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Performance evaluation of a dual-mode solar distillation system for desalinating seawater: Evidence from Java's northern coast

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ABSTRACT

The clean water crisis in Indonesia's coastal regions has become worse because of seawater intrusion and excessive groundwater usage which needs affordable sustainable water treatment solutions. The research will test how well a basic solar-powered distillation unit creates fresh water from saltwater while studying two distinct operational methods which include System A by solar heating alone and System B that adds an electric heater to the system. The glass distillation unit operated through two separate modes which allowed seawater samples to be processed by both systems. The testing of distillation outcomes together with wastewater analysis followed standard water quality testing procedures through physical and chemical and microbiological assessments which included salinity measurement and total dissolved solids (TDS) evaluation and pH level detection and Cr^{6+} content analysis and nitrate measurement and total coliform and fecal coliform testing. The study results demonstrate that both systems achieve 99.94–100% salinity reduction and 99.93–99.95% TDS removal while achieving over 99% efficiency in Cr^{6+} and nitrate elimination. Microbiological testing results showed all coliforms and fecal coliforms were completely eliminated during the process. The distillate product created a solution with pH levels that fell below the drinking water standards which needed extra processing. Solar distillation produces safe water according to the research but adding an electric heater stabilizes the process without water quality changes. The system operates under two main restrictions because it depends on weather patterns and requires distillate remineralization before people can drink it. The dual-mode system provides an effective solution which coastal communities can apply to address their water needs. The research makes a unique contribution through its combined system design and complete assessment of both distillate and process wastewater quality which demonstrates solar distillation effectiveness as a sustainable water supply.

Keywords: seawater desalination, water quality, renewable energy, low-cost desalination.

INTRODUCTION

Access to clean and safe water is a fundamental aspect in ensuring public health, environmental sustainability, and socio-economic development (Nguea, 2024; Wibowo et al., 2024). In Indonesia, especially in urban and coastal areas, the demand for clean water continues to increase along with population growth, urbanization, and changes in people's lifestyles (Rudiarto et al., 2018). Based on data from the Central Bureau of Statistics (BPS, 2023), national clean water distribution in 2022 reached 5,267.5 million cubic meters, an increase of 0.28% from the previous year and an increase of 7.75% compared to 2012 (BPS, 2013). In addition, Bappenas (2021) noted that the average daily water demand per capita in Indonesia has reached 157 liters in 2020-the highest figure so far. Unfortunately, this increased demand has not been matched by adequate diversification of water resources. To date, most Indonesians still rely heavily on groundwater as the main source of their daily needs (Khasanah et al., 2021). This dependence, coupled with a lack of sustainable water resources management, has led to declining groundwater levels, land subsidence, and widespread seawater intrusion in coastal areas (El Shinawi et al., 2022; Hussain et al., 2019).

In facing these challenges, seawater is one of the potential alternative resources. Seawater covers about 97.5% of the total volume of water on Earth (Issaoui et al., 2022), and Indonesia, as an archipelago, has a coastline of more than 81,000 km and a sea area of 5.8 million km² (Jayawibawa, 2024). Therefore, the utilization of seawater through desalination technology is a strategic choice in meeting clean water needs, especially in coastal areas. Desalination is the process of removing salt and other solutes from seawater so that it can be used as consumable water. One desalination method that is relevant for remote and low-power areas is thermal distillation, which is heating seawater until it evaporates, then condensing the water vapor into fresh water (Younos and Lee, 2020). Compared to the reverse osmosis method, which requires high pressure and expensive infrastructure, solar distillation is more suitable in areas without adequate access to electricity (Shalaby et al., 2022). Several previous studies have shown that simple distillation systems can reduce salinity, total dissolved solids (TDS), and heavy metal content such as chromium and nitrate (Aijaz et al., 2022; Arunkumar et al., 2021). However, there are still limitations that have not been studied, such as the pH stability of the distilled water, microbiological safety, and the environmental impact of the process wastewater (Ahmad et al., 2022; Chowdhary et al., 2017).

However, despite these advancements, previous studies generally evaluated only single-mode distillation systems and did not examine how different heating configurations influence purification efficiency, process stability, and the chemical–microbiological quality of the distillate and wastewater. This indicates a clear knowledge gap and highlights an unresolved scientific problem regarding the lack of comprehensive empirical evidence on the performance of simple solar-driven distillation systems, particularly when auxiliary electric heating is incorporated.

This work presents a new perspective by assignment of a dual-mode distillation system based on the combination of natural-solar heating electricity with supplementary heating. The goal is to enhance the evaporation efficiency and speed up the freshwater production process, while ensuring the energy sustainability. As opposed to the other works, which would either assess a single system, the two systems are compared simultaneously: System A (solar system) and System B (solar system accompanied with electric heating). Moreover, this study utilizes a wider range of assessment framework unit types, covering physical (salinity, TDS), chemical (Cr^{6+}, nitrate), microbiological (total and fecal coliform) and wastewater quality assessment parameters. Pemalang district, Central Java, a northern coastal region of Java Island where seawater intrusion is high, was selected as the study site. Asyifa and Wibowo (2020) reported that the share of sources of water in the region that account for more than 11% is salty to taste and odor, and 55.55% of the water is turbid, then becomes the coverage area of interest for the development of cheap, alternative technology of local very urgent to be implemented.

The primary purpose of this study was to investigate the performance of a low-cost large-scale solar energy driven distillation system for the production of freshwater from seawater in the coastal zone which is facing a fresh water crisis as a result of seawater encroachment. Two systems were investigated with/without electric heating for salinity/TDS reduction, pH stabilization, and removal of chemical and pathogenic contaminants. Furthermore, it addressed the field quality of the effluent escaping in connection with the distillation to secure that there was no contribution to the environmental pollution. In accordance to national drinking water quality standards (SNI) and international guidelines (WHO), we anticipate the results of this research to become the foundation for environmentally sustainable, locally renewable energy based and replicable solutions for clean water access in coastal areas throughout Indonesia a limited access to water supply under threat due to climate change and other hydrologic stresses.

Based on the identified research gap, this study aims to generate new scientific understanding of the relationship between heating configuration, evaporation performance, contaminant removal efficiency, and overall distillate and wastewater quality. This study specifically seeks to determine whether a hybrid configuration (solar heating and electric heating) can improve operational stability without reducing the effectiveness of the purification process. The main hypothesis proposed is that both systems are capable of achieving high desalination and contaminant removal performance, but the hybrid system is expected to provide more stable thermal regulation, resulting in more consistent evaporation rates and more uniform contaminant reduction outcomes. In addition, this study scientifically expect that variations in heating mode will show a measurable relationship with key performance indicators such as salinity reduction, TDS removal, pH stabilization, and the reduction of chemical and microbiological contaminants. These hypotheses are formulated to provide empirical evidence on how dual-mode heating influences distillation efficiency and water quality an aspect that has not been adequately explored in previous studies.

MATERIAL AND METHODS

Study area

This research was conducted in the coastal area of Pemalang Regency, Central Java Province, Indonesia (Figure 1), with a special focus on the Kertosari Beach area. Kertosari Beach is in Kertosari Village, Ulujami Subdistrict, which is one of the coastal areas in the northern part of Pemalang Regency. Geographically, this location is on the north coast of Java Island which is directly adjacent to the Java Sea. Kertosari Beach is known as a local tourist destination, but it is also an area that is vulnerable to environmental impacts such as tidal flooding and seawater intrusion due to sea level rise and land subsidence. This area was chosen as the study site because it shows real problems related to the quality and availability of clean water. Based on the findings of Asyifa and Wibowo (2020), more than 11% of clean water sources in the Pemalang coastal area have a salty taste and unpleasant odor due to seawater intrusion. In addition, around 55.55% of the water is classified as cloudy and not suitable for direct consumption without additional processing. This phenomenon is exacerbated by community activities that still rely on shallow wells and groundwater as the main source of daily needs, even though the quality of groundwater in coastal areas is increasingly degraded due to salinity contamination. These geographical and hydrological conditions make Kertosari Beach an appropriate location for testing seawater distillation systems into fresh water. With representative environmental characteristics of coastal areas in general, research at this location is expected to provide an applicative picture of the effectiveness of solar distillation-based desalination technology that can be widely applied in other coastal areas of Indonesia that face similar challenges in terms of clean water availability.

Apparatus components and structural design of the distillation system

This study employs a field-adaptable solar desalination system designed to be low-cost, replicable, and operable in remote coastal environments.

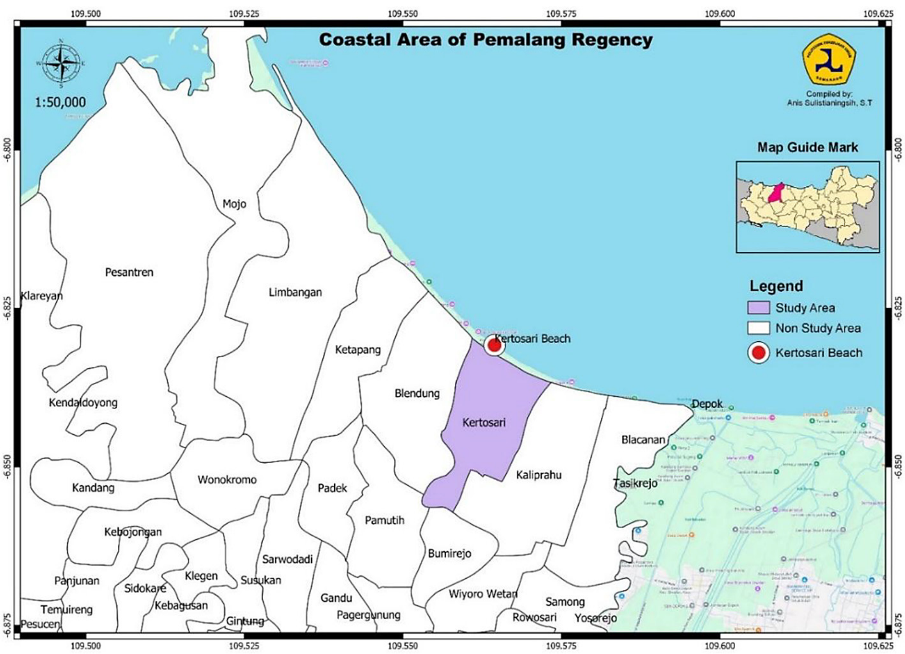

Figure 1. Study map

The apparatus consists of two distillation units fabricated using locally available materials and optimized for passive and hybrid (solar-electric) thermal energy inputs. The objective of the design is to test and compare the distillation performance and water quality output between a solar-only system (System A) and a solar-electric hybrid system (System B) under real environmental conditions. Each unit adopts a simple box-like structure with a transparent glass envelope forming the walls and roof. As shown in Figure 2, the roof is a triangular prism configuration with a 60° slope, designed to maximize solar radiation capture while promoting efficient gravitational runoff of condensed water droplets. This sloped design also increases the surface area for condensation, thereby enhancing collection efficiency. The glass panels (Component A in Figure 3) serve a dual function as both solar collectors and condensers. The transparency of the glass allows solar radiation to penetrate and heat the internal seawater, while the inner surface of the roof facilitates condensation of water vapor into liquid. The interior water basin (Component B) is positioned at the base of each unit and is used to contain raw seawater during operation. These basins are made of waterproof, heat-resistant material and have a high thermal mass to retain heat throughout the day. Each basin is partially filled to allow sufficient headspace for evaporation. To increase the surface area for evaporation and enhance capillary-driven heat distribution, flannel cloths are suspended inside each unit. These cloths are hung in such a way that they are partially submerged, drawing water upward via capillary action and distributing it across the fabric. This facilitates faster and more uniform evaporation. Though not visible in Figure 3, this internal component plays a critical role in the thermal efficiency of the system. A central feedwater tank (Component C), made from polyethylene, stores raw seawater and delivers it via a PVC piping network (Component D) to both units. This gravity-fed system ensures consistent flow and minimizes the need for pumping, which is ideal for off-grid settings. The PVC piping is lightweight, corrosion-resistant, and easy to install or replace. The condensed water produced inside the units is channeled via sloped interior surfaces to outlet valves and connectors (Component F). From there, the distillate flows through outlet tubes into jerry cans (Component E) placed outside each unit. These containers serve as clean water storage and are routinely sampled for physicochemical and microbiological analysis.

In System B, an auxiliary electric heater is installed beneath the water basin to increase evaporation temperatures during periods of low solar irradiance, such as cloudy days or early mornings. This component is not visible in the photograph (Figure 3) but is included in the schematic (Figure 2) and described in the text. The heater is controlled manually and monitored using a digital thermometer (not shown) to avoid overheating and ensure safety. To further support the functionality of the setup, a blue tarpaulin (Component G) is included on site. This tarpaulin is used for two main purposes: (1) to cover the system during nighttime or inclement weather to reduce heat loss and contamination risk, and (2) as an insulating layer placed underneath or around the basin if ambient temperatures are too low. The system is intentionally designed to minimize moving parts, reduce reliance on complex infrastructure, and be operable by local communities with minimal technical training. The use of glass, PVC, and basic thermal principles makes the design accessible and maintainable. By comparing the performance of the two systems under identical environmental conditions, the study aims to isolate the effect of auxiliary electric heating on freshwater yield, process stability, and contaminant removal efficiency. Figure 2 presents the conceptual schematic of the system's structure and functional elements. Figure 3 depicts the actual field implementation in Pemalang, with key components labeled (A–G) to enhance clarity and ensure direct correspondence between the described apparatus and the visual documentation. Internal components, such as the flannel cloth and electric heater, are not externally visible but are explicitly discussed in both text and schematic.

Experimental procedure

The experimental procedure was redesigned and described in a step-by-step manner to ensure full transparency, reproducibility, and consistency with the actual field setup shown in the figures. The entire workflow follows the sequence illustrated in Figure 4, starting from seawater collection to final data analysis. First, seawater samples were collected from the coastal site and passed through a pre-filtration stage to remove coarse sediments and suspended particles. The pre-filtered water was then characterized using standard field instruments (salinity, TDS, conductivity, pH) to establish baseline conditions before treatment.

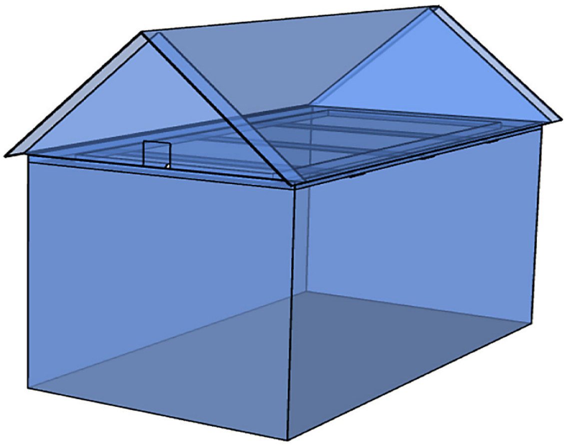

Figure 2. Visualization of the dual-mode solar distillation system

Following water characterization, the glass distillation units were fabricated according to the design shown in Figure 2. After construction, both units were thoroughly cleaned and dried to prevent contamination. The flannel cloth was installed in each unit in a partially submerged orientation, allowing it to draw water upward through capillary action and increase the effective evaporation surface area. This configuration is essential for stabilizing thermal distribution across the basin.

The experimental setup was then arranged in the field as shown in Figure 3. Seawater from the feed tank was directed into each unit via the PVC piping network. System A was operated using solar radiation only, while System B incorporated an auxiliary electric heater, activated under controlled conditions to evaluate the influence of supplemental heat on evaporation performance. During operation, solar and electric heating gradually increased the basin temperature, causing seawater to evaporate. Water vapor rose and contacted the inner surface of the sloped glass collector, where a temperature gradient allowed condensation to occur. Condensed droplets flowed downward along the glass surface into integrated channels and through outlet pipes into distillate jerry cans. Distillate and brine samples were collected at predetermined intervals, ensuring a representative comparison of both systems. All samples were then taken to the laboratory for physicochemical and microbiological assessment in accordance with national and international water quality guidelines. To support replicability, each step; water collection, filtration, distillation operation, sampling, laboratory testing, and performance evaluation was visually documented. This documentation ensures alignment between the written methodology and the actual experimental workflow. Figure 4 presents the complete visual sequence of the experimental procedure, covering sample collection, filtration, system operation, and final analysis.

RESULT AND DISCUSSION

Salinity and TDS reduction

The performance of the two systems is presented in Table 1 and illustrated through the

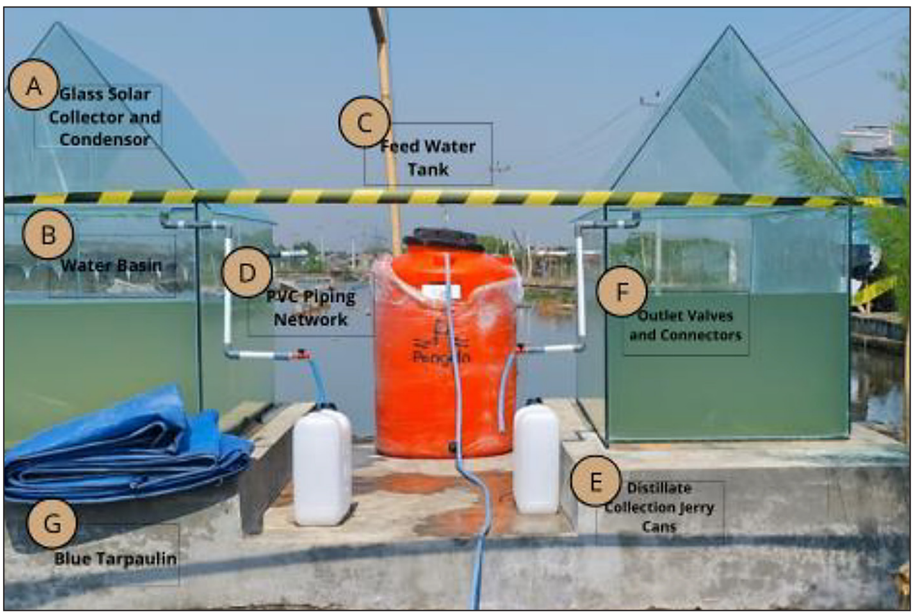

Figure 3. Field implementation of the dual solar distillation units in Pemalang coastal site

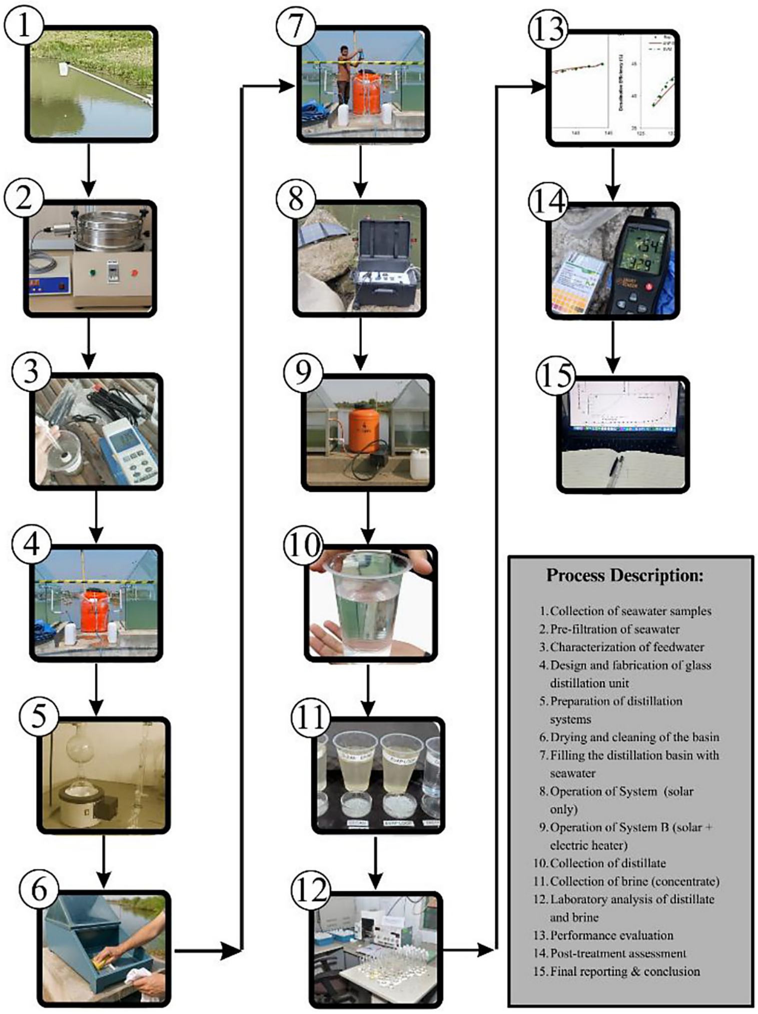

Figure 4. Experimental study

corresponding graphs, allowing direct comparison of the inlet seawater with the distillate produced by both systems. Instead of describing the numerical values in text, this section now focuses on interpreting the trends shown in the table, following the reviewer's instruction. The values in Tables 1 and 2 were obtained from direct measurements conducted during the experiment, where seawater inlet and distillate samples were analyzed using a portable digital water quality meter (Hanna Instruments HI98192). All measurements were carried out by the research team in August 2024, with each parameter measured in triplicate and averaged to ensure accuracy and reproducibility. The comparison clearly indicates a substantial decline in both salinity and TDS after treatment.

Thus, both systems have successfully reduced salt and solute levels in seawater to well below the clean water quality threshold. Technically, the system with auxiliary heating (B) showed more optimal performance than the system without auxiliary heating (A), especially in terms of total salinity elimination. However, it should be noted that the use of electric heating also means increased energy consumption and operational costs, which should be considered in the context of efficiency and sustainability. These findings are in line with the results of the study by Thomas (1997) who reported that a solar distillation system was able to reduce salinity from 28,000 ppm to below 100 ppm with a TDS removal efficiency of more than 99%. In addition, Wilson et al. (2019) also emphasized that the utilization of auxiliary heaters can increase the evaporation rate and contaminant removal efficiency, albeit at a higher energy cost. Furthermore, Maity et al. (2024) emphasized that in the context of energy sustainability, the use of solar-based systems remains the most economical and environmentally friendly option, especially in tropical regions with high sun exposure throughout the year. The results of this study prove that simple distillation

Table 1. Results of solar-heated distillation (System A)

Parameter	Unit	Seawater (Inlet)	Distilled water	Removal efficiency (%)
Total dissolved solids (TDS)	mg/L	35,020.00	23.03	99.93%
Salinity	ppm	29,943.00	19.00	99.94%

Note: (Measured using HI98192; triplicate measurements; August 2024).

Table 2. Distillation Results with Additional Electric Heater (System B)

Parameter	Unit	Seawater (Inlet)	Distilled water	Removal efficiency (%)
Total dissolved solids (TDS)	mg/L	35,020.00	16.41	99.95%
Salinity	ppm	29,943.00	0.00	100.00%

Note: (Measured using HI98192; triplicate measurements; August 2024).

systems based on solar energy, both with and without additional heaters, have excellent potential to be applied in processing seawater into clean water in coastal areas experiencing a clean water crisis due to seawater intrusion.

The primary difference between these two tables stems from the heating system arrangement which produces different distillate quality outcomes. System A delivers its performance through the first table by using solar energy as the only heating source. The system achieves a 99.94% efficiency rate to lower salinity from 29,943 ppm to 19 ppm and produces a 99.93% efficiency rate to decrease TDS from 35,020 mg/L to 23.03 mg/L. The second table shows the results of System B which operates with solar heating together with electric heating. System B demonstrated superior results because it achieved 0 ppm salinity (100% efficiency) and reduced TDS to 16.41 mg/L (99.95% efficiency). The two tables show different heating systems and System B demonstrates better performance in removing salt and dissolved substances. Both systems successfully reduce salinity and dissolved solids to levels well below clean-water thresholds, demonstrating the potential of solar-based and hybrid solar-electric distillation for small-scale seawater treatment in coastal communities exposed to seawater intrusion. However, System B requires higher energy input, creating a trade-off between improved water quality and operational sustainability.

pH and thermal characteristics

The pH behavior of the distillate from both systems shows a clear downward shift when compared to the raw seawater, indicating that the distillation process reduces the original alkalinity and produces water that tends to be slightly acidic. The system utilizing additional heating exhibits a more pronounced decrease, implying that higher thermal input enhances the removal of buffering minerals that normally stabilize pH. This indicates that the distillate is slightly acidic, especially in the system with the additional heater. This phenomenon is consistent with the findings of Foureaux et al. (2020) who noted that the distillation process tends to produce pure water that tends to be acidic due to the absence of buffering minerals that can maintain pH in the neutral range. To make distilled water suitable for consumption, post-distillation treatment is highly recommended, for example by adding pH-neutralizing materials such as limestone or activated carbon, or through mixing with remineralization. Without this process, the long-term direct use of low-pH distilled water can have an impact on health, especially on the electrolyte balance in the human body.

From a thermal perspective, the average temperature of the distillation process in system A was recorded at 43 °C, while system B reached a temperature of 44 °C. This temperature difference is relatively small, but it has a real influence on the effectiveness of the evaporation process. The increasing the heating temperature will accelerate the evaporation process and the volume of water condensed, thereby increasing the efficiency of clean water production (He et al., 2021). However, this thermal efficiency must also be weighed against energy consumption. System A, which relies entirely on solar energy, offers economic and sustainability advantages, although it takes longer to produce the same volume of water than system B. Overall, both in terms of pH characteristics and thermal performance, the two distillation systems showed good results but still require further processing to meet drinking water quality standards. This opens opportunities for the development of hybrid systems with the integration of post-treatment processes and energy efficiency as part of a sustainable clean water technology strategy in coastal areas.

Evaluation of chemical pollutant removal and compliance with water quality standards

The effectiveness of the distillation process in this study is not only measured based on the reduction in salinity and TDS levels, but also from its ability to remove harmful chemical pollutants that have the potential to harm human health. The main parameters tested include hexavalent chromium heavy metals (Cr^{6+}), nitrate (NO_3-), as well as total coliform and fecal coliform which are indicators of microbiological pollution. In addition, the pH value was also evaluated to determine whether the distilled water meets the standards of comfort and safety for consumption. Raw seawater from the Kertosari location contains Cr^{6+} concentrations that exceed the safe threshold, according to SNI 6989.78-2009. After going through the distillation process, both systems were able to reduce Cr^{6+} to very low levels, reflecting high removal effectiveness without repeating numerical values. Meanwhile, shows a decreasing trend in both systems, indicating the ability of distillation to further improve water quality. On the microbiological aspect, the initial seawater showed high total and fecal coliform contamination, and test results showed that the distillation process successfully eliminated these microorganisms in both systems. To provide a comprehensive overview, Table 3 below presents a comparison of all distilled water quality parameters with baseline values and national and international quality standards.

The results showed that the distillation process used had a very high ability to remove almost all chemical and microbiological contaminant parameters. The only parameter that does not fully meet the quality standards is pH, which is still below the minimum threshold for drinking water. Therefore, additional post-treatment such as remineralization or pH buffering is required to stabilize the acidity before the water is used for human consumption. The performance of both distillation systems is also consistent with previous studies by Qasem et al. (2021), which showed that simple distillation is very effective for removing heavy metals and pathogens but tends to produce pure water with low pH. This supports the conclusion that this system deserves further development as a safe and sustainable seawater treatment solution for coastal areas affected by seawater intrusion.

Wastewater evaluation

In addition to evaluating the quality of the distilled water, it is also important to analyze the quality of the wastewater (effluent) generated during the process. The evaluation of wastewater aims to ensure that the remaining water from the distillation process does not pollute the environment if discharged directly into water bodies or open sanitation systems. The main parameters analyzed in this study include biological oxygen demand (BOD), chemical oxygen demand (COD), total suspended solids (TSS), pH, oil and fat content, ammonia, and microbiological content in the form of total coliform.

Based on laboratory test results, wastewater (inlet) before the treatment process contains BOD, COD, and TSS levels that exceed domestic wastewater quality standards, as regulated by the Minister of Environment Regulation No. 68 of 2016. After the distillation process, the remaining process water (outlet) shows a clear decrease in these pollutant parameters, although COD and TSS remain above the permissible limits, indicating that distillation alone is not sufficient to meet the required standards. The pH of the effluent shifts toward the neutral range and meets the regulatory requirement. The oil and grease content also decreases noticeably, and the ammonia content shows a reduction, although the final ammonia level still does not comply with the maximum allowable standard. For microbiological parameters, the total coliform in the initial wastewater was recorded at high contamination levels, and in the final effluent it increases slightly, suggesting possible recontamination during handling or storage. The Table 4 represented the comparison between the wastewater parameters before and after the distillation process and their conformity to the standard. From the results, it can be concluded that the distillation process contributed to the reduction of most of the polluting parameters in the wastewater, particularly BOD, pH, oil and grease.

However, some parameters such as COD, TSS, and ammonia still exceed the threshold and require further treatment processes such as suspended solids filtration, biological aeration, or adsorption using activated carbon before the

Table 3. Summary of pollutant removal results and compliance with quality standards

Parameter	Unit	Seawater (Inlet)	Distillation without Heater	Distillation with Heater	Quality standard	SNI/Method
Total dissolved solids (TDS)	mg/L	35,020	23.03	16.41	<300	SNI 6989.27-2019
Salinity	ppm	29,943	19	0	–	–
pH	–	8.6	6.3	5.2	6.5–8.5	SNI 6989.11-2019
Hexavalent chromium (Cr^{6+})	mg/L	0.232	0.002	0.002	<0.05	SNI 6989.78-2009
Nitrate (NO_3^-)	mg/L	3.7	3.3	2.7	<10	WHO / SNI (Nitratrid)
Total Coliform	CFU/100 ml	2000	0	0	0	SMMEW 2005
Fecal Coliform	CFU/100 ml	1000	0	0	0	SMMEW 2005

wastewater can be safely discharged into the environment. Periodic monitoring as well as the integration of an integrated wastewater treatment system are important in the application of this distillation technology, especially if it is to be developed on a communal or industrial scale in coastal areas. These findings are consistent with prior studies such as Vegas Mendoza et al. (2019), who observed that thermal distillation units often improve organic load parameters (e.g., BOD and oil content), but tend to be less effective for suspended particles and nutrients without complementary filtration stages. Similarly, Othman et al. (2021) highlighted that combining distillation with activated carbon or membrane polishing significantly enhances ammonia and COD removal in small-scale coastal sanitation systems. Therefore, while the present study affirms the partial effectiveness of distillation for wastewater refinement, it also supports existing literature on the necessity of post-treatment integration for full regulatory compliance.

Limitations and future recommendations

Despite the satisfactory performance of solar desalination in terms of salinity, TDS, heavy metals, and the microbiological menace, there exist some limitations for the practical use of the current distillation system, and there are scopes to improve these further. A main constraint is the low yield of water, that is directly related to the solar irradiation. The reliance of the system on sunlight, makes the evaporation process very sensitive toward the environment, for instance, to the presence of clouds or rain, being therefore unreliable for harsh weather conditions. The addition of supplemental electric heating can improve evaporation efficiency and water production while adding energy and operation expense, favoring long-term sustainability of the system in low resource locations (such as coastal cities), however, may not be cost effective in the long term. A further constraint is about the chemical nature of the deionized water, specifically its pH. The distilled water pH is lower than the acceptable pH for potable water, 6.3 for solar only and 5.2 for hybrid with electric heating. Although, distill-water is free from harmful impurities, the acidity of the product stream causes unwanted consequences, as distribution pipelines corrosion and chronic human health hazards due to drinking. This in turn requires post-treatment measures to bring the water back into chemically balanced and biologically safe condition (e.g. pH buffering, etc.).

Moreover, the concentration of COD, TSS and TAN in the wastewater after the distillation process is still far higher than the discharge limits stipulated by national environmental protection standards. These results indicate that a simple distillation process alone may be inadequate not only to handle the overall effect of wastewater disposal, but also that secondary treatment processes such as biological oxidation, sedimentation or adsorption systems are also necessary to meet environmental regulations. It is suggested that the future work should be devoted to the optimization of the use of renewable energy sources in order to guarantee that the thermal performances remain stable in any condition of weather. In addition, progress in modularity of systems may permit more scalability and flexibility to different geographical and socio-economic settings. Simple and cheaper post-treatment systems will also be crucial to achieve the required health and environmental based water quality at the delivery point. Although solar still technology provides an effective low-tech means for producing freshwater in areas that are plagued with seawater intrusion along the coast, its technology needs to

Table 4. Wastewater quality evaluation results before and after the distillation process

Parameter	Unit	Seawater (Inlet)	Distillation without Heater	Distillation with Heater	Quality Standard	SNI/Method
TDS	mg/L	35,020	23.03	16.41	<300	SNI 6989.27-2019
Salinity	ppm	29,943	19	0	–	–
pH	–	8.6	6.3	5.2	6.5–8.5	SNI 6989.11-2019
Cr^{6+} (hexavalent chromium)	mg/L	0.232	0.002	0.002	<0.05	SNI 6989.78-2009
Nitrate (NO_3^-)	mg/L	3.7	3.3	2.7	<10	WHO / SNI (Nitratrid)
Total Coliform	CFU/100 ml	2000	0	0	0	SMMEW 2005
Fecal Coliform	CFU/100 ml	1000	0	0	0	SMMEW 2005

be improved to improve its application as an integrated and sustainable water treatment system.

CONCLUSIONS

This research shows that a simple solar energy-based distillation system, either using natural solar heat or equipped with an additional electric heater, has high effectiveness in converting seawater into freshwater in coastal environments experiencing seawater intrusion. The distillation process developed significantly reduced salinity TDS levels, with removal efficiencies reaching 100% for salinity and 99.95% for TDS. In addition, the system also proved capable of substantially reducing the levels of chemical pollutants such as hexavalent chromium (Cr^{6+}) and nitrate, as well as eliminating microbiological contaminants such as total and fecal coliform to undetectable levels, signifying the effectiveness of the system in meeting clean water quality standards based on SNI and WHO. However, the distilled water showed pH values that were below the minimum drinking water quality standards, especially in the electrically heated system, requiring post-treatment such as pH buffering or remineralization before water consumption. In terms of wastewater management, despite a decrease in BOD, oil and grease, and an increase in pH towards neutral values, several parameters such as COD, TSS, and ammonia still exceed the set thresholds. This indicates the need for integration of the distillation system with additional effluent treatment units to ensure compliance with environmental regulations. The results of this study indicate that renewable energy-based distillation technology has great potential as an environmentally friendly water supply solution and can be adopted decentralized in coastal areas affected by water crisis. The comparative evaluation between two system configurations makes an important contribution to the design of a more efficient and adaptive system. For further development, optimization of the modular design, more stable utilization of renewable energy sources, and implementation of cost-effective post-distillation processes are recommended to make the system widely applicable and sustainable in various geographical and socio-economic contexts. In conclusion, this study successfully achieved its objectives, namely to provide new scientific insights into the effect of heating configuration on purification effectiveness and the stability of simple distillation processes. This study also fills an important gap in the literature by presenting a comprehensive evaluation of both the quality of the distillate and the quality of the wastewater produced from an aspect that has not been widely studied in previous research. These new findings open up prospects for the development of a more stable, easily replicable dual-mode distillation system that has the potential to be optimized for wider-scale implementation in coastal areas with limited access to clean water.

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