

The Water Quality Analysis of Sustainable Seawater Desalination System Using Ultrafiltration

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Abstract

Freshwater scarcity is a growing global issue intensified by population growth, urbanization, and climate change. This study focuses on the development and evaluation of a compact and energy-efficient seawater desalination system that integrates ultrafiltration and reverse osmosis technologies. The system was designed to address diverse environmental conditions while ensuring high-quality freshwater production in compliance with Malaysian Water Quality Standards. The desalination system achieved significant improvements in water quality, reducing salinity from 8.33 g/L to 0.27 g/L, TDS from 7216 mg/L to 286 mg/L, and stabilizing pH at 7.99. Ultrafiltration effectively removed large particles, microorganisms, and organic contaminants, minimizing fouling and extending the lifespan of reverse osmosis membranes. This multi-stage approach proved critical in achieving sustainable and efficient desalination performance. With its compact design, energy efficiency, and adaptability, the system is particularly suitable for applications in disaster relief, remote areas, and off-grid locations. By demonstrating the feasibility of producing high-quality freshwater with minimal environmental impact, this research highlights the potential of integrated filtration technologies as scalable and eco-friendly solutions to mitigate global freshwater scarcity.

1. Introduction

Freshwater scarcity is a global challenge, affecting over 50% of the population, particularly in arid and semi-arid regions. Factors such as population growth, urbanization, pollution, and climate change threaten freshwater availability and quality. Conventional desalination methods, including reverse osmosis (RO) and thermal distillation, are widely used to address water shortages but are energy-intensive and have significant environmental impacts [1]. The discharge of brine and chemicals from these processes further harms marine ecosystems, emphasizing the need for sustainable solutions [2]. Integrating renewable energy into desalination systems, such as solar-powered RO, offers a sustainable approach to reduce costs and environmental footprints [3].

The key challenge is to develop a compact seawater desalination system that is energy-efficient and environmentally sustainable. Existing technologies, while effective, are not well-suited for remote or disaster-affected areas due to their high energy demands and infrastructure requirements. Hybrid desalination methods and renewable energy integration have shown potential in reducing operational costs and environmental impacts [4]. Additionally, sustainable brine management and performance optimization of the system's filters are essential to ensure high-quality freshwater production with minimal ecological harm [5].

The primary objective of this study is to design a compact seawater desalination system that can operate efficiently under diverse environmental conditions, particularly in remote or disaster-affected areas. This involves evaluating the effectiveness of ultrafiltration as a pre-treatment step to improve the overall efficiency of the desalination process. Additionally, the study aims to conduct performance testing to assess the combined use of ultrafiltration and reverse osmosis technologies in producing high-quality freshwater. The ultimate goal is to develop a sustainable and portable desalination system that addresses freshwater scarcity while minimizing environmental impacts.

2. Literature Review

Desalination has emerged as a vital technology in addressing global water scarcity, providing a sustainable source of freshwater from seawater and brackish water. Among the various desalination technologies, ultrafiltration has garnered significant attention due to its efficiency and effectiveness in removing impurities, pathogens, and suspended solids. Recent studies highlight the potential of integrating ultrafiltration systems with renewable energy sources, such as solar power, to enhance energy efficiency and reduce the ecological footprint of desalination processes [6][7].

2.1 Reverse Osmosis

Reverse osmosis (RO) is widely used for desalination, which is the process of removing salts and minerals from saline water to produce freshwater suitable for human consumption or industrial use. This method leverages a semi-permeable membrane to separate pure water from dissolved salts and other impurities. RO is a key technology in various applications, particularly in regions where freshwater resources are scarce.

One of the primary applications of RO is in seawater desalination. This process is crucial for providing potable water in coastal regions and arid areas with limited access to natural freshwater sources. In seawater desalination, raw seawater is first pre-treated to remove larger particles and organic matter that could clog or damage the RO membranes. The pre-treated seawater is then pumped into a high-pressure vessel, where it is forced through a semi-permeable membrane under high pressure [8].

The RO membrane acts as a selective barrier, allowing only water molecules to pass through while rejecting salts, minerals, and other dissolved solids. As a result, the permeate, or the water that passes through the membrane, is significantly lower in salinity and suitable for drinking or industrial use. The remaining concentrated brine, which contains the rejected salts and impurities, is typically discharged back into the sea or treated further to minimize environmental impact [8].

2.2 Ultrafiltration

Desalination of seawater using ultrafiltration is a crucial process in water treatment, particularly for seawater desalination plants. Ultrafiltration (UF) serves as a pre-treatment method for reverse osmosis (RO) desalination, effectively removing biological, organic, and particulate contaminants from seawater before it enters the RO system. UF is preferred due to its ability to deliver superior water quality compared to conventional treatment methods, very fine pore structure that ensures a continuously good filtrate quality independent of feed water quality variability. This capability not only enhances the performance and longevity of RO membranes but also reduces the operational costs and environmental impact of desalination plants [9].

The role of ultrafiltration in seawater desalination is pivotal in ensuring that the water entering the reverse osmosis stage is of high quality, minimizing the fouling and scaling of RO membranes. By removing suspended solids, colloids, bacteria, and viruses, UF membranes act as a robust barrier, providing a first line of defense against contaminants. This pre-treatment step is essential for maintaining the efficiency and effectiveness of the RO process, which is highly sensitive to feed water quality [10].

In addition to improving the operational efficiency of desalination plants, ultrafiltration also contributes to their sustainability. The technology requires lower chemical usage compared to traditional methods, reducing the chemical footprint and the subsequent environmental impact. Furthermore, UF systems typically have a smaller physical footprint, which makes them suitable for integration into existing desalination infrastructure or for deployment in remote or space-constrained locations [9].

2.2.1 Fundamentals of Ultrafiltration (UF)

Ultrafiltration (UF) is a pivotal process in seawater desalination systems due to its effective removal of particles, colloids, bacteria, and macromolecules through a semipermeable membrane with pore sizes typically ranging from 0.01 to 0.1 microns [11]. Operating at pressures between 1 to 10 bar (15 to 150 psi), UF systems are noted for their energy efficiency compared to processes like reverse osmosis (RO) [12]. Organic (polymeric) membranes, favored for their flexibility and cost-effectiveness, dominate UF applications in desalination [13]. UF achieves high removal efficiencies, exceeding 99% for particles larger than the membrane's pore size, making it

an effective pretreatment step for RO by reducing fouling potential and extending membrane life [14]. UF systems offer robustness, scalability, and ease of operation and maintenance, with applications extending to wastewater treatment, drinking water purification, and various industrial processes [15][16].

2.2.2 Advantages of Ultrafiltration

Ultrafiltration (UF) offers several advantages for desalination processes, particularly when used as a pretreatment step for reverse osmosis (RO). These advantages enhance the efficiency, reliability, and sustainability of desalination systems.

UF membranes effectively remove suspended solids, bacteria, viruses, and colloids from seawater. This results in a consistent and high-quality feed water for RO systems. The lower silt density index (SDI) values achieved through UF pretreatment indicate a reduced potential for membrane fouling, which is crucial for maintaining RO system performance and longevity [10].

The use of UF as a pretreatment step reduces the fouling rate of RO membranes. This translates to less frequent cleaning and maintenance, leading to lower operational costs and extended membrane life. Studies have shown that UF pretreatment can significantly improve the overall efficiency of desalination plants by minimizing downtime and ensuring continuous operation [17].

UF reduces the need for chemical pretreatments, such as coagulants and disinfectants, that are typically required to condition feed water before RO. This not only lowers the operational costs associated with chemical procurement and handling but also reduces the environmental impact of chemical discharges. The minimal chemical usage aligns with sustainable water treatment practices [18].

By providing a cleaner feed water to the RO system, UF reduces the energy required for desalination. Cleaner feed water means less fouling and fewer pressure drops across the RO membranes, leading to lower energy consumption. This contributes to the overall energy efficiency of the desalination process, making it more sustainable and cost-effective [19].

UF contributes to the sustainability of desalination operations by improving the efficiency of the process and reducing the environmental footprint. The ability to treat and reuse brine and wastewater generated from desalination plants further minimizes the environmental impact. Sustainable management of these by-products is critical for reducing the ecological effects associated with desalination [20].

3. Methodology

This methodology aims to address the challenges of RO membrane fouling, a major issue in desalination systems, by integrating ultrafiltration (UF) as a pre-treatment step. UF reduces suspended solids, microorganisms, and organic matter in feed water, mitigating fouling and extending RO membrane lifespan. The chapter outlines procedures for feed water characterization, UF system design, operational parameter determination, and UF-RO integration.

Pilot testing is included to validate and optimize the UF-RO system for real-world conditions. The methodology highlights the benefits of UF pre-treatment, such as improved water quality, enhanced efficiency, and reduced environmental impact. By systematically addressing these aspects, it provides a framework for developing sustainable and efficient desalination solutions.

3.1 Flow of Design

The flow of design for this project will involve five main stages of filtration, which are the feed water intake, screening, ultrafiltration system, reverse osmosis unit and post treatment.

3.1.1 Feed Water Intake

The process begins with the collection of seawater from *Pantai Minyak Beku*. The necessary preservation steps taken to ensure the water quality parameter is controlled to take necessary data for the study. This water is initially screened using coarse screens to remove large debris like seaweed, leaves, and other floating materials. This step is crucial to protect downstream equipment from damage and to prevent large particles from entering the pre-treatment system, which could lead to clogging and reduced efficiency.

3.1.2 Screening

In this stage, water is screened using coarse screens to remove large debris like seaweed, leaves, and other floating materials. This step is crucial to protect downstream equipment from damage and to prevent large particles from entering the pre-treatment system, which could lead to clogging and reduced efficiency. This pre-treatment step is also essential to enhance the efficiency and lifespan of the ultrafiltration (UF) membranes by minimizing fouling [21].

3.1.3 Ultrafiltration System

The conditioned water is pumped into the ultrafiltration (UF) membrane modules using low-pressure pumps. These UF membranes, which can be hollow fiber or flat sheet types, filter the water by removing particulate matter, colloids, microorganisms, and some organic materials. The UF membranes typically have a pore size ranging from 0.01 to 0.1 micrometres, allowing them to effectively remove contaminants while permitting the passage of clean water, or permeate. The permeate is collected, while the concentrate, containing the retained impurities, is disposed of appropriately. This step is critical for ensuring that the water entering the reverse osmosis (RO) system is of high quality, thereby protecting the RO membranes from fouling and scaling. Research has shown that UF as a pre-treatment significantly enhances RO performance by reducing fouling and improving the quality of feedwater [22].

3.1.4 Reverse Osmosis Unit

The UF-treated water is then fed into the reverse osmosis (RO) system using high-pressure pumps. The RO process involves passing the water through semi-permeable membranes that remove dissolved salts and other impurities, producing desalinated water (permeate) and concentrated brine (reject). The clean, desalinated water is collected for further treatment or use, while the concentrated brine is managed and disposed of properly. This step is the core of the desalination process, producing water that meets the quality standards for various applications. Reverse osmosis remains the dominant desalination technology, offering high efficiency and scalability in addressing water scarcity challenges [23].

Two types of RO are used in the system. One of it is a standard 10-inch RO membrane and another one is a 40-inch RO membrane. The details of the 40-inch RO membrane as below:

Table 1: Details of 40-inch RO membrane used

MR-SW 4040	
Effective membrane area (ft ²)	85 ft ²
Operating pressure (psi)	800 psi
Water Production (GPD)	1950 GPD
Salt Rejection (%)	99.7%
Boron-removing Rate (%)	93%
Recovery Rate (%)	8%
Maximum Working Pressure (psi)	1000 psi
Test Water Concentration (ppm)	32800 ppm

3.1.5 Post-Treatment

The RO permeate undergoes post-treatment to stabilize it, which includes adding minerals (remineralization) and adjusting the pH to make the water suitable for consumption or industrial use. The treated water is then stored in clean storage tanks before being distributed to end users. This final step ensures that the water meets all regulatory standards for quality and safety, making it suitable for its intended use. Proper post-treatment and storage are crucial for maintaining water quality and preventing contamination during distribution.

3.2 Prototype Development

The development of a desalination system utilizing ultrafiltration follows a structured prototyping process involving several critical phases. Initially, a detailed SketchUp model is constructed to optimize the design and identify potential structural or operational challenges. The selection of materials prioritizes lightweight, durable, and corrosion-resistant components to enhance system longevity and performance. The prototype assembly process is conducted with a focus on seamless integration of key components, including pre-treatment filters, an energy-efficient pump, the ultrafiltration membrane, and post-treatment stages. Comprehensive testing is performed to assess water quality, flow rate, and energy consumption, with any identified issues—such as leaks or membrane fouling—systematically addressed. The system is then refined through iterative modifications and field testing in real-world conditions to ensure adaptability and efficiency. Finally, user feedback is incorporated into the design refinement process, ensuring that the final prototype is robust, efficient, and user-friendly.

3.2.1 Sketch Up Modelling

Prototype development for a desalination system using ultrafiltration involves creating a detailed Sketch Up model, simulating performance, and selecting lightweight, durable materials. The prototype is assembled with key components like pre-treatment filters and an efficient pump. Thorough testing and iterative adjustments

optimize water quality, flow rate, and energy consumption. Field testing and user feedback refine the design, ensuring robustness and efficiency.

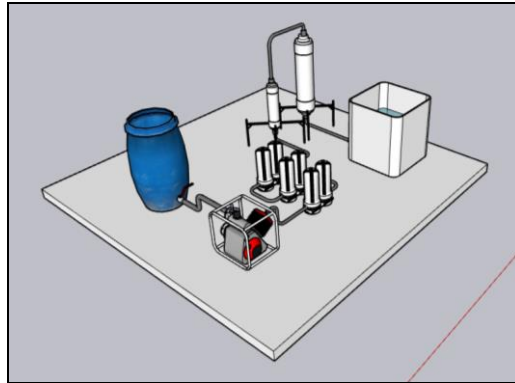


Fig. 1: Sketch Up model of the desalination system

3.2.2 Build a Prototype

Assemble the prototype according to design specifications, ensuring all components fit seamlessly and function as intended. Conduct thorough testing and iterative adjustments to optimize performance, followed by field testing and user feedback to refine the design.

3.2.3 Testing and Optimization

Conduct thorough testing to evaluate water quality, flow rate, and energy consumption, addressing issues like leaks or membrane fouling. Optimize the system for efficiency and reliability through necessary adjustments.

3.2.4 Performance Evaluation

The desalinated water was tested for salinity, Total Dissolved Solids (TDS), and other physio-chemical contaminants to ensure compliance with the desired standards for potable water. Additionally, the flow rate and water recovery rate were measured to evaluate the system's efficiency in converting seawater into clean water. Continuous monitoring of power consumption was conducted to ensure that the system operated within acceptable limits and maintained energy efficiency, particularly in off-grid applications where power sources might be constrained. These comprehensive evaluations verified the system's performance and reliability, ensuring the consistent delivery of high-quality drinking water while minimizing energy consumption. The testing and parameter measurements were carried out according to each design phase of the desalination process.

4. Data Analysis and Discussion

This section is focused on the physical and chemical properties of water sample after filtration using the designed desalination system. This section will mainly cover on the salinity, TDS, pH, temperature, ORP, DO, conductivity and resistivity test that was done to the water sample. Last, the filtered water quality index parameter of water sample was tabulated and compared to National Water Quality Standard. In the end, the effectiveness of the desalination system is discussed in this chapter.

4.1 Salinity

The salinity levels of seawater were measured at various filtration stages to assess the performance of the desalination process based on Figure 2.

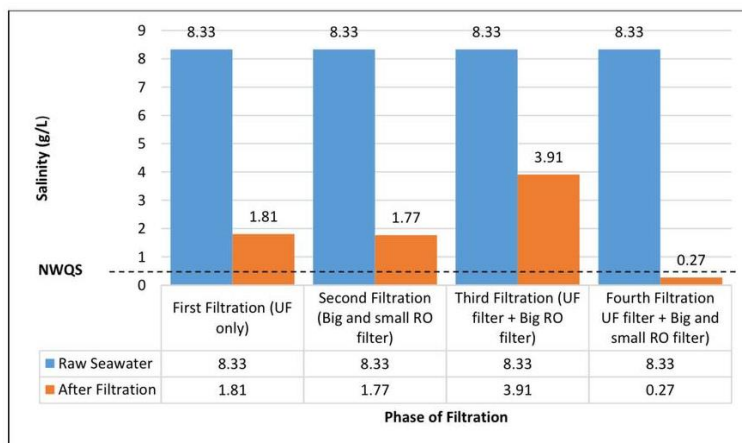


Fig. 2: Graph of comparison of salinity value before and after filtration

In the first stage of filtration, ultrafiltration technology was utilized to address larger particles and suspended solids. This stage reduced the salinity significantly to 1.81 g/L, a remarkable improvement that underscores the efficiency of ultrafiltration in removing larger contaminants and preparing the water for subsequent treatment. Ultrafiltration not only lowers salinity but also plays a crucial role in protecting downstream reverse osmosis membranes from fouling, extending their operational life and maintaining system performance.

The second filtration stage employed reverse osmosis (RO), a widely recognized technology for removing dissolved salts and minerals. At this stage, salinity was further reduced to 1.77 g/L. The marginal reduction compared to the first stage demonstrates the precise capability of RO membranes to filter out smaller dissolved ions that pass-through ultrafiltration. This finding aligns with existing studies highlighting reverse osmosis as one of the most effective methods for desalination [25].

The third stage integrated ultrafiltration with a single reverse osmosis filter. Interestingly, this combination resulted in a salinity of 3.91 g/L, which was higher than the value achieved in the second stage. This unexpected increase could be attributed to potential limitations in the single reverse osmosis filter's capacity or operational issues such as membrane fouling, where contaminants accumulate on the membrane surface, reducing its efficiency. Such an anomaly underscores the need for careful monitoring and regular maintenance of the system to prevent performance degradation.

The fourth and final filtration stage incorporated both large and small reverse osmosis filters in addition to ultrafiltration. This advanced configuration achieved a significantly reduced salinity level of 0.27 g/L, well within the potable water standards set by Malaysian guidelines. This result highlights the superior performance of combining multiple RO filters with ultrafiltration, offering a robust solution for achieving high-quality desalinated water suitable for consumption.

4.2 Total Dissolved Solids (TDS)

The total dissolved solids (TDS) levels of seawater were measured at various filtration stages to evaluate the efficiency of the desalination system referring to Figure 3.

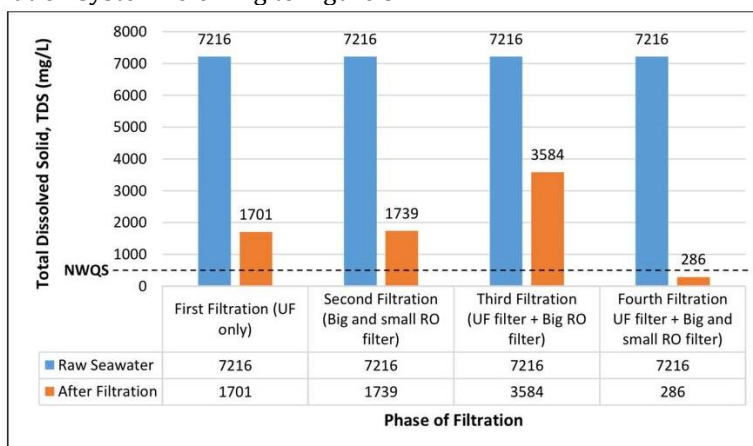


Fig. 3: Graph of comparison of total dissolved solid (TDS) value before and after filtration

Based on the figure above, the raw seawater used in this study had a total dissolved solids (TDS) concentration of 7,216 mg/L, which aligns with the standard range for Malaysian water quality. This high TDS level reflects the

presence of dissolved salts and minerals, typical of seawater in coastal regions. To address this, a multistage filtration system was employed, combining ultrafiltration and reverse osmosis technologies to progressively improve water quality.

In the first stage, ultrafiltration technology was applied to remove suspended particles and larger contaminants, reducing the TDS significantly to 1,739 mg/L. This marked a notable improvement, demonstrating the effectiveness of ultrafiltration as a preliminary treatment step in seawater desalination.

The second stage involved the use of reverse osmosis (RO) filtration, a well-established method for removing dissolved salts and smaller impurities. This stage further decreased the TDS to 1,701 mg/L. The incremental reduction highlighted the precision of reverse osmosis in targeting and removing minute particles and dissolved salts that passed through the ultrafiltration membrane [26].

The third stage integrated ultrafiltration with a larger reverse osmosis filter, resulting in a TDS level of 3,584 mg/L. Interestingly, this stage showed a slight increase in TDS compared to the second stage. This outcome suggests potential limitations or inefficiencies when combining specific filtration systems under certain conditions, warranting further investigation into factors such as membrane fouling or operational inconsistencies.

The fourth and final stage involved a comprehensive setup that combined ultrafiltration with both large and small reverse osmosis filters. This configuration achieved a TDS concentration of 286 mg/L, representing the lowest value obtained in the study. This level is well within the potable water standards established by the National Water Quality Standard (NWQS) of Malaysia, making the treated water suitable for safe human consumption [26][27]. This final result underscores the critical role of multi-stage treatment systems in achieving high-quality desalinated water and highlights the importance of optimizing each stage for maximum efficiency and performance.

4.3 pH

From Figure 4, the pH levels of seawater were measured at different filtration stages to assess the impact of the desalination process on water acidity and alkalinity.

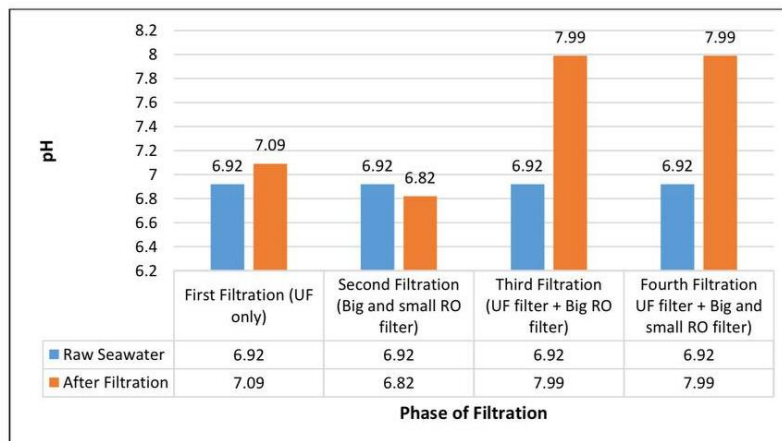


Fig. 4: Graph of comparison of pH value before and after filtration

The raw seawater used as the initial input for the desalination process exhibited a pH level of 6.92, which is slightly acidic compared to typical seawater values. Naturally, seawater has a pH range of 8.0 to 8.3 due to the presence of alkaline compounds such as bicarbonates, carbonates, and borates that act as natural buffers. The observed deviation in pH for the raw seawater could be attributed to local environmental factors such as freshwater inflows, organic matter decomposition, or industrial discharges in the region, which can lower the pH of coastal waters [28].

In the first stage of the desalination process, ultrafiltration technology was employed to remove larger particles, organic matter, and other suspended solids. Following this stage, the pH level increased to 7.09. This rise in pH is likely due to the removal of acidic substances, such as dissolved organic acids or carbon dioxide, that contribute to the initial acidity of seawater. Ultrafiltration not only enhances water clarity but also plays a role in stabilizing pH by eliminating particulate matter that can influence the water's acidity-alkalinity balance. The second stage involved reverse osmosis (RO) filtration using both large and small RO filters. After this treatment, the pH decreased to 6.82. This reduction can be explained by the concentration of dissolved ions during the reverse osmosis process. When water passes through the RO membranes, non-volatile acids, and salts are concentrated on the reject side, and a minor amount may diffuse back into the permeate, contributing to a

slight acidity. Additionally, reverse osmosis can remove buffering compounds, such as bicarbonates, which can further shift the pH towards acidic levels.

In the third stage, which combined ultrafiltration with a large reverse osmosis filter, the pH increased significantly to 7.99. This marked increase suggests that the filtration process at this stage was more effective in balancing the ionic composition of the treated water. The combined treatment might have reduced the presence of residual acidic ions while retaining or selectively allowing alkaline components to pass through, resulting in a near-neutral pH level.

The fourth and final stage, which incorporated ultrafiltration alongside both large and small reverse osmosis filters, also produced water with a pH of 7.99. This consistency in pH between the third and fourth stages reflects the optimized design of the filtration system in maintaining the chemical stability of the treated water. The stability achieved in this stage underscores the efficiency of the system in meeting both desalination and water quality objectives. The increase in pH observed during the desalination process can be attributed to several key factors, primarily the removal of acidic substances, selective ion retention, and changes in the buffering capacity of the treated water. Initially, the raw seawater exhibited a slightly lower pH of 6.92, which can be linked to the presence of dissolved carbon dioxide (CO₂) and organic acids.

Throughout the desalination process, the pH levels observed remained well within the Malaysian water quality standard for drinking water, which specifies an acceptable pH range of 6.5 to 8.5. Maintaining a pH within this range is critical, as it ensures that the water is neither too acidic nor too alkaline, minimizing risks to human health and preventing corrosion or scaling in water distribution systems [28].

5. Conclusion

This thesis presents a detailed study on the design, development, and evaluation of a seawater desalination system to address critical water scarcity issues. The system integrates ultrafiltration and reverse osmosis technologies and was assessed for its ability to reduce salinity, Total Dissolved Solids (TDS), and stabilize pH levels. The findings demonstrate that the system can transform raw seawater into high-quality potable water meeting Malaysian Water Quality Standards, proving its effectiveness for use in regions with limited freshwater resources. This achievement highlights the significant potential of advanced filtration technologies in mitigating global water shortages. The study focused on key water quality parameters, with salinity reduced from 8.33 g/L to 0.27 g/L. The fourth filtration stage, which combined ultrafiltration with both large and small reverse osmosis filters, was particularly effective in achieving these reductions. This result underscores the importance of multi-stage filtration in optimizing desalination performance. Similarly, TDS levels were reduced from 7216 mg/L to 286 mg/L, demonstrating the system's efficiency in eliminating dissolved impurities to ensure safe and suitable water for consumption. Stabilizing pH was another vital outcome of the system, as raw seawater with an initial pH of 6.92 was adjusted to a neutral and safe value of 7.99. This stabilization not only ensured the chemical safety of the desalinated water but also reinforced the system's reliability in providing consistently high-water quality. The dual role of the system in purification and chemical stabilization highlights its capability to meet stringent water quality standards. In conclusion, this research emphasizes the critical role of desalination technology in addressing one of the most pressing challenges of the 21st century: access to clean and sustainable water. The integration of ultrafiltration and reverse osmosis technologies demonstrated a practical and efficient approach to seawater desalination. By achieving water quality standards, promoting sustainable practices, and offering a foundation for future advancements, this study reaffirms the importance of advanced desalination systems as a key strategy for ensuring water security in a growing and resource-constrained world.

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Conflict of Interest

Authors declare that there is no conflict of interest regarding the publication of the paper.

Author Contribution

This journal requires that all authors take public responsibility for the content of the work submitted for review.

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