Architecture Image Studies
AIS Scientific Journal

Vol.6, Issue 3, pp.287-296, 2025
DOI: https://doi.org/10.62754/ais.v6i3.221

https://journals.ap2.pt/index.php/ais/index

The Water Quality Analysis of Sustainable Seawater Desalination System Using Ultrafiltration and Reverse Osmosis

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Abstract

Freshwater scarcity remains a pressing global challenge, exacerbated by population growth, urbanization, and climate change. This study focuses on the design, development, and evaluation of a sustainable seawater desalination system that integrates ultrafiltration as a pre-treatment to reverse osmosis. The research include designing a compact and energy-efficient desalination system suitable for diverse environmental conditions, evaluating the effectiveness of ultrafiltration in reducing fouling and improving the lifespan of reverse osmosis membranes, and assessing the system's ability to produce high-quality freshwater in compliance with the National Water Quality Standard (NWQS). The experimental results demonstrated significant improvements in water quality across key parameters. Salinity levels were reduced from 8.33 g/L in raw seawater to 0.27 g/L, while total dissolved solids (TDS) decreased from 7216 mg/L to 286 mg/L. Additionally, the system effectively stabilized the pH at 7.99, ensuring chemical safety and potable suitability. Ultrafiltration membranes proved highly effective in removing large particles, microorganisms, and organic contaminants, reducing fouling and enhancing the overall performance of reverse osmosis membranes. These findings underscore the importance of multi-stage filtration in achieving sustainable and efficient desalination. This research highlights the potential of integrating ultrafiltration and reverse osmosis technologies as a scalable and eco-friendly approach to addressing global freshwater scarcity.

Keywords: *Seawater Desalination, Ultrafiltration, Reverse Osmosis, Freshwater Scarcity, Water Quality*

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].

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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].

Desalination systems typically utilize membrane-based technologies such as ultrafiltration and reverse osmosis. Ultrafiltration serves as a pre-treatment step that removes suspended solids, bacteria, and larger contaminants, thereby enhancing the efficiency and lifespan of reverse osmosis membranes. Reverse osmosis, on the other hand, is a widely adopted technique that employs semi-permeable membranes to remove dissolved salts and impurities, producing freshwater from seawater. The integration of ultrafiltration with reverse osmosis improves overall system performance, reduces membrane fouling, and enhances water recovery rates, making it a viable solution for sustainable desalination.

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. 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.

Methodology

Flow of Design

The flow of design for this project will involve five main stages of filtration as shown in Fig.1.

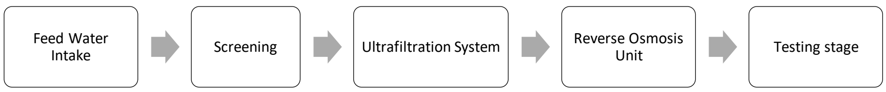

Fig. 1. Flow Design of System

The design flow of this system consists of five key stages, beginning with feed water intake, where raw seawater is collected from natural sources. The water then undergoes screening, a crucial step to remove large particles, debris, and other contaminants that could damage the filtration system.

Following this, the ultrafiltration system plays a vital role in removing suspended solids, ensuring that the water entering the next stage is free from larger contaminants. The reverse osmosis unit is the core of the desalination process, where water is forced through a semi-permeable membrane under high pressure to eliminate dissolved salts, heavy metals, and other impurities, producing fresh and purified water. Lastly, the testing stage ensures that the final water meets the required quality standards by following the Malaysian National Water Quality Standard (NWQS).

This systematic filtration process not only enhances the quality of desalinated water but also ensures sustainability by optimizing energy use and minimizing environmental impact. The study likely focuses on analyzing key water quality parameters such as salinity, pH and total dissolved solids (TDS) before and after treatment, assessing the efficiency of the UF-RO system. By implementing these advanced filtration technologies, the research aims to contribute to the development of a more efficient and eco-friendly seawater desalination approach.

Phase Filtration of Whole System

The phase filtration of the whole system follows a multi-stage process to ensure efficient seawater desalination.

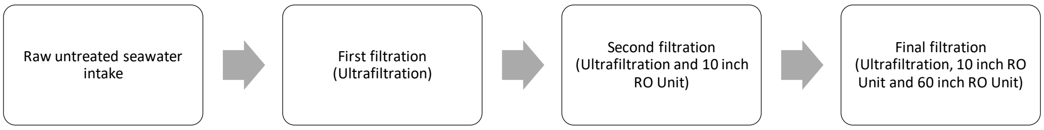

Figure 2: Phase Filtration of Whole System

The Fig. 2 illustrates a multi-phase filtration process in a seawater desalination system, designed to enhance water purification efficiency. The process begins with the intake of raw, untreated seawater, which contains suspended solids, microorganisms, and dissolved salts. In the first filtration stage, ultrafiltration is applied to remove large particles, bacteria, and organic matter, serving as a crucial pre-treatment step to protect downstream filtration components. The second filtration phase combines ultrafiltration with a 10-inch reverse osmosis (RO) unit, where high pressure is used to separate dissolved salts and smaller contaminants, improving water quality. Finally, the water undergoes a final filtration stage incorporating ultrafiltration, the 10-inch RO unit, and an additional 60-inch RO unit. This last phase ensures maximum purification, achieving high-quality freshwater suitable for consumption or industrial applications. By implementing a stepwise filtration approach, the system optimizes desalination efficiency, minimizes membrane fouling, and enhances sustainability in freshwater production.

Feed Water Intake

The process begins with the collection of seawater from *Pantai Minyak Beku, Johor*, Malaysia which serves as the raw water source for the desalination system. This location is selected based on its accessibility, water quality, and suitability for desalination studies. To ensure that the collected seawater is representative and reliable for analysis, specific preservation steps are taken to maintain its natural characteristics and prevent contamination or degradation before filtration.

To ensure the collected seawater from *Pantai Minyak Beku, Johor, Malaysia remains* representative and uncontaminated before laboratory testing, several preservation steps are implemented. First, seawater is collected using sterile, non-reactive containers such as high-density polyethylene (HDPE), which are pre-rinsed with the sample water to prevent contamination. To maintain water quality, the samples are immediately stored at 4°C in an insulated cooler with ice packs to slow down biological activity and prevent microbial growth. Then the particulate removal is removed by passing the seawater through a 0.45 µm sterile membrane filter to eliminate suspended solids while preserving dissolved ions and microorganisms. To minimize external interference, the samples are stored in dark containers or wrapped in aluminium foil to protect them from light-induced degradation, and bottles are tightly sealed to prevent gas exchange, which could alter pH and dissolved oxygen levels. Finally, the samples are transported to the laboratory as soon as possible, ideally within 24 hours, to ensure accuracy in analysis. These preservation steps are crucial in maintaining the seawater's natural characteristics, ensuring reliable and accurate results for desalination studies.

One of the primary concerns during feed water intake is the control of water quality parameters, such as salinity, pH, and total dissolved solids (TDS). These parameters are monitored and recorded to assess the effectiveness of the UF and RO treatment in improving water quality.

Screening

In this stage, water is screened using 400 mesh in 38-micron gauze nylon filter 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 UF membranes by minimizing fouling [6].

Ultrafiltration System

The conditioned water is pumped into UF membrane modules using low-pressure pumps. These UF membranes were hollow fibre type, and it filter the water by removing particulate matter, colloids, microorganisms, and some organic materials. The filter adopts advanced ultra-fine microporous membrane technology to remove suspended colloids up to 0.01 micron while keeping essential mineral intact, eliminates up to 99.99% water borne micro-organism, bacteria and even viruses in the water.

The UF membranes 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 [7].

TABLE 1: DETAILS OF ULTRAFILTRATION (UF) FILTER

UF Membrane Filter (UF Ultrafiltration)	
Size (inch)	10
Filter Material	Polyacrylonitrile (PAN)
Pore Sizes (micron)	0.01- 0.1
Maximum Temperature (° C)	45
Working Pressure (Mpa)	0.1 – 0.4

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 testing, while the concentrated brine is managed and disposed properly.

Direct Ocean Discharge is the most used method for disposing of brine waste from seawater reverse osmosis (SWRO) desalination plants. Additionally, controlled discharge points help regulate the flow rate, preventing excessive accumulation of salts in one area. Since brine disposal can significantly impact marine life, desalination plants must adhere to strict environmental regulations that govern factors such as discharge location, flow velocity, and monitoring requirements. Effective brine management strategies, such as deep-sea discharge and pre-dilution with seawater, are crucial to minimizing ecological harm. Proper implementation of direct ocean discharge ensures that desalination remains a viable and sustainable solution for addressing freshwater scarcity while reducing its environmental footprint [15].

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 [8].

Two types of RO are used in the system, 1 unit for each type. One of it is a standard 10-inch RO membrane and another one is a 40-inch RO membrane. The details of the 10-inch and 40-inch RO membrane as below:

TABLE 2: DETAILS OF 10-INCH RO MEMBRANE

MR-SW 4040 (Reverse Osmosis Membrane)	
Effective membrane area (ft^2)	3.5-10.33
Operating pressure (psi)	65
Water Production (GPD)	204-760
pH Value	6.5-7.5
Stable Desalting Rate (%)	97%
Maximum Inlet Water Temperature (° C)	45
Recovery Rate of Single Membrane Element	15
Maximum Working Pressure (psi)	300
Test Water Concentration (ppm)	500

TABLE 3: DETAILS OF 40-INCH RO MEMBRANE

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

Prototype Development

Prototype development for a desalination system using ultrafiltration involves several key steps. First, create a detailed Sketch Up model to optimize the design and identify potential issues. Select lightweight, durable, and corrosion-resistant materials for assembly. Assemble the prototype, ensuring seamless integration of components such as pre-treatment filters, an energy-efficient pump, the ultrafiltration membrane, and post-treatment stages. Conduct thorough testing to evaluate water quality, flow rate, and energy consumption, addressing any issues like leaks or membrane fouling. Optimize the system through iterative adjustments and field testing in real-world conditions.

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 as illustrated in Fig. 3. Thorough testing and iterative adjustments optimize water quality, flow rate, and energy consumption.

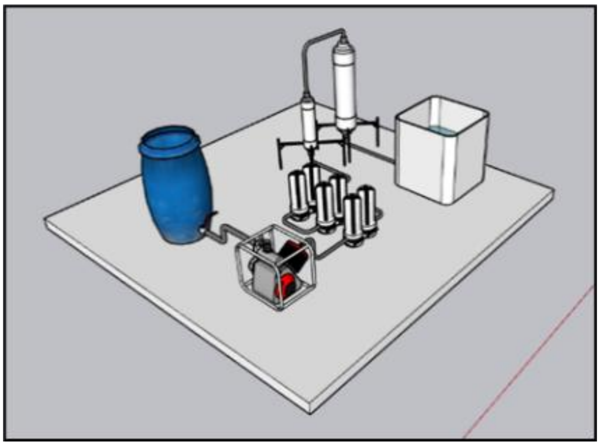

Figure 3: Sketch Up Model of the Desalination System

Build Prototype

The prototypes were assembled according to design specifications, ensuring all components fit seamlessly and function as intended as shown in Fig. 4. Testing was conducted and iterative adjustments to optimize performance, followed by field testing and user feedback to refine the design.

Figure 4: The Desalination Prototype

Testing and Optimization

Testing was conducted to evaluate water quality, flow rate, and energy consumption, addressing issues like leaks or membrane fouling. The system was optimized for efficiency and reliability through necessary adjustments.

Result and Discussion

This section presents the results and analysis of pH, Total Dissolved Solids (TDS), and Salinity at each stage of the filtration system. These parameters are crucial in assessing the efficiency of the desalination process and ensuring the production of high-quality freshwater.

Analysis of pH Enhancement

The ability of the desalination system to stabilize pH levels throughout the filtration process is a critical factor in ensuring the chemical safety and potability of the treated water [9]. Fig. 5 illustrates the raw seawater initially exhibited a slightly acidic pH of 6.92, which is common due to the presence of dissolved carbon dioxide and other acidic components in marine environments. Upon undergoing ultrafiltration, the pH increased to 7.09, likely due to the removal of particulate matter and organic acids that contribute to acidity. This stage effectively acted as a pre-treatment, reducing the burden on subsequent filtration stages while slightly altering the water's chemical properties.

However, in the second stage, where reverse osmosis (RO) filtration was introduced, the pH decreased slightly to 6.82. This reduction can be attributed to the nature of RO membranes, which selectively remove ions and alter the balance of dissolved gases, leading to changes in pH. Specifically, the removal of alkaline minerals, such as bicarbonates and carbonates, can result in a temporary decrease in pH. This phenomenon is well-documented in desalination processes and is typically managed through post-treatment stabilization techniques.

By the final stage, the system successfully stabilized the pH at 7.99, bringing it within the neutral to slightly alkaline range recommended for potable water. This stabilization suggests that the combined effect of ultrafiltration and multi-stage RO filtration not only removes contaminants but also contributes to achieving a balanced chemical composition in the treated water. The increase in pH at the final stage may be influenced by the removal of acidic compounds and the potential leaching of minor alkaline components from the filtration materials.

Maintaining a stable and appropriate pH in desalinated water is essential for both consumer health and the longevity of distribution systems. Water with a low pH can be corrosive to pipes, potentially leaching metals such as lead and copper, while excessively high pH levels can affect the taste and efficiency of chlorine disinfection. The results of this study demonstrate that the desalination system effectively addresses these concerns by producing water with a balanced pH, ensuring that it meets both safety and quality standards.

These findings highlight the importance of multi-stage filtration design in not only removing salinity and impurities but also in ensuring the chemical stability of desalinated water. Future research may focus on optimizing pH stabilization techniques, such as remineralization or chemical adjustment, to further enhance the quality of treated water, particularly in large-scale desalination applications. This stabilization indicates the system's ability to maintain the water's chemical equilibrium while effectively removing contaminants, making the final output safe and suitable for drinking [10].

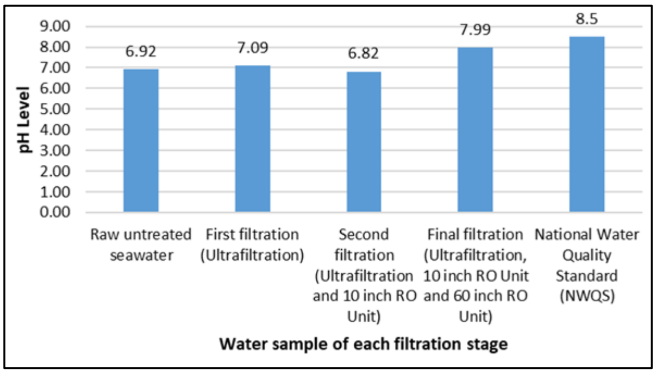

Figure 5: Graph of comparison of pH level at each filtration stage with NWQS

Analysis of Total Dissolved Solid Enhancement

The reduction in Total Dissolved Solids (TDS) concentration throughout the desalination process is a critical indicator of the system's effectiveness in removing dissolved impurities and ensuring the production of potable water. TDS encompasses a wide range of dissolved inorganic salts, organic matter, and minerals, which contribute to the overall quality and taste of water. High TDS levels can affect the palatability of water and pose potential health risks, making their reduction an essential objective in desalination.

Fig. 6 shows the initial TDS concentration in raw seawater was measured at 7216 mg/L, a level characteristic of typical coastal seawater. The first ultrafiltration stage resulted in a significant reduction, bringing TDS down to 1739 mg/L. While ultrafiltration primarily removes suspended solids, bacteria, and macromolecules, its role in reducing TDS is more limited. The observed decrease suggests that ultrafiltration contributed to the removal of certain larger dissolved particles and organic compounds, which in turn facilitated more efficient performance in subsequent filtration stages.

The second stage, which incorporated both large and small reverse osmosis (RO) filters, led to a further reduction in TDS to 1701 mg/L. The relatively small decrease in this stage indicates that while reverse osmosis membranes were effective in rejecting smaller dissolved particles, some salts and dissolved ions remained in the water. This outcome highlights the importance of optimizing RO membrane selection, operating pressure, and recovery rate to maximize salt rejection. Additionally, factors such as membrane fouling and osmotic pressure gradients may have influenced the efficiency of this stage. Further analysis of membrane performance and operational adjustments could help enhance the removal efficiency at this step.

The most substantial reduction in TDS occurred in the fourth stage, where a combination of ultrafiltration and both large and small reverse osmosis filters resulted in a final TDS concentration of 286 mg/L. This value falls well within the acceptable limits specified by the Malaysian Water Quality Standard [13] for potable water, confirming the system's capability to produce high-quality drinking water. The dramatic reduction in this stage can be attributed to the cumulative effect of multiple filtration layers, where each membrane played a role in progressively removing finer dissolved impurities. The presence of both large and small RO filters ensured that different particle size ranges were effectively targeted, leading to a more thorough purification process.

These findings emphasize the necessity of a multi-stage filtration approach for optimal desalination performance. The integration of ultrafiltration as a pre-treatment step proved beneficial in reducing the initial contaminant load, thereby preventing excessive strain on the reverse osmosis membranes and improving overall system efficiency. Furthermore, the staged RO process demonstrated its ability to achieve high levels of TDS removal, ensuring that the final water output met potable water standards.

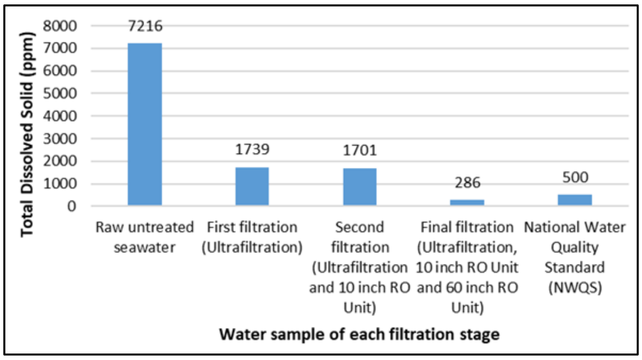

Figure 6: Graph of Comparison of Total Dissolved Solid (TDS) Level at each Filtration Stage with NWQS

Analysis of Salinity Enhancement

The significant reduction in salinity observed throughout the desalination process highlights the effectiveness of the system's multi-stage filtration approach as depicted in Fig. 7. Salinity, a key parameter in seawater desalination, must be reduced to levels that comply with potable water standards to ensure both safety and palatability. The initial salinity of the raw seawater was measured at 8.33 g/L, a typical value for coastal seawater, indicating the necessity of a robust filtration mechanism to achieve substantial desalination.

In the first stage, ultrafiltration alone reduced salinity to 1.81 g/L, demonstrating the ability of ultrafiltration membranes to remove a substantial portion of contaminants [11]. Ultrafiltration, as a pre-treatment step, plays a crucial role in reducing the load on subsequent filtration stages by eliminating larger impurities, organic matter, and microorganisms that may otherwise clog or degrade the performance of reverse osmosis membranes. Although ultrafiltration does not remove all dissolved salts, it serves as an essential preparatory step in the desalination process.

The second stage, incorporating reverse osmosis (RO) filters, resulted in a marginal decrease in salinity to 1.77 g/L. This slight reduction suggests that while the RO process effectively removes finer impurities and dissolved salts, its efficiency may be influenced by operational factors such as membrane fouling, pressure differentials, and recovery rates. In practical applications, optimizing the RO membrane configuration and operating conditions is essential to achieving maximum salt rejection efficiency. The minimal reduction between the first and second stages indicates that the first RO stage primarily served to refine water quality rather than provide significant additional desalination.

The most pronounced reduction in salinity was observed in the fourth filtration stage, where ultrafiltration was combined with both large and small reverse osmosis filters, bringing salinity down to 0.27 g/L. This result underscores the importance of integrating multiple RO membranes with varying pore sizes to enhance the removal of dissolved salts. The synergistic effect of ultrafiltration and staged RO filtration allowed for a more thorough elimination of salts and other dissolved ions, demonstrating that a multi-stage approach is highly effective for desalination. The final salinity value of 0.27 g/L falls well within the acceptable range for potable water, meeting the Malaysian Water Quality Standards and other international drinking water guidelines. This value meets the acceptable standards for potable water, demonstrating the system's capacity to effectively remove salt content [12].

The findings reinforce the necessity of multi-stage filtration in seawater desalination, where each stage contributes incrementally to the reduction of salinity while also addressing other water quality parameters such as turbidity, microbial contamination, and chemical stability. Moreover, the efficiency of the fourth stage highlights the advantages of utilizing a combination of large and small RO membranes, which optimize salt removal by targeting different particle size ranges and improving overall system performance.

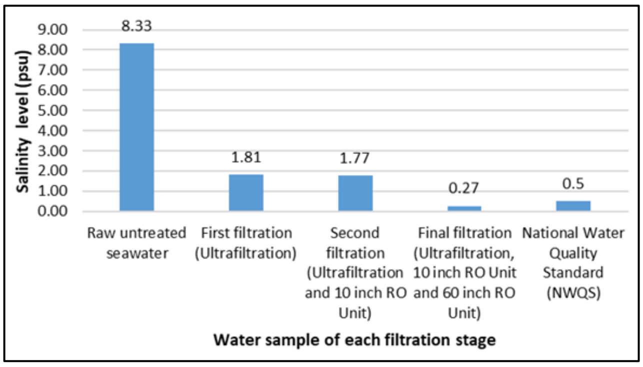

Figure 7: Graph of Comparison of Salinity Level at each Filtration Stage with NWQS

Conclusion

An investigation has been conducted on the development and performance evaluation of a seawater desalination system integrating ultrafiltration and reverse osmosis technologies. Some key conclusions from the study are as follows:

- The system successfully reduced salinity from an initial 8.33 g/L to 0.27 g/L, with the most significant reduction occurring in the fourth filtration stage, demonstrating the effectiveness of multi-stage filtration.
- A substantial reduction in Total Dissolved Solids (TDS) was achieved, decreasing from 7216 mg/L in raw seawater to 286 mg/L in the final output, ensuring compliance with potable water standards.
- The pH of the desalinated water stabilized at 7.99, within the recommended neutral to slightly alkaline range, ensuring the chemical balance and safety of the treated water.
- The integration of ultrafiltration and reverse osmosis technologies proved to be an effective approach in producing high-quality potable water, addressing critical water scarcity challenges.
- The study highlights the potential of advanced desalination technologies as a sustainable solution for freshwater shortages, contributing to the optimization and future development of efficient water purification systems.

In conclusion, the research conducted highlights the vital role of desalination technology in addressing one of the most pressing environmental challenges to access clean and sustainable water. The successful integration of ultrafiltration and reverse osmosis technologies in the proposed system demonstrates a practical and efficient approach to seawater desalination [14]. By achieving water quality standards and emphasizing sustainable practices, this study provides a foundation for further research and development in the field. As the global population continues to grow and freshwater resources become increasingly scarce, the findings of this thesis reaffirm the importance of advanced desalination systems as a cornerstone of future water sustainability strategies.

Acknowledgment

I would like to express my sincere gratitude to the Laboratory Geo-Environment at the Research Centre for Soft Soil (RECESS), Institute of Integrated Engineering, Universiti Tun Hussein Onn Malaysia, Parit Raja, for providing the necessary facilities to conduct this study. Special thanks are extended to UTHM Geran Penyelidikan Pascasiswazah (GPPS Vot: Q676) and UTHM Matching Grant (Vot: Q843) for their financial support, which made this research possible.

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