Eco-Friendly Desalination under Tropical Conditions Using Low-Grade Heat on Indonesian Seawater

Ahmad Zikri[1,2*], *Muhsin* Kılıç[2], *Engkos* Achmad Kosasih[3], *Dieter* Rahmadiawan[4], and *Muhammad* Irfan Dzaky[5]

[1]Department of Mechanical Engineering, Faculty of Engineering, Universitas Sumatera Utara, 20155 Medan, Indonesia
[2]Department of Mechanical Engineering, Faculty of Engineering, Bursa Uludag University, 16059 Bursa, Türkiye
[3]Department of Mechanical Engineering, Faculty of Engineering, Universitas Indonesia, Kampus UI Depok, 16424 West Java, Indonesia
[4]Department of Mechanical Engineering, National Cheng Kung University (NCKU), Tainan, Taiwan
[5]Department of Mechanical Engineering, Politeknik Negeri Sriwijaya, Palembang 30139, South Sumatera, Indonesia

Abstract. Global freshwater shortage and growing energy consumption underscore the demand for emerging environmentally friendly and energy-efficient desalination technologies. The United Nations World Water Development Report predicts that almost six billion people will face water scarcity by 2050. Being the world's largest archipelagic country, Indonesia has a wide range of issues in supplying clean freshwater especially in small islands and remote coastal areas where the availability of groundwater is overwhelmingly limited and threatened with seawater intrusion and seasonal variation. Although desalination presents a promising solution, conventional systems remain highly energy-intensive. This study investigates a renewable, eco-friendly vacuum thermal desalination system that integrates a throttling process with a cyclone separator at the pilot scale. A thermodynamic simulation is conducted to evaluate the influence of heat source temperature (34–90 °C) and post-throttling vacuum pressure (0.7–3.4 kPa) on system performance, expressed in terms of Specific Aquadest Production (SAP) and Specific Energy Consumption (SEC). The results show that SAP increases nearly linearly with heat source temperature, ranging from 0.014 to 0.148 kg/s, with lower vacuum pressures consistently producing higher yields. Meanwhile, SEC values remain within 0.05–0.15 kJ/kg (equivalent to 0.014–0.042 kWh/m³), indicating competitive energy performance compared to conventional thermal desalination systems. These findings support the potential of portable, energy-efficient, and eco-friendly desalination technologies to address freshwater scarcity in tropical island communities such as those in Indonesia.

* Corresponding author: ahmadzikri@usu.ac.id

1 Introduction

The clean water crisis has become one of the most crucial issues facing humanity in the 21st century. The United Nations World Water Development Report (UN-WWDR) predicts that by 2050, nearly 6 billion people on the planet will struggle to access fresh water [1]. Factors such as population explosion, unstoppable urbanization, and the impacts of climate change are exacerbating this situation [2]. Rising global temperatures are increasing evaporation rates, while changing rainfall patterns are reducing the reliability of water supplies in many regions. These conditions urge the development of sustainable, efficient, and eco-friendly clean water supply technologies [3, 4].

Regionally, Indonesia faces unique challenges related to clean water. As the world's largest archipelagic nation with more than 17,000 islands, water resources are unevenly distributed. Many small islands and coastal villages experience limited access to fresh water due to seawater intrusion, limited groundwater reserves, and seasonal rainfall variability [5]. During the dry season, communities on small islands often rely on expensive water distribution from the mainland. Therefore, the need for simple, portable desalination technology suited to tropical climate conditions is crucial to supporting water security in the region [6].

By 2050, the need for desalination will have grown by 40–50% [1]. To meet Sustainable Development Goal (SDG) 6, "clean water and sanitation for all," new technologies need to be tested and put into use in areas that don't already have a reliable source of clean drinking water [7]. Various desalination approaches have been developed, but they still face significant limitations. Reverse Osmosis (RO) technology dominates more than 65% of global desalination capacity due to its efficiency in producing fresh water. This dominance is also reflected in market projections, where the global RO membrane market is estimated to reach USD 9.08 billion by 2032, with a Compound Annual Growth Rate (CAGR) of 10.3% over the 2025–2032 period [8]. Despite its capacity advantages, RO technology still has major drawbacks, particularly related to energy requirements and membrane fouling issues. Innovations in membrane technology, such as high-throughput, low-energy membranes, have facilitated the reduction in SEC (Specific Energy Consumption). Contemporary membranes can attain SEC values as low as 2.0 kWh/m³ under optimum circumstances [9]. Implementing an energy recovery system can reduce the SEC value to 2.5–3.5 kWh/m³, but electricity consumption remains the most significant component of operational costs [9, 10]. Furthermore, scaling has been shown to be a major cause of performance degradation, leading to increased energy consumption due to increased operating pressure and reduced membrane lifespan [7].

Thermal-based desalination technologies, such as Multi-Stage Flash (MSF) and Multi-Effect Distillation (MED), are also widely used, although they face their own limitations. MSF requires a large amount of heat energy, resulting in a relatively low Coefficient of Performance (COP) of 4–7. In contrast, MED offers a higher COP of around 8–12 and shows promising market growth [11]. However, MSF and MED still rely on high-quality heat sources (typically >120°C) and require large-scale infrastructure [12]. This factor results in relatively high initial capital costs and increased operational complexity, making these technologies less suitable for the needs of communities on remote islands or for portable applications.

This research gap opens up opportunities to explore alternative desalination systems that are more efficient and tailored to local needs. Thermal-based vacuum desalination systems are a promising desalination technology because they can operate with low-temperature heat, such as industrial waste heat [3, 4] or solar energy [13]. However, most research still focuses on large-scale solutions, while the urgent need lies in small-scale, portable solutions. Innovations in design, component integration, and thermodynamic performance evaluation

are needed to make this technology a practical solution in the field, particularly in coastal areas.

Thus, this study aims to propose and analyse an eco-friendly portable vacuum desalination system, particularly for tropical island regions such as Indonesia. The studied system integrates a throttling valve for controlled pressure reduction and a cyclone separator for efficient vapor–liquid separation. This integration enables stable low-pressure operation, enhances energy efficiency, and provides portability-features that distinguish this work from previous vacuum desalination studies focused mainly on large-scale or natural vacuum configurations. Performance evaluation is conducted using an energy approach, through the Specific Energy Consumption (SEC) and System Performance Ratio (SAP) parameters. This analysis is expected to provide a more comprehensive understanding of the potential for improving the efficiency of the desalination system, especially a pilot-scale desalination system.

2 Methodology

2.1 System Description and Operating Principle

The desalination system studied in this study is designed with five core components: a pump, a seawater heater, a throttling valve, a cyclone separator, and an air-cooled condenser. Figure 1 shows a schematic of the studied desalination system, where the process begins with pumping seawater into the heating unit at ambient conditions (temperature T_0 and atmospheric pressure). Here, the water temperature is raised to an operating range of 34–90°C (with study intervals of 8°C) using a low-temperature heat source, such as industrial waste heat or a solar collector. This operating window was selected to reflect practical low-grade heat sources available in tropical regions. Temperatures around 40–70 °C are typical for solar-heated water in Indonesia, while waste heat from small-scale to medium-scale industries often falls below 100 °C. An upper limit of 90 °C was chosen to ensure system safety and to represent the practical threshold of many low-grade heat recovery systems.

After reaching the target temperature, the seawater is then flowed through a throttling valve. This valve suddenly reduces the pressure to a very low vacuum, between 0.7–3.4 kPa (with intervals of 0.3 kPa). This drastic pressure drop instantly causes some water to evaporate (flash evaporation) in the vacuum chamber. The mixture of water vapor and remaining water droplets is then flowed into the cyclone separator. Inside the separator, centrifugal force effectively separates the saturated vapor from the liquid droplets. The separated pure vapor is then condensed in an air-cooled condenser to be converted into fresh water and stored.

The main advantage of this system design is its ability to actively control the vacuum pressure, unlike natural vacuum systems that rely on gravity. Furthermore, integration with a cyclone separator significantly increases the efficiency of steam-water separation. This combination allows the system to operate more stably at low pressures and supports a portable design.

Beyond focusing solely on fresh water production, this system is also designed with brine waste (concentrated salt water) in mind. The concentrated solution produced by the cyclone separator is channelled to a brine tank for further processing. Further processing can involve a final evaporation unit or thermal crystallization to extract the salt. The extracted salt is then stored in a storage unit for further use, either for industrial or commercial purposes. This integrated approach supports the Zero-Liquid Discharge (ZLD) principle, which ensures that no liquid waste is discharged directly into the environment. Thus, this system is not only

more sustainable and reduces the environmental impact of brine discharge into the sea, but also adds economic value through its by-product, salt.

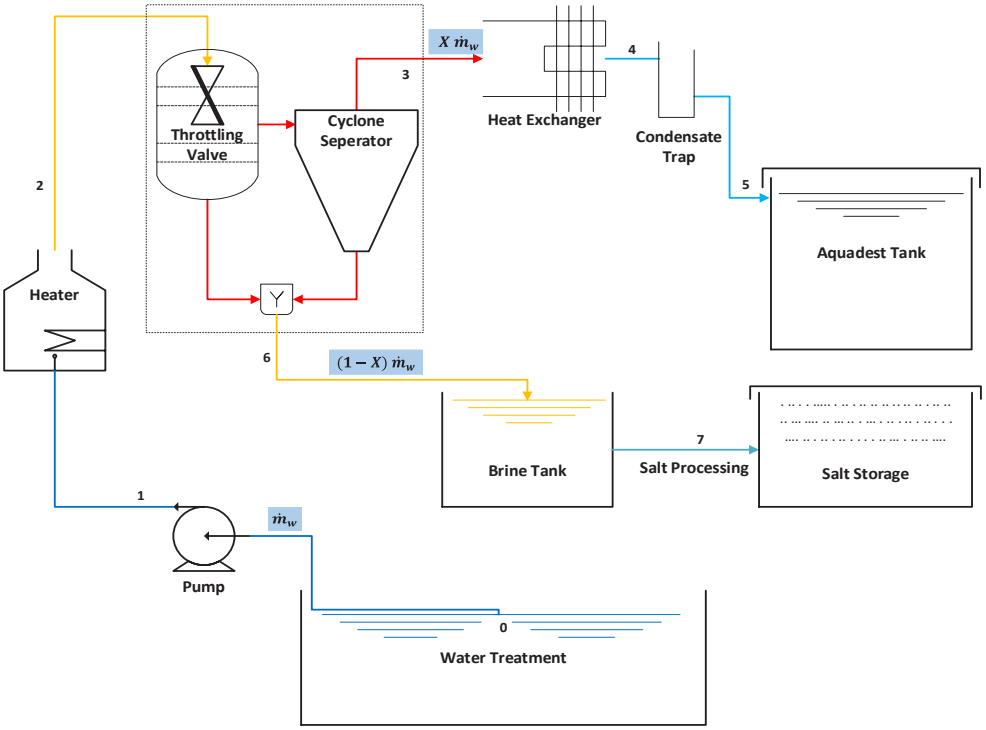

Fig. 1. Schematic diagram of a desalination system.

2.2 Theoretical Analysis

The desalination system studied in this study is a low-grade heat-based thermal desalination system that operates on the principle of flash evaporation under low pressure (vacuum) through throttling and phase separation using a cyclone separator, and vapor condensation in an air-cooled condenser. The analysis was conducted using an approach adapted from analytical models validated in the literature, but adapted for systems with controlled vacuum pressure (via a throttling valve) and mechanical vapor separation (using a cyclone separator). In short, the analysis in this study was conducted using an energy and exergy balance approach, and refers to the first and second laws of thermodynamics under steady-state conditions.

The desalination system begins with seawater at atmospheric pressure (p_0 = 1 atm) and ambient temperature (T_0) pumped from the water treatment tank to the heater. The mechanical energy required by the pump (pump ratio = 5) to increase the pressure is calculated based on the change in enthalpy, where the enthalpy after the pump (h_1) is obtained from:

$$h_1 = h_0 + v_f(p_1 - p_0) \quad (1)$$

with a pump efficiency of 85% used to determine the actual power. The value of v_f here is the specific volume of liquid water (m^3/kg) and p_1 is the output pressure to the closed

system (kPa). Therefore, to calculate the pump power (W_p), the following equation can be used:

$$W_p = \dot{m}_{sw}\,(h_1 - h_0) \quad (2)$$

The pumped water is then heated using a low-grade heat source (34–90°C), such as an electric heater or solar collector. This process increases the water temperature from T_1 to T_2, with the energy requirement ($Q_{in} = W_h$) calculated using the equation:

$$Q_{in} = \dot{m}_{sw}\,c_{p,sw}\,(T_2 - T_1) \quad (3)$$

wherein, $\dot{m}_{sw}$ is the mass flow rate of seawater (kg/s) and $c_{p,sw}$ is the specific heat of seawater (kJ/kg.K). This energy is completely transferred to the seawater, assuming no loss to the environment.

After reaching the specified temperature, the hot water flows to the throttling valve. This process is isenthalpic ($h_2 = h_3$), causing a drastic pressure drop from atmospheric conditions to vacuum conditions (0.7–3.4 kPa), resulting in some of the seawater immediately undergoing spontaneous evaporation (flash evaporation). The fraction of vapor (X) formed from this mixture can be calculated from:

$$h_3 = h_f + X\,h_{fg} \quad (4)$$

where h_f is the liquid enthalpy at vacuum pressure (kJ/kg) and h_{fg} is the latent heat of vaporization (kJ/kg). Therefore, the resulting vapor mass flow rate ($\dot{m}_v$) is then obtained from $\dot{m}_v = X\,\dot{m}_w$; where the vapor mass flow rate or distilled water mass flow rate ($\dot{m}_{aq}$) can also be referred to as SAP (specific distilled water production).

The fluid (vapor and liquid mixture) from the vacuum chamber flows to a cyclone separator. This component utilizes centrifugal force to separate the liquid particles from the saturated vapor, and the remaining liquid flows as brine to the salt recovery unit. Near-perfect separation efficiency is assumed, so only dry vapor proceeds to the heat exchanger (air-cooled condenser).

The separated water vapor enters an air-cooled condenser, equipped with fins and a fan. In this heat exchanger, steam is condensed isobarically at saturation temperature (T_{sat}), and the following equation calculates the heat released during the process (Q_c):

$$Q_c = \dot{m}_v\left[h_{fg} + c_{p,w}\,(T_c - T_{sat})\right] \quad (5)$$

This energy is transferred to the incoming cooling air at an initial temperature ($T_{a,i}$). The increase in air temperature ($T_{a,o}$) as a result of the absorption of condensation heat can be calculated using the energy balance:

$$Q_c = \dot{m}_a\,c_{p,a}\left(T_{a,o} - T_{a,i}\right) \quad (6)$$

Assuming that the air pressure remains constant and its specific heat capacity remains constant, the stability of the liquid phase after condensation is crucial to prevent re-evaporation, especially in this low-pressure, air-cooled condenser system. After condensation, the liquid water cools to approximately 27°C (air temperature). However, the pressure inside the condenser is still a vacuum (e.g., 0.7 kPa); at this pressure, liquid water at 27°C is well above its boiling point (1.88°C). Therefore, thermodynamically, the liquid will

tend to re-evaporate if not immediately removed or transferred to atmospheric pressure. Thus, to prevent re-evaporation and transfer the water to the atmospheric-pressure aquadest tank, a pressure difference (vacuum → atmospheric) can be created by using a one-way valve (check valve) placed between the condenser and the aquadest tank. This forces the water into the aquadest tank and prevents it from returning to the vacuum area.
Through this thermodynamic modelling, various combinations of temperature (low-grade heat source) and vacuum pressure will be numerically simulated, in order to evaluate the influence of these parameters on the efficiency and output of the system (both SAP and SEC). Where, to obtain the specific energy consumption (SEC) which is the total power requirement/energy consumption (EC) per unit mass flow rate of distilled water ($\dot{m}_{aq}$) used in this desalination system, it can be determined using the following equation.

$$SEC = \frac{EC}{\dot{m}_{aq}} = \frac{W_p + W_h}{\dot{m}_{aq}} \quad (7)$$

3 Results and discussion

Comprehensive thermodynamic analysis was conducted to evaluate the performance of an environmentally friendly desalination system under tropical conditions using low-grade heat from Indonesian seawater. Two main parameters were used to describe the system performance: Specific Aquadest Production (SAP), which represents the quantity of freshwater produced per unit of input heat energy, and Specific Energy Consumption (SEC), which indicates the energy requirement per unit mass of distillate. These two parameters were analysed by varying the heat source temperature (34–90 °C with 8 °C intervals) and the vacuum pressure after throttling (0.7–3.4 kPa with 0.3 kPa intervals). The results provide an overview of the relationship between operating conditions, energy efficiency, and system productivity, while also indicating potential operating points for practical applications in tropical areas with low to medium temperature heat availability.

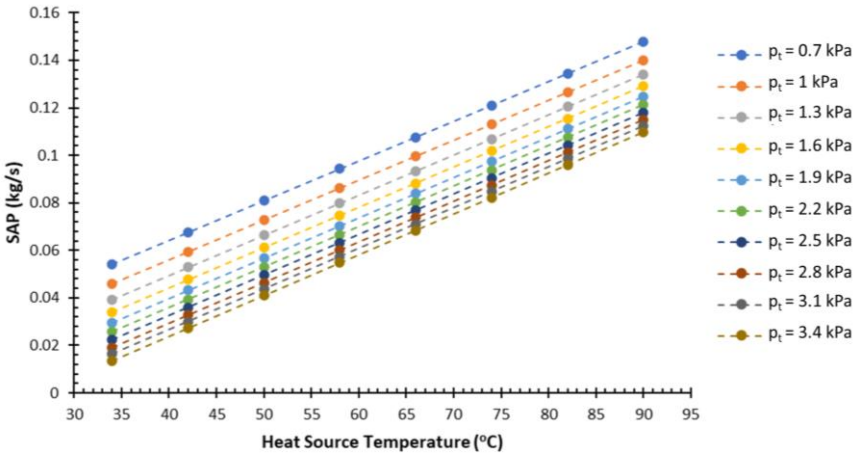

Fig. 2. Specific Aquadest Production (SAP) at various heat source temperatures and throttling pressures.

The **Fig. 2** shows that SAP increases linearly with increasing heat source temperature at all vacuum pressure conditions. At low temperatures (34°C), SAP remains relatively small (<0.06 kg/s), but increases sharply to over 0.148 kg/s at 90°C for the lowest vacuum pressure (0.7 kPa). This linear relationship is consistent with the flash evaporation theory, where the

higher the heat energy supplied, the greater the fraction of vapor (X) formed, thus increasing the freshwater production rate.

In addition to temperature, vacuum pressure significantly influences SAP. Lower vacuum pressures (0.7 kPa) increase SAP, while at higher pressures (3.4 kPa), SAP decreases by almost a quarter at the same temperature (90°C). This value is due to the greater difference in effective enthalpy of vaporization at lower pressures, which increases the flash evaporation fraction. In other words, deeper vacuum conditions facilitate greater spontaneous evaporation even with the same heat energy input.

When both parameters are considered together, it is clear that the combination of high heat source temperature and low vacuum pressure yields the highest SAP. For example, at 90°C and 0.7 kPa, the SAP reaches around 0.15 kg/s, while at the same conditions but at a higher pressure (3.4 kPa), the SAP is only about ~0.11 kg/s. This value means the performance difference between operating conditions can be more than 25%.

Upon closer analysis, the slope of the SAP curve versus temperature varies across vacuum pressures. At very low vacuum pressures (0.7–1 kPa), the slope is relatively high, at around 0.00166 kg/s·°C, meaning that every 10°C increase in heat source temperature results in an additional production of approximately 0.0166 kg/s of distilled water. Conversely, at higher vacuum pressures (3.1–3.4 kPa), the slope decreases to only 0.00100 kg/s.°C, or an increase in SAP of approximately 0.01 kg/s for every 10°C increase. This value shows that the effect of increasing the heat source temperature on SAP is more significant under low vacuum pressure conditions (0.7–1.0 kPa) than under higher vacuum pressure conditions (2.5–3.4 kPa).

The **Fig. 3** shows the relationship between Specific Energy Consumption (SEC) and vacuum pressure after throttling within the range of 0.7–3.4 kPa at varying heat source temperatures (34–90 °C). It can be seen that SEC decreases with increasing vacuum pressure. At high vacuum conditions (around 0.7–1.3 kPa), the SEC value is relatively large because the liquid–vapor enthalpy difference is significant, requiring more energy to produce the vapor phase. Conversely, when the pressure is increased to around 2.8–3.4 kPa, the energy requirement per unit mass of fresh water decreases, indicating that the process is more efficient at lower vacuum conditions.

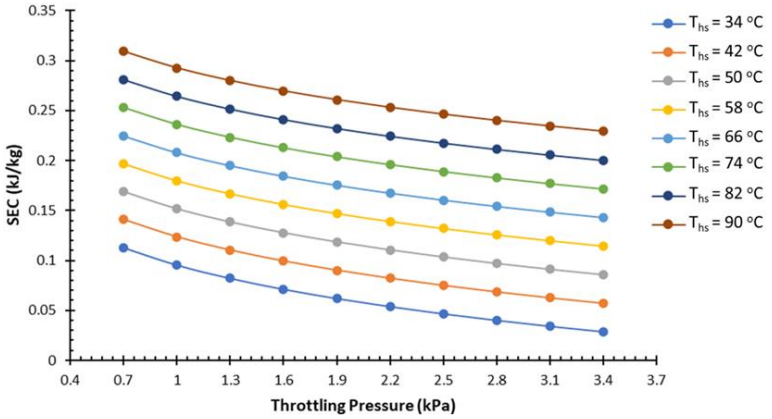

Fig. 3. Specific Energy Consumption (SEC) at various throttling pressures and heat source temperatures.

Furthermore, the heat source temperature also consistently affects system behaviour. Increasing the temperature from 34 °C to 90 °C results in an increasing trend in SEC. SEC reaches a minimum value at lower temperatures, for instance, around 0.028 kJ/kg (0.008 kWh/m³) at 34 °C and a pressure of 3.4 kPa. However, at high temperatures, such as 90°C,

the SEC value can increase to over 0.229 kJ/kg (0.063 kWh/m³) at the same pressure. This phenomenon indicates that although higher heat source temperatures increase the evaporation rate, the energy required to maintain the liquid-vapor enthalpy difference also increases, resulting in higher specific energy consumption.

In terms of feasibility, the system demonstrates a Specific Energy Consumption (SEC) of 0.028–0.229 kJ/kg (0.008–0.063 kWh/m³), which is far below the values typically reported for established desalination technologies. For comparison, seawater reverse osmosis (SWRO) usually requires 1.88–5.2 kWh/m³ depending on design and operating conditions [14]. Multi-stage flash (MSF) is among the most energy-demanding processes, with SEC values of about 25 kWh/m³, while multi-effect distillation (MED) is more efficient than MSF but still higher than RO, with SEC around 12 kWh/m³ when low-grade steam is sourced from turbines [15]. Although this work does not include a full cost assessment, the results suggest that the proposed system provides a considerable energy advantage, particularly for decentralized use in tropical settings.

The interaction between temperature and pressure shows that the effect of pressure is more dominant at low temperatures. For instance, at 34°C; the decrease in SEC with increasing pressure is significant, while at high temperatures, such as 90°C; the difference in SEC across pressure variations is smaller. This value indicates that increasing temperature tends to suppress the benefits gained from adjusting the vacuum pressure. From an operational perspective, the combination of intermediate temperatures (50–66°C) with moderate pressure (around 1.9–2.5 kPa) can be considered optimal, as the SEC is relatively low while avoiding technical requirements such as extreme vacuum and high temperature.

4 Conclusions

This study shows that the performance of the thermal desalination system is significantly influenced by the heat source temperature and vacuum pressure after throttling. Specific Aquadest Production (SAP) increases almost linearly with increasing heat source temperature (34–90 °C), with the highest values achieved at low vacuum conditions (0.7–1.0 kPa). The significant variation of SAP, around 0.014–0.148 kg/s, highlights the system's sensitivity to changes in operating parameters and the importance of maintaining a stable deep vacuum to maximize freshwater production. In the moderate temperature range (50–70 °C), operation at low pressure (0.7–1.3 kPa) provided the best balance between energy consumption and distillate yield. Specific Energy Consumption (SEC) values in the range of 0.05–0.15 kJ/kg (0.014–0.042 kWh/m³) indicate high efficiency compared to conventional thermal desalination technologies. Beyond freshwater generation, the system also shows potential for supporting Zero-Liquid Discharge (ZLD) strategies, as the concentrated brine can be further utilized or processed to recover valuable minerals, thereby minimizing environmental impact. These findings highlight the potential of portable vacuum thermal desalination systems with low-temperature to medium-temperature heat sources, such as solar energy or industrial waste heat, as a sustainable and resource-efficient solution for freshwater supply in tropical regions.

Acknowledgements

The authors would like to express their sincere gratitude to Universitas Sumatera Utara (USU), Universitas Indonesia (UI), and Bursa Uludag University (BUU), Türkiye, for their support and collaboration in the development of this research. This work has greatly benefited from the exchange of knowledge, facilities, and expertise enabled through this academic partnership. The authors also acknowledge the contributions of colleagues and students who helped prepare this manuscript until the end.

References

[1] A. Boretti and L. Rosa, "Reassessing the projections of the world water development report," *NPJ Clean Water,* vol. 2, no. 1, p. 15, 2019.

[2] H. Zou, F. Wang, Z. Zeng, J. Zhu, L. Zha, D. Huang, J. Li, and R. Wang, "Next-generation water-saving strategies for greenhouses using a nexus approach with modern technologies," *Nature Communications,* vol. 16, no. 1, p. 2091, 2025.

[3] M. I. Dzaky, E. A. Kosasih, and A. Zikri, "Thermodynamic Simulation in Eco-Friendly Aquadest Production Through Compression System Method Combined with Steam Power Plant as Heat Source," *Journal of Advanced Research in Fluid Mechanics and Thermal Sciences,* vol. 100, no. 1, pp. 63-76, 2022.

[4] A. Zikri and M. Kılıç, "Thermodynamic assessment of a desalination system integrated with combined cycle power plant via throttling process by using a vapour compressor," *International Journal of Exergy,* vol. 46, no. 3-4, pp. 200-215, 2025.

[5] T. Solihuddin, J. Prihantono, A. Daulat, R. Bramawanto, J. Risandi, T. L. Kepel, A. Heriati, and E. Mustikasari, "Assessment of a small island's groundwater resilience under the pressure of anthropogenic and natural stresses on Tunda Island, Indonesia," *Environmental Earth Sciences,* vol. 83, no. 12, p. 380, 2024.

[6] A. Zikri, E. A. Kosasih, M. I. Dzaky, and M. P. Wibisono, "Investigation of outlet temperature on heat exchanger 1 and cyclone pressure of specific energy consumption and cooling heat in renewable desalination systems," in *AIP Conference Proceedings*, 2021, vol. 2376, no. 1: AIP Publishing LLC, p. 090014.

[7] L. Abkar, A. A. Mehrizi, M. Jafari, S. E. Beck, A. Ghassemi, and M. C. Van Loosdrecht, "Optimizing energy efficiency in brackish water reverse osmosis (BWRO): A comprehensive study on prioritizing critical operating parameters for specific energy consumption minimization," *Science of the Total Environment,* vol. 932, p. 172772, 2024.

[8] M. A. Ahmed, S. Amin, and A. A. Mohamed, "Fouling in reverse osmosis membranes: monitoring, characterization, mitigation strategies and future directions," *Heliyon,* vol. 9, no. 4, 2023.

[9] C. Wang, L. Wang, L. Dong, H. K. Shon, and J. Kim, "Specific energy consumption of seawater reverse osmosis desalination plants using machine learning," *Desalination,* vol. 602, p. 118654, 2025.

[10] R. Saeed, A. Konsowa, M. S. Shalaby, M. S. Mansour, and M. Eloffy, "Optimization of integrated forward–reverse osmosis desalination processes for brackish water," *Alexandria Engineering Journal,* vol. 63, pp. 89-102, 2023.

[11] Y. R. Temsamani, A. Al Mers, and Y. F. Baba, "Renewable-Powered Seawater Desalination: Technologies, Challenges, and Opportunities with a Focus on Morocco," in *EPJ Web of Conferences*, 2025, vol. 326: EDP Sciences, p. 04001.

[12] Y. Zheng, R. A. Cáceres González, M. C. Hatzell, and K. B. Hatzell, "Challenges and roadmap for solar-thermal desalination," *ACS ES&T Engineering,* vol. 3, no. 8, pp. 1055-1082, 2023.

[13] B. Winchester, G. Huang, H. Beath, P. Sandwell, J. Cen, J. Nelson, and C. N. Markides, "Lifetime optimisation of integrated thermally and electrically driven solar desalination plants," *npj Clean Water,* vol. 7, no. 1, p. 65, 2024.

[14] J. Feo-García, A. Pulido-Alonso, A. Florido-Betancor, and N. R. Florido-Suárez, "Cost studies of reverse osmosis desalination plants in the range of 23,000–33,000 m3/day," *Water,* vol. 16, no. 6, p. 910, 2024.

[15] M. Darwish, F. Al Asfour, and N. Al-Najem, "Energy consumption in equivalent work by different desalting methods: case study for Kuwait," *Desalination,* vol. 152, no. 1-3, pp. 83-92, 2003.