV Feedback on the Initial Design

The proposed design will be discussed with the supervisor who is the best mentor for this process before sharing the framework with experts. Both qualitative and quantitation data will be collected through conducting a survey for experts in different fields. The google form will be used in collecting the responses. Experts' valuable information can help in improving the understanding of some processes and providing accurate data about technical work.

B.V Proposed Framework

After discuss the experts' feedback and consider it then the framework became the proposed framework.

III. Results & Disccussion

Figure 7 demonstrates the initial framework design after literature review . Also, it shows three themes which are; the Reverse Osmosis AI Driven theme, the data Analysis theme , and the management requirements and their Role . The three themes are connected to each other.

- 1st Theme: The Reverse Osmosis (RO) AI Driven

The RO AI-driven theme demonstrates the components and processes of desalination the occurred on the site. So, the components are camera, sensors, network, and server. These component are necessary to be on the site for taking high resolutions images, collecting water quality data, data sharing with management and analysis themes, and uploading the predictable models' software, respectively. Therefore, any observation such as decline on the permeate flux in the site location that can not be optimized will be shared with analysis team for investigation. As a result of this theme operational and water quality data are recorded. Also, images are recorded in order to check fouling presence on RO membranes. All these types of recorded data shared with the analysis team for further analysis.

- 2nd Them: The Data Analysis theme

The aim of this theme is conducting predictive analysis using artificial intelligence predicting models. This theme may contain junior analyst to analyze the data using the suggested AI models. Data are collected using sensors such as time, water quality parameters of both feed and permeate, Operating conditions in the 1st step. Then, data preprocessed where data mining, feature selection, and cross validation are applied to the dataset (Niu et al, 2023). The suggested AI models could be Artificial Neural Nettworks (ANNs), Genetic Programming (GP), and Fuzzy Logic (FL) for Sttructured data such as water quality and operation data recorded on the site. ALso, Convolutional Neural Networsk (CNNs)used for data recorded as images. The data is preprocessed before implementing AI predictive models (Bagheri et al, 2019). Therefore the results of this analysis is considered as input for the management requirement themes to support taking dicision.

- 3rd Theme: The Management Requirements the**me**

After aligning the entity goals with governmental strategic goals and keep following up the main KPIs related to operation and maintenance such as RO availability KPI where change in the performance of RO plant is reflected on these KPIs, the management team can take proper decision based on the Key performance indicators and analysis themes' results. The senior analyst can use the optimization method such as particle swarm optimization (PSO) or genetic algorithm (GA). If the results match and in the range of good operating conditions otherwise an action to be taken is required. So, a meeting/call is conducted to negotiate the status of the plant and analysis results and take a decision of either chemical cleaning or membrane replacement.

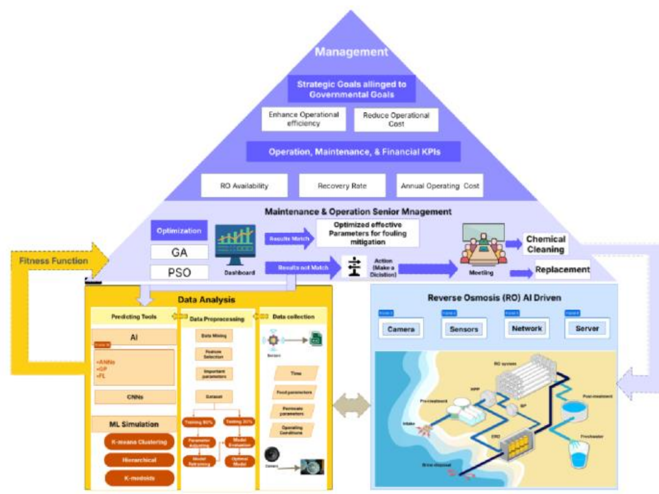

Figure 7: Initial framework design.

IV. Conclusion and Future Work

The literature review conducted in this study highlights the critical role of artificial intelligence (AI) and machine learning (ML) in addressing the challenges associated with membrane fouling in reverse osmosis (RO) systems, particularly in the context of water treatment and desalination. Membrane fouling remains a significant obstacle in the efficient operation of RO systems, leading to reduce permeate quality, increase the operational costs, and the need for frequent maintenance. The review underscores the potential of AI-driven tools and frameworks to predict, monitor, and control membrane fouling, thereby optimizing the performance of RO systems.

The comparative analysis of existing frameworks and AI tools reveals that hybrid models, such as Particle Swarm Optimization-Artificial Neural Networks (PSO-ANN), outperform single models in predicting membrane fouling. These hybrid models leverage the strengths of both optimization techniques and neural networks, providing more accurate predictions and enabling better decision-making for maintenance teams. Additionally, the review identifies the importance of integrating multiple AI models, such as image recognition and cluster analysis, to enhance the predictive capabilities of these frameworks.

This investigation can be completed by conducting a questionnaire for experts and analyzed the collected data to reach to the final results and the proposed framework.

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