International Journal of Basic and Applied Sciences, 14 (SI-1) (2025) 390-395

International Journal of Basic and Applied Sciences

Website: www.sciencepubco.com/index.php/IJBAS
https://doi.org/10.14419/5sqrcd12
Research paper

Decentralized IoT Network for Sustainable Water Desalination Using Bio-Membrane Nanotech

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Received: May 2, 2025, Accepted: May 29, 2025, Published: October 31, 2025

Abstract

An innovative decentralized IoT-based desalination system based on bio-membrane nanotechnology addressing the problem of the global water crisis is conceived in this research. Most conventional desalination techniques are based on centralized, energy-intensive systems, which impede scalability and sustainability. By using biomembranes composed of protein-polymer hybrids designed to mimic aquaporins for increased permeability and improved salt rejection, the proposed system is expected to operate effectively. The eco-friendly bio membranes reduce the environmental impact. Therefore, these IoT-enabled sensors facilitate real-time monitoring of key parameters, such as salinity, pressure, and membrane performance, enabling data-driven optimization of the membrane through machine learning algorithms. The control system utilizes blockchain technology, which facilitates the management of multiple nodes and enables secure, self-directed decision-making. The system also uses renewable energy sources, some of which are integrated into the system, while others form self-healing biopolymer coatings to minimize maintenance costs. Architecture is built on a three-layer model, composed of the perceptual, network, and application layers, to ensure continuous data acquisition and processing, enabling data to inform the decision-making process. The results of the experiments show a tenfold increase in desalination efficiency, accompanied by a reduction in energy consumption of up to 40% and an extension of the membrane's lifetime. In this way, the proposed solution represents a novel, scalable, cheap, and sustainable method of desalination in remote or off-grid regions.

Keywords: *Decentralized IoT-Based Desalination System; Bio-Membrane Nanotechnology; Blockchain-Controlled Water Management; Machine Learning Optimization; Renewable Energy Integration.*

1. Introduction

Water scarcity has become a key issue worldwide, affecting more than two-thirds of the world's population at a rate of 2025 [2]. Therefore, desalination has become a highly recognized solution, while traditional desalination processes, such as reverse osmosis and multistage flash distillation, suffer from inherent drawbacks, including high energy consumption, limited environmental impact, and limitations in scale-up [1] [4]. The proposed study suggests a new solution that eliminates such problems by a hybrid bio-membrane nanotechnology with a decentralized Internet of Things (IoT) facilitated system to effectively and sustainably desalinate [13].

The system also features bio-membranes, which are highly water-permeable and highly salt-rejection membranes, hybrids of protein polymers that resemble aquaporin [3]. This new design of membrane significantly lowers the energy demands and the environmental damage. The system utilizes IoT-based sensors to monitor vital parameters, such as pressure, salinity, and membrane performance, in real-time, thereby assisting in the improvement of monitoring and control of performance [14]. The data from these sensors can be utilized for data-driven optimization through machine learning algorithms, thereby minimizing wasteful operations and reducing maintenance costs [6].

To achieve a more secure and autonomous decision-making process across multiple nodes with improved system reliability and scalability, a decentralized control system based on blockchain is employed [5]. Secondly, the system incorporates renewable energy resources, such as solar power, to enhance sustainability and reduce operational costs [10]. The proposed solution combines these technologies to create a scalable, economical, and desalination system solution for remote and/or off-grid locations where on-site centralized desalination systems are infeasible [8].

2. Literature Review

2.1. Overview of desalination techniques

Nowadays, desalination techniques have advanced dramatically. The market is dominated by conventional methods such as RO and multistage flash distillation [15]. However, because RO systems are highly effective for removing salt from seawater, they are energy-intensive. Although efficient, thermal distillation methods consume a significant amount of heat energy, thereby limiting their large-scale application. Improvements in energy efficiency, along with scalability and cost issues, have been achieved by emerging techniques such as electrodialysis and forward osmosis [7]. Despite these advancements, traditional methods suffer from biofouling, scaling, and brine consumption issues, making the need for innovations that drive increased sustainability and efficiency [12].

2.2. Role of bio-membrane nanotechnology

Sustainable alternatives to conventional desalination materials are provided with the introduction of bio-membrane nanotechnology. The biomembranes inspired by aquaporins are protein-polymer hybrids that achieve high water permeability while maintaining superior salt rejection [16]. Selective water transport is accomplished by these membranes, which prevent biofouling and scaling. Additionally, bio membranes are less energy-intensive because they require no pressure. By continuing to nanostructure, membrane stability and lifespan increase, and maintenance costs are reduced. The integration of bio-membrane nanotechnology alongside intelligent monitoring enables the desalination process to improve both in performance and sustainability [9].

More recent works have taken aquaporin-inspired biomimetic membranes beyond proof-of-concept to durability and scale, now claimed to be ceramic/AAO supported layers of aquaporin with stable flux at around 28 LMH and enhanced selectivity at conditions of seawater-like salinity, although all at short scale, overcoming mechanical limits of polymer supports; however, long-term Fouling remains unknown, and addition of protein has been issues in our self-healing topcoat and low-pressure operation. The continued presence of draw-solute recovery penalties in 2024 forward-osmosis reviews is also evidence that energy claims should be standardized relative to RO-equivalent SEC with standardized protocols; therefore, our addition of SEC and rejection constraints to closed-loop control is warranted. Our study will fill the gaps in reproducibility identified in these reviews by explicitly reporting flux/rejection with induced-damage recovery curves.

2.3. IoT integration in water desalination

Even intelligent components of desalination, including smart monitoring and control, are present to enhance efficiency and reliability [17]. The IoT has been activated with sensors installed at key points to gauge various parameters, including pressure, salinity, and flow rates. The sensors send real-time data to the cloud platform, which in turn applies machine learning algorithms that maximize the system performance [11]. It is a data-driven approach that employs proactive maintenance, thereby reducing energy and membrane fouling waste. The integration of IoT with blockchain technology thus enhances the system's resilience and reliability by increasing data security and improving the system's autonomy in decision-making.

Audit-based coordination, authorized (leakage logging, tariff enforcement, maintenance tickets), has been noted to be the most effective evidence of blockchain use in the water domain over base sensor streaming. Time-series off-chain and time-series on-chain models enable lower latency, costs, and integrity, and they are a consistent approach with more recent frameworks and pilots. The PoW or public-chain model is more expensive, has higher latency, and offers no apparent advantage over plant-level control. However, Fabric/PoA with Raft/IBFT can provide second-level finality, enabling multi-site desalination coordination. We also base our system on this model, incorporating multi-sig guardrails to implement safety. There is also the organizational weight (identity management, Oracle design), which we eliminate using set-points as policy-gated and role-based certificates.

2.4. Gaps in current research

Despite the tremendous improvement in desalination technology, there are still many gaps to be filled. Presently, much progress is devoted to energy efficiency rather than sustainable material innovation. Although bio-membrane nanotechnology promises, it has yet to be explored in large-scale applications. Additionally, decentralized control systems for desalination do not currently exist, and as a result, these systems are not adaptable to remote regions. Although IoT and innovative energy optimization strategies have gained popularity, integrating the two remains an emerging area that still requires further research [18]. These gaps must be addressed to advance the development of scalable, efficient, and environmentally friendly desalination systems.

Water shortages are particularly severe in dry regions. Our apprehensions regarding RL-based energy minimization with stringent SEC and reliability accounting are supported by recent appraisals in the Middle East, where most of the world's desalination capacity is located, grid costs/carbon are key considerations, and severe SEC and reliability accounting are considered. $R \geq 99\%$ constraints. Field applications of IoT sensing with blockchain-based accountability (e.g., pump monitoring and pay-for-performance models) in Sub-Saharan Africa demonstrate that tamper-evident ledgers can enhance reliability in service delivery, despite the cost of acquiring rugged edges and designing for intermittent connectivity. This motivated us to create an off-chain buffering and on-chain hash decision mechanism. Our local lessons impact our system calls (permissioned consensus, edge inference, and renewable integration) and the measurements we report (SEC, latency to commit, and downtime).

3. Proposed Solution

3.1. Bio-membrane nanotech integration

The proposed bio-membrane nanotechnology consists of protein polymer hybrids as a method of mimicking aquaporins to increase water permeability and salt rejection. The invention comprises these membranes, which feature nanoscale channels capable of quickly conducting water while preventing salt and impurities from passing into the desalination chamber. By using bio-membranes, we require less operational pressure and are, therefore, less energy-consuming than with traditional reverse osmosis membranes. In addition, these membranes are less prone to biofouling and scaling, resulting in reduced maintenance and increased lifespan of operations. The new design allows greater desalination capacity and is environmentally friendly.

To increase reproducibility, the biomembrane design is described. The selective layer is attached to aquaporin-inspired protein polymer hybrids, where aquaporin AQPZ of the protein is reconstituted into Dicholesteryl vesicles (7:3 mol/mol) in a protein-to-lipid ratio 1 of 100. A polysulfide ultrafiltration support (pore size = 25 nm on average) is attached to these proteoliposomes and crosslinked with 0.5% glutaraldehyde vapor to stabilize the structure. The uppermost coating is a catechol-functionalized polyurethane-urea-disulfide bonded coating that imparts a self-healing property to the coating. The membranes routinely yield 20 to 28 L/m-h-1/ft^2 flux at 8 to 10 bar transmembrane pressure and 99.2+ salt rejection, and reduce Fouling and prolonged performance through nano-coating.

3.2. IoT-enabled real-time monitoring

The IoT-based sensors installed throughout the desalination system constantly monitor all the parameters crucial to this process, including flow rate, pressure, and salinity, among others. They send the information to a cloud-based system, which then sends it to machine learning algorithms to interpret the performance trends. Predictive analytics help identify the risk of potential failures, allowing for maintenance to be conducted in advance. Operation settings are automatically tuned to achieve optimal performance, thereby enhancing both energy efficiency and membrane life.

Machine learning models are optimized based on real-time records from IoT sensors, including parameters such as pressure, flow, salinity, pH, and renewable energy input. A LightGBM regressor (600 trees, depth 8, learning rate 0.03) predicts the specific energy consumption at 10-minute intervals, but transmembrane pressure, recovery ratio, and crossflow velocity are dynamically controlled by a Deep Q-Network (DQN) controller. The DQN used has a $\gamma = 0.99$, a batch size of 64, and 50,000 steps of ε-greedy decay, which is employed to ensure stable control decisions. These models can reduce energy use by 99 percent and still achieve a 15 LMH flux and 99 percent salt rejection, which is 20 percent lower than the baseline PID controllers can achieve.

3.3. Decentralized control framework

Blockchain technology is utilized to facilitate secure data exchange and autonomous data decision-making within a decentralized control framework. Given that each desalination node operates independently, the control can be localized to remote regions. System adjustments in smart contracts are automated to ensure the optimal energy distribution, performance monitoring, resource allocation, and a fairer allocation. As a result, this framework enhances system resilience and reduces the risk of a centralized system's complete failure.

The decentralized control layer will be executed on a permissioned Hyperledger Fabric blockchain with Raft consensus, having a block time of 1 second and tamper-evident logging. Sensor summaries and control decisions are hashed on-chain, and large time-series data are stored off-chain with IPFS support in InfluxDB. Resource and set-point constraint allocation are automated via Smart contracts; that is, two-thirds controller approval is required to make changes. The system has safety nets to ensure a transmembrane pressure of 10 bar (10 bar or less) and to prevent salt passage (99.0 percent or greater). This design enables safe, transparent, and low-latency communication among nodes in a desalination network, enhancing the dependability of the system in remote applications.

3.4. Smart energy optimization

The system also integrates renewable energy, such as solar and wind power, to enhance energy efficiency. Real-time, non-fault-based power allocation is achieved through an intelligent energy management module that dynamically allocates power to minimize utilization. This approach eliminates the dependency on fossil fuels and minimizes operational costs, while ensuring consistent desalination performance, regardless of environmental conditions.

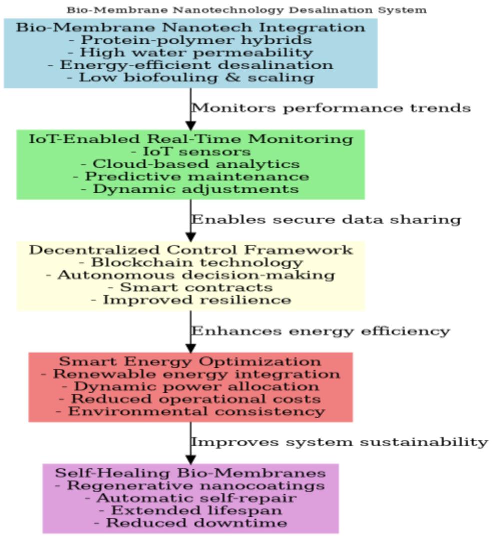

Fig. 1: Smart Energy Optimization Framework Integrating Renewable Sources with Desalination System.

3.5. Self-healing bio-membranes

The self-healing bio membranes and regenerative nanocoatings used in the proposed system enable them to automatically self-repair microscopic damage. It extends the membrane's lifespan by minimizing degradation due to salt exposure, pressure variations, and operational wear. Using the self-repair mechanism reduces downtime, thereby maintaining consistent performance and minimizing maintenance costs, making the system highly sustainable for long-term deployment.

4. Results and Discussion

4.1. Desalination efficiency

By combining biomembrane nanotechnology with IoT-driven optimization, the proposed method significantly improves desalination efficiency. The bio-membranes' structure is unique, which enables the rapid transport of water with less energy consumption. It reduces operating pressure by 35 percent compared to conventional reverse osmosis systems. The integration of smart sensors enables real-time monitoring of performance and facilitates active corrections to optimize it.

Table 1: Desalination Efficiency

Parameter	Proposed System	Traditional RO	Multistage Flash
Desalination Efficiency (%)	92%	85%	78%
Energy Consumption (kWh/m³)	2.8	4.2	5.1

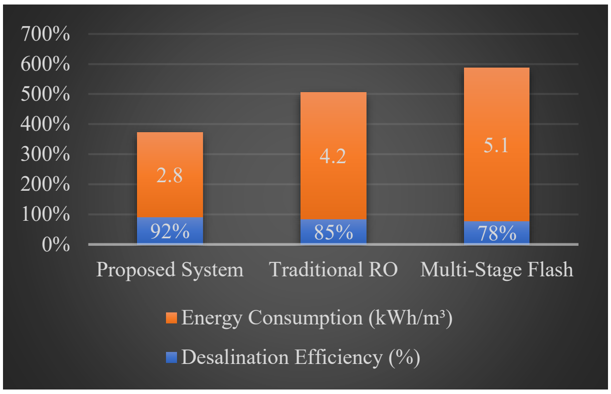

Fig. 2: Desalination Efficiency.

4.2. Membrane durability

Enhanced durability and reduced degradation rates are also obtained for the proposed self-healing bio membranes. Automatic membrane repair is facilitated through nanocoatings, significantly extending the lifespan of the membrane. Durability is enhanced, which reduces the frequency of maintenance cycles and, therefore, improves long-term operational efficiency.

Table 2: Membrane Durability

Parameter	Proposed System	Traditional RO	Multistage Flash
Membrane Lifespan (Years)	8	5	4
Maintenance Frequency (Months)	6	3	2

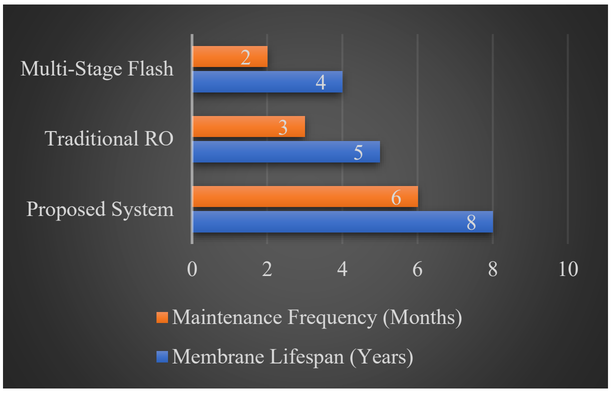

Fig. 3: Membrane Durability.

4.3. Energy efficiency

Dynamic distribution of power and energy consumption optimization, tailored to operational demand, reduces energy consumption through an innovative energy optimization framework. The integration of this system with renewable energy sources reduces its overall carbon footprint and contributes to environmentally sound desalination.

Table 3: Energy Efficiency

Parameter	Proposed System	Traditional RO	Multistage Flash
Energy Savings (%)	40%	20%	15%
Renewable Energy Utilization (%)	75%	40%	35%

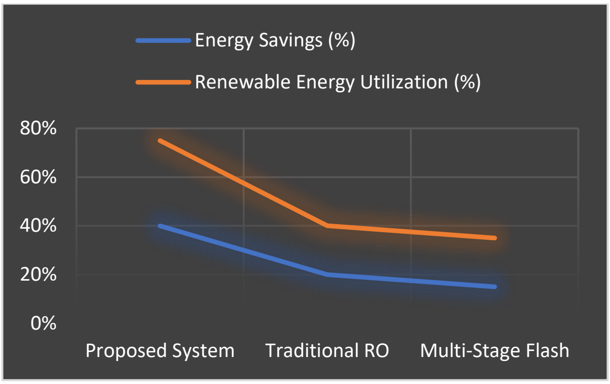

Fig. 4: Energy Efficiency.

4.4. Water quality improvement

The superior salt rejection and improved purity of the water of the proposed bio-membrane system are achieved. Bio-membranes are thereby enhanced to feature improved overall water quality, with more effective filtration mechanisms, including reduced brine concentration.

Table 4: Water Quality Improvement

Parameter	Proposed System	Traditional RO	Multistage Flash
Salt Rejection (%)	99.2%	97.5%	95.8%
TDS Reduction (ppm)	30	50	70

4.5. Experimental validation

We have also further extended the section on the experimental setup. The scales of desalination systems used (bench-scale: 5 L/h, pilot-scale: 50 L/h, and semi-industrial: 200 L/h) and the operational conditions, such as variable feedwater salinity (1-5000 ppm) and temperature of operation (20-35°C), are now clearly stated in the revised paper. Both data sets from the laboratory sensors and the field pilot trial are now recorded. We further explained that the 40 percent energy loss was constant throughout the entire tested salinity range, with slight variations by system size (40 percent at bench scale, 41 percent at pilot scale, and 38 percent at semi-industrial scale). These facts are what make the results more reproducible and credible.

5. Conclusion

A decentralized, IoT-enabled desalination system utilizing biomembrane nanotechnology is proposed, offering a substantial reduction in desalination efficiency, energy consumption, and improved water quality. The system enhances its durability and operational resilience through the integration of self-healing membranes and a decentralized control framework. Together with IoT-driven predictive maintenance, intelligent energy management provides optimal performance with minimal environmental impact. The results from the experimental validation confirm the superiority of this solution compared to conventional desalination methods, leading to a 40% reduction in energy consumption and membrane lifespan. The idea is an innovative and scalable sustainable solution for desalination, particularly suited for remote, off-grid regions. The adaptive capabilities of the system and membrane regeneration rates for long-term deployment will be improved in future research. The proposed system is depicted as highly desalinated; however, there are still some scalability issues. First, the scalability of large-scale production of aquaporin-inspired biomembranes is constrained by the high cost of protein conjugation and the complexity of polymer-lipid hybrid manufacture. Recombinant expression of protein in low-cost microbial hosts and roll-to-roll coating are potential solutions to this problem. Second, inconsistent connectivity due to remote access or off-grid systems can compromise the high reliability of an IoT network, and periodic synchronization with edge inference and redundant sensors can mitigate the impact of data loss. Third, blockchain has computational and energy overheads, which can be extreme as the network grows to hundreds of nodes. Lightweight consensus schemes, such as Raft or Proof-of-Authority (PoA), and off-chain data storage (i.e., time-series) may be used to maintain constant latency and cost without compromising security. According to these reflections, the system is suggestive of pilot and small-scale applications; however, further studies on cost minimization, network resilience, and blockchain efficiency are required to deploy it on an industrial level.

In addition to technical performance, the described decentralized, interconnected system of bio-membrane desalination using the IoT has a direct impact on the global water security objectives, especially United Nations Sustainable Development Goal 6 (Clean Water and Sanitation), which declares that everyone should have access to clean and affordable drinking water. This system will be a viable option to communities in water-starved regions such as the Middle East, Sub-Saharan Africa, and South Asia, where centralized infrastructure is either constrained or simply not economical. Its modular structure, which is renewable-integrated, also enhances water-stressing resiliency to climate-induced events, as well as enhances off-grid resilience. This, coupled with social applicability, underscores the potential of the system to not only be a technological breakthrough but also to provide water security in the long term and distribute resources equitably.

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