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IMPLEMENTATION OF A MULTI-STAGE DOUBLE-SLOPE SOLAR STILL FOR SALT AND DISTILLED WATER PRODUCTION UNDER TROPICAL RAINY CONDITIONS

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The object of this study is a multi-stage double-slope solar still used for simultaneous distilled water production and seawater concentration into salt crystals under tropical rainy conditions. The problem solved in this study is the discontinuity of conventional salt production during the rainy season, when open evaporation ponds become less effective because of rainfall, high humidity, and unstable solar radiation. Experiments were conducted in Malang as a laboratory environment and in Lamongan as a coastal salt production area. The results showed that the system could operate continuously during the rainy season and increase seawater salinity from 3.5% to about 29%. The cumulative distilled water production was almost identical in both locations, reaching 36.57–36.58 L/m^2. However, seawater concentration was faster in Malang, requiring 25 days, compared with 29 days in Lamongan. This difference was explained by the larger temperature gradients between water, fins, glass cover, and ambient air in Malang, which improved evaporation and condensation. Salt from Malang also had higher NaCl content, 92.33%, than salt from Lamongan, 86.95%, supported by lower Mg and S contents. FTIR detected O–H, sulfate, and carbonate groups, while XRD confirmed halite as the dominant crystalline phase. Macro images showed that Malang salt crystals were more uniform and regular. The distinctive feature of the system is the tiered double-slope configuration, which enables gradual brine concentration while still producing distilled water in a closed solar-driven process. These results show that the system can be practically applied in tropical coastal salt-producing areas with high rainfall to support more continuous salt and distilled water production

Keywords: solar still, multi-stage, double-slope, salt production, distilled water, rainy conditions

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1. Introduction

Salt is a crucial commodity utilized in various sectors, including food processing, chemical industries, pharmaceuticals, water treatment, and energy-related applications [1]. It is, therefore, crucial for industrial activities and food security that salt be in continuous availability in sufficient quantity and quality. Open evaporation ponds are still widely used to produce salt in coastal regions such as Indonesia [2]. It is a cheap and easy method, but its productivity is significantly influenced by atmospheric variables like solar radiation, precipitation, air humidity, wind speed and ambient temperature [3].

The reliance of traditional salt production on weather variability has emerged as a key scientific and practical challenge. In rainy seasons, open evaporation ponds harvest less effective solar radiation; at the same time, they can be subject to direct rainfall that yields an undesired dilution of the brine and ultimately decelerates or completely stops the crystallization process [4]. It diminishes the output of salt and breaks the chain in the provision of salt. In tropical countries, where high humidity, frequent rainfall and seasonal variability in climate result in shortened effective salt production period, this is more serious [5]. Thus, the study into salt production technologies that will work more continuously under worse weather conditions is quite relevant.

It is also part of the larger climate adaptation problem that many coastal production systems face. Salt production zones are usually situated in areas open to the coast, where they can show a degree of exposure to fluctuations in rainfall regimes. Producers have much less control over production when it relies solely on natural evaporation in open ponds. As a result, changes in weather conditions at the molecular level affect brine concentration, crystallization time and salt quality. Thus, study on controlled solar evaporation systems is still required to offer technological alternatives more resilient than the climatic perturbations.

Solar driven evaporation and desalination technologies have gained significant interest due to their use of renewable energy, low environmental impact, and feasibility for coastal areas with abundant seawater resource. Of these, solar stills are more promising since they incorporate both evaporation and condensation processes in a closed system. It consists of a system that can create distilled water and make saline water more concentrated at the same time. The closed (convective configuration) of solar still in principle, isolated it from direct helping disturbances of rainfall compared to open evaporation ponds and can be a good alternative even under tropical rainy conditions for salt production [6].

In fact, when solar still technology is concerned, this situation is urgent from scientific aspect as well, because the performance of such systems are influenced significantly by environment and their investigations remains certainly very important driven due to heat and mass transfer processes [7]. The heat input comes from solar radiation, and the relative thermal gradients of saline water, absorber surface, cover glass and ambient air determine evaporation and condensation rates. Moisture evaporates from the glass cover and makes the recondensation process temperature-dependent. Consequently, there is a necessity for more knowledge related to the performance of solar still at tropical daily rainy climates in order to improve the design and application of solar salt production systems [8].

Solar still technology has been widely studied for the production of freshwater, but only limited study into its application as a main product producing salt. The majority of studies has mainly concentrated on the enhancement of distillate yield, thermal efficiency, heat storage or anti-salt-fouling mechanisms. In salt-producing areas, especially those with long rainy seasons, it is not only the generation of freshwater that is needed. This indicates that study on solar stills for production of salt and distilled water simultaneously, under tropical rainy conditions is still required.

Furthermore, the practical significance is evident for coastal salt-producing populations. It has been suggested that during the rainy season, a solar still system which can continue to concentrate seawater and produce distilled water could be helpful for reducing dependence on open pond evaporation, which also leads to more stable salt production, as well as compensating for rainwater with concentrated seawater in addition to serving as an alternative source of distilled water [9]. This technology is particularly important for small- and medium-scale salt producers in tropical countries where production continuity and income stability are highly impacted by weather uncertainty [10].

Therefore, study on the development of solar still technology for continuous salt and distilled water production under tropical rainy conditions is relevant and necessary. This topic is important because it addresses the scientific problem of heat and mass transfer in solar-driven evaporation-condensation systems under humid and rainy climates, while also responding to the practical need for more sustainable salt production in tropical coastal areas.

2. Literature review and problem statement

The paper [4] presents the results of salt production using a spraying and heating method as an alternative to conventional evaporation. This method converts brine into fine droplets using a nozzle and accelerates evaporation with airflow from a blower and heat from a heater. The best result was obtained using a 0.1 mm nozzle, producing 1067.67 g of salt in 1 h 50 min, while a blower speed of 4.9 m/s produced 1026 g in 2 h 5 min. However, the study still has limitations. The system requires external energy, which may increase operational costs, and only nozzle diameter and blower speed were mainly investigated. Other important factors, such as heater temperature, brine concentration, flow rate, and energy efficiency, were not fully evaluated.

The paper [5] presents the results of a low-cost laser-printing evaporator for solar interfacial evaporation and salt crystal recovery. The study showed that salt crystals can autonomously drop from the evaporation interface by gravity, helping to prevent salt fouling and support resource recovery. The results also indicated that the ratio of water supply to evaporation capacity (Qs/Qe) is a key factor controlling the continuous salt-dropping process, and the method can be applied to concentrated salt solutions, mixed salts, and salt solutions containing organic matter. However, this study still has limitations. The performance strongly depends on precise control of water supply and evaporation rate. In addition, further study is needed to evaluate long-term stability, large-scale application, material durability, and performance under real outdoor conditions.

The paper [9] presents the results of a four-stage solar distiller integrated with a Fresnel lens to improve freshwater productivity. The multi-stage system utilizes latent heat released from each stage, while the Fresnel lens helps concentrate solar radiation as a low-cost alternative to CSP technology. The results showed that the multi-stage system achieved higher productivity and efficiency, with 0.164 g/kJ and 39.5%, compared with the single-stage solar distiller, which produced 0.104 g/kJ and 23.5%. However, this study still has limitations. The performance depends on solar radiation availability, and the use of a Fresnel lens may require precise positioning and maintenance. In addition, further study is needed to evaluate long-term operation, material durability, cost effectiveness, and performance under different climatic conditions.

The paper [11] presents the results of a solar-powered multistage membrane distillation system designed to improve freshwater production and salt resistance. The study introduced a confined saline layer as an evaporator to generate strong thermohaline convection, which helps reduce salt accumulation and enhance heat transfer. Using a ten-stage device, the system achieved high solar-to-water efficiencies of 322–121% at salinity levels of 0–20 wt% under one-sun illumination. The device also showed strong salt resistance, operating continuously for 180 h with 20 wt% concentrated seawater. However, this study still has limitations. The system may require careful design of the confined saline layer to maintain stable thermohaline convection. In addition, further study is necessary to evaluate long-term durability, scalability and membrane fouling.

The paper [12] presents the results of a scalable mangrove-mimicked solar vapor generation device for freshwater production and passive salt collection without brine discharge. The device uses capillarity-driven saline water supply through anti-corrosion porous wicking stems and multilayer leaves made from low-cost superhydrophilic nanostructured titanium meshes. The results showed that salt precipitated at the leaf edge during daytime evaporation and peeled off by gravity at night after rewetting. These porous salt patches enhanced vaporization by 1.6 times. The system achieved stable photothermal efficiency of around 94% under one sun using synthetic seawater with 3.5 wt% salinity and produced 2.2 $L \cdot m^{-2} \cdot day^{-1}$ of freshwater from real seawater under outdoor conditions. However, this study still has limitations. The device performance may depend on stable capillary water transport, outdoor solar intensity, and long-term durability of the titanium mesh structure.

The paper [13] presents the results of a paper-based thermal radiation-enabled evaporation system (TREES) for sustainable solar desalination and salt collection. The system uses a dynamic evaporation front formed by the accumulated salt layer, where water acts as its own absorber through energy down-conversion. When treating 7 wt% brine, the paper-TREES achieved a high evaporation rate of 2.25 $L \cdot m^{-2} \cdot h^{-1}$ under one-sun illumination and operated continuously for more than 366 h. However, this study still has limitations. The performance may depend on stable salt-layer formation, paper durability, and environmental heat availability.

The paper [14] presents the results of an integrated solar still system combined with a latent/sensible heat packed bed thermal energy storage unit to achieve stable freshwater production during both day and night. A numerical model was developed and evaluated under Sinai Desert solar conditions using different phase change materials, sensible heat storage materials, and geometric parameters. The results showed that RT65 provided the best Phase Change Material (PCM) performance, with 40.94% thermal efficiency and 26.17 kg/day freshwater production. Quartzite rock was the best sensible heat storage material, producing 21.90 kg/day with 34.31% efficiency. Further optimization using 20 mm storage capsules, 0.22 bed porosity, and optimized solar still geometry increased freshwater production to 29.51 kg/day. However, this study still has limitations. The work was mainly based on numerical simulation and specific Sinai Desert conditions, so experimental validation under real long-term operation is still needed. In addition, further study is required to evaluate system cost, material durability, PCM stability, maintenance requirements, and performance under different climates.

The paper [15] presents the results of an analytical study on active solar basin stills, focusing on the effect of water depth and the number of stages on freshwater productivity. The proposed model was validated using Karimi's experimental data with acceptable accuracy. The results showed that increasing the number of stages from one to four increased freshwater production by 42%, 72%, and 94%, respectively. The study also found that water depth has an optimum value, because too much or too little water in the basin can reduce daily freshwater output. However, this study still has limitations. The analysis was mainly based on an analytical model, so further experimental validation is needed under real operating conditions. In addition, the study focused mainly on water depth and stage number, while other factors such as climatic variation, material durability, energy efficiency, and economic feasibility were not fully investigated.

This literature review [4, 5, 9, 11–15] shows that solar desalination and evaporation technologies have strong potential to improve freshwater production, salt recovery, and system efficiency through various approaches, including spraying-heating systems, interfacial evaporation, multistage distillation, thermal storage, and optimized basin depth. However, most previous studies have mainly focused on freshwater production, thermal efficiency, or salt-resisting mechanisms, while simultaneous salt and distilled water production using a multi-stage double-slope solar still under tropical rainy conditions remains limited. The novelty of this study lies in the use of a tiered configuration to control the gradual increase in seawater salinity, performance testing at two locations with different environmental characteristics, and salt quality evaluation through argentometry, Fourier Transform Infrared Spectroscopy, X-Ray Fluorescence, and X-Ray Diffraction analyses. Therefore, this study is important to evaluate the ability of the system to maintain continuous salt production during the rainy season while also characterizing the quality of the produced salt.

Many interior investigations have been performed to fabricate solar evaporation and desalination technologies, however, numerous questions are still left unanswered in previous works. The main reason for this is that the majority of studies related to solar stills has been primarily focused on freshwater productivity, thermal efficiency, heat storage and interfacial evaporation, membrane distillation sludge separation, or salt-resistance mechanism rather than treating secondary product (salt production) as a major challenge. Moreover, many of the previous systems were evaluated using controlled indoor lab tests, in dry climates or operated outdoors for limited periods where rain, high humidity and variable irradiance resources were not the dominant limitations. In tropical rainy climates, salt crystallization was more challenging due to the effects from fluctuating solar radiation levels, ambient humidity, rainfall events and change in wind speeds during the evaporation process. This increase in time required to reach cage stability makes continuous concentration of seawater under low lying conditions more challenging, needing longer timescales of observations as a result. In addition, many of the system from previous reports have demands for external energy input, special materials, membrane parts, accurate water-supply control or concentrated solar devices that are not easily useful to small and medium salt manufacturers located at tropical beaches. Hence, the co-generation of distilled water and salt with a simple multi-stage double-slope solar still in tropical rainy condition is yet to be investigated.

3. The aim and objectives of the study

The aim of this study is to evaluate the implementation of a multi-stage double-slope solar still for producing distilled water and salt under tropical rainy conditions and to characterize the quality of the salt produced. This will allow the determination of the potential of the solar still system to maintain continuous salt production during the rainy season, support sustainable salt production in tropical regions, and provide practical information for the development and implementation of solar-powered salt production technologies.

To accomplish this aim, the objectives of the study are as follows:

– to analyze the performance of a multi-stage double-slope solar still in producing distilled water and salt under different environmental conditions during the rainy season;

– to characterize the quality of the produced salt through laboratory testing, including argentometric analysis, Fourier Transform Infrared Spectroscopy, X-ray Fluorescence, X-ray Diffraction, and macro photography analysis.

4. Materials and methods

4. 1. The object and hypothesis of the study

The object of this study is a multi-stage double-slope solar still system used to produce distilled water and salt through evaporation-condensation and gradual brine concentration during the rainy season. The multi-stage double-slope solar still system operating to provide distilled water and salt production based on evaporation-condensation along with progressive brine elimination during the rainy season. It is formed of a number of 4 double slope solar still units placed in layers. Each unit is covered with glass shaped like a roof that has two sloped condensation surfaces, and seawater is passed from one stage to another on the basis of a predetermined salinity level. This makes it possible to continue to produce distilled water and slowly concentrate the seawater until crystals of salt are formed.

The hypothesis of this study is that the implementation of a multi-stage double-slope solar still under tropical rainy conditions can produce distilled water while gradually concentrating seawater until salt crystallization occurs. Differences in environmental conditions, including solar radiation intensity, ambient temperature, relative humidity, and wind speed, are expected to influence the evaporation-condensation process, salinity increase, distilled water productivity, and the quality of the produced salt.

In this study, a number of assumptions and simplifications were made. Initially, it was considered that the salinity of seawater at both trials sites is close to 3.5%. Secondly, by keeping the geometry, materials, number of stages and orientation constant among both locations and operational process identical during testing for maximum yield, it was ensured that differences in migratory behavior were affected largely due to environmental conditions. Third, significant differences in the thermal transmittance of wall and bottom insulation were overcome through the application of identical insulating material creating similar losses between the two test sites. Last but not least, the impact of dust, minor leakage, slight variations in cleanliness of the glass and local shading were ignored in this study. Fifth, the average daily data of measured temperature, solar radiation, humidity and wind speed as well as distilled water productivity and salinity was calculated. Sixth, the quality of the salt produced was assessed based on selected physicochemical parameters such NaCl content by argentometric analysis, functional groups using Fourier Transform Infrared Spectroscopy (FTIR), elemental composition using Energy Dispersive X-Ray Fluorescence (XRF), crystal phase using X-Ray Diffraction (XRD) and morphological characterization through macro photography.

The double-sloped solar stills were arranged in tiers with the aim of enabling continuous production of distilled water and salt, while the testing conducted during the rainy season is expected to provide evidence that the solar stills can operate year-round. The testing was carried out at two different locations to identify the impact of environmental factors on the solar stills' performance in producing fresh water and salt.

This study compares the system performance under two different environmental conditions: a laboratory environment in Malang and a coastal salt production area in Lamongan.

The first experiment was conducted in September 2025 at the Solar Energy and Alternative Energy Laboratory, Department of Mechanical Engineering, Universitas Widyagama Malang, East Java, Indonesia. Malang is located at approximately 7°58′–8°02′ S and 112°36′–112°40′ E and is characterized as a highland area with a relatively cool tropical climate. The second experiment was conducted in November 2025 at Garam Dua Musim, Brondong District, Lamongan Regency, East Java, Indonesia, located at approximately 6°52′–6°54′ S and 112°17′–112°20′ E. The second experiment was conducted in November 2025 at Perseroan Terbatas Garam Dua Musim, Brondong District, Lamongan Regency, East Java, Indonesia, located at approximately 6°52′–6°54′ S and 112°17′–112°20′ E. This site is located in the northern coastal area of Java Island, directly adjacent to the Java Sea, and represents a lowland coastal environment suitable for salt production.

4. 2. Solar still materials

The double-sloped solar still consists of an absorber plate, a retaining wall, a roof-shaped top cover, and an insulator. The double-slope solar still used in this study consists of transparent glass with a roof shape formed by two inclined glass surfaces. The two slope glass covers are set inverted V-shaped condensation surface, inducing the water vapor produced from saltwater basin to condensate at both sides of glass cover. It expands the area of condensation and transmits distilled water from both sides. In this present work, double-slope solar stills were connected in multi-stage or tier arrangements through which seawater was transferred from one stage to another based on its salinity level until crystallizing salt.

The absorber plate is made of mortar with a mixture of 2 parts sand to 1 part cement, then molded into blocks measuring 0.4 × 0.6 cm and 5 cm thick. Additionally, fins are integrated into the absorber plate, measuring 2 cm thick, 10 cm high, and 50 cm long, made from the same material. Inlet and outlet channels for seawater are also created in the absorber plate to facilitate the transfer of seawater to the next double-slope solar still. The absorber plate is painted with a matte black finish that does not react with seawater and enhances the absorption of solar radiation.

The boundary walls use 5 mm thick mirrored glass to increase the solar radiation received by the absorber plate. The top cover uses a roof-like design to expand the condensation surface and ensure continuous solar radiation throughout the day. The top cover uses 3 mm thick clear glass. To seal the joints and reduce heat loss between the glass panels, the glass is bonded using glass adhesive (Sealent). Meanwhile, to reduce heat loss through the walls and the underside of the absorber plate, 3 cm thick Styrofoam insulation is installed.

4. 3. Measuring equipment

The measurement equipment consists of 20 Type K thermocouples with an accuracy of ±0.1°C, installed on the absorber plate/basin, fins, cover glass, and the surrounding environment. A Sentec SEM228A Solar Radiation Sensor pyranometer with an accuracy of ±1.0 W/m^2 is used to measure solar radiation intensity. A GM816 anemometer is used to measure wind speed. A 100-ml measuring cylinder with an accuracy of ±0.1 m/s is used to measure freshwater productivity. A SF400A digital scale is used to measure the mass of salt produced. The measured data on temperature, solar radiation, and wind speed are processed using an Arduino Mega2560. The obtained data is then displayed and stored on a computer for further analysis.

4. 4. Experimental procedure

At both test sites, the sun shone from east to west, so the double-sloped glass covers were oriented toward the east and west to maximize the intensity of solar radiation received. A total of 42 L/m^2 of seawater with a salinity of 3.5% was introduced into the first-stage solar still. In the first-stage solar still, once the seawater salinity reached approximately ±5%, it was transferred to the second-stage solar still. In the second-stage solar still, once the seawater salinity reached approximately ±7.5%, it was transferred to the third-stage solar still. In the third-stage solar still, once the seawater salinity reached approximately ±13%, it was transferred to the fourth-stage solar still. In the fourth-stage solar still, once the seawater salinity reaches approximately ±29%, the salt is ready for harvest. After harvesting, the salt is drained and dried under direct sunlight to reduce its moisture content to less than 2%. The mass of the produced salt is then measured. The salt obtained was then tested for salt content using argentometric analysis, FTIR (Fourier Transform Infrared Spectroscopy) to identify functional groups and detect organic and inorganic impurities in the salt, and XRF (X-Ray Fluorescence) to analyze the chemical composition (elemental analysis) of the salt, XRD (X-Ray Diffraction) testing to determine the crystal structure and mineral phases in the salt sample, and macro photography to observe and analyze the physical characteristics of the salt crystal surface at close range. Measurements of temperature, solar radiation intensity, and wind speed are taken every 5 minutes from 7:00 AM to 5:00 PM, then accumulated and averaged for each day. Freshwater/distilled water samples were collected in the afternoon and morning and then totaled. The collected freshwater was then tested to determine the water's pH and TDS (Total Dissolved Solids).

4. 5. Solar still efficiency

In a solar still system, energy efficiency is a crucial factor in assessing its suitability for converting seawater into freshwater, as it directly determines how much solar energy can be converted into heat used in the distillation process. The efficiency equation from [16], was then expanded to:

$$\eta_d = \frac{\dot{m}_w \times \left[\left(h_{fg.w} + h_{fg.w}\right)/2\right]}{\left(I_d \times A_s\right)}, \quad (1)$$

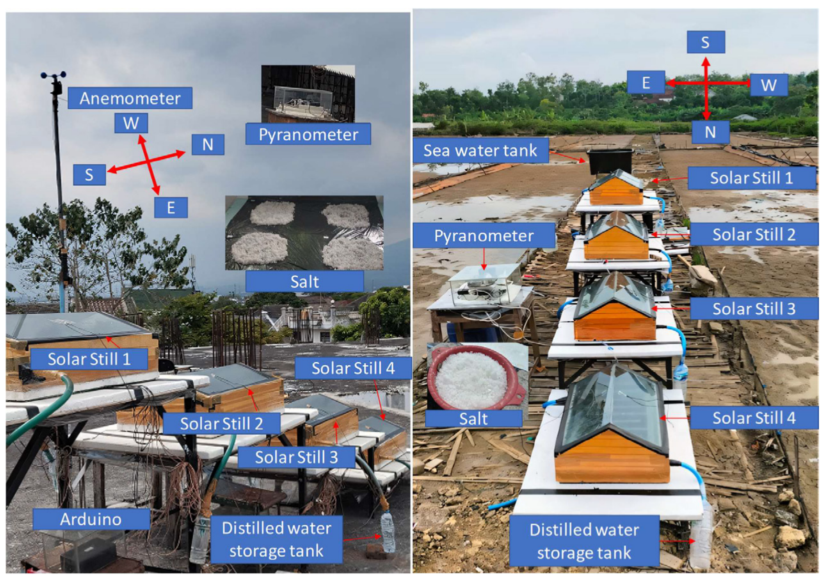
$$I_d = \frac{I_t \times (t \times 60)}{1000}, \quad (2)$$

where $\dot{m}_w$ (kg/s) – the mass flow rate of distilled water, $h_{fg,w}$ (kJ/kg) – the latent heat of vaporization of water in the basin, and $h_{fg,w}$ (kJ/kg) – the latent heat of vaporization of water on the mortar fins. I_t (W/m^2) – the accumulated solar radiation intensity, I_d (kJ/m^2) – the daily accumulated solar radiation intensity. t (minutes) – the duration of data collection. A_s (m^2) – the effective surface area of the solar still, and a factor of 1000 is used to convert units from joules to kilojoules.

4. 6. Setup of research equipment

During the equipment setup, four solar stills were arranged in a tiered configuration, along with the solar still stands and measuring instruments, all assembled into a test setup ready for testing. The testing equipment used at the Solar and Alternative Energy Laboratory, Department of Mechanical Engineering, Widya Gama University, Malang, is the same as that used at PT. Garam Dua Musim in Brondong Subdistrict, Lamongan Regency.

During the experimental preparation stage, four solar still units were arranged in a tiered configuration and equipped with supporting frames and the necessary measuring instruments, forming a complete test system ready for operation. The testing equipment and configuration used at the Solar and Alternative Energy Laboratory, Department of Mechanical Engineering, Widya Gama University, Malang, were identical to those employed at the salt production site of PT. Garam Dua Musim in Brondong District, Lamongan Regency. The layout and configuration of the equipment at both testing locations are shown in Fig. 1.



a *b*

Fig. 1. Experimental setup of the multi-stage double-slope solar still at two testing sites:
a — Solar and Alternative Energy Laboratory, Widya Gama University, Malang;
b — Perseroan Terbatas Garam Dua Musim, Lamongan

Fig. 1, *a* shows testing at the Solar and Alternative Energy Laboratory, Department of Mechanical Engineering, Widya Gama University, Malang, and Fig. 1, *b* at PT. Garam Dua Musim in Brondong Subdistrict, Lamongan Regency. The intensity of solar radiation moves from east to west, so the equipment is arranged facing north. Both locations were selected to test the performance of the solar still in producing distilled water and salt under laboratory conditions and at a salt production site.

5. Results of performance tests on a double-slope solar still with a tiered design and salt characteristics

5. 1. Results of performance testing of multi-stage solar stills in different environments

5. 1. 1. Average wind speed and solar radiation intensity from tests of multi-stage solar stills in different environments

Fig. 2 presents data on average wind speed and solar radiation intensity from observations in Malang and Lamongan. The figure shows a correlation between solar radiation intensity and wind speed, wherein an increase in solar radiation intensity tends to be followed by an increase in wind speed. The relationship between solar energy potential and wind energy has been widely reported in studies of renewable energy systems, particularly in coastal and tropical regions, because surface heating due to solar radiation can trigger an air pressure gradient that increases air mass movement or wind speed [17].

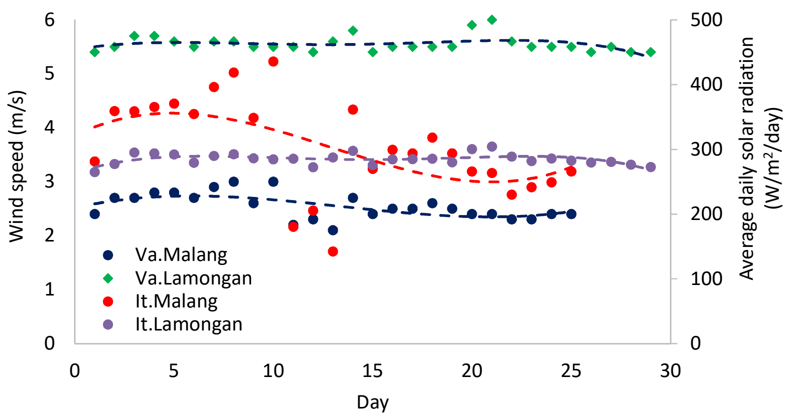


Fig. 2. Average wind speed and solar radiation intensity during testing in Malang and Lamongan

Fig. 2. shows the variations in daily wind speed and solar radiation data at both locations. The test in Lamongan had higher and more stable wind speeds (around 5.4–5.7 m/s), while the test in Malang showed lower wind speeds (around 2.3–2.8 m/s) with a slight decrease in the middle to the end of the observation period. In terms of average solar radiation intensity, the test in Malang showed significant fluctuations, particularly a decrease in the middle of the period, while the test in Lamongan was relatively more stable in the range of 280–310 W/m^2/day. The stability of wind speed and solar radiation in coastal areas is generally influenced by marine wind circulation and atmospheric conditions that support the continuity of renewable energy [18].

These differences in characteristics indicate that the testing site in Lamongan has more consistent renewable energy potential, both from wind and solar sources, thereby better supporting energy system efficiency. The stability of meteorological parameters such as solar radiation, ambient temperature, and wind speed is known to significantly influence the performance of solar still systems, particularly during the evaporation and condensation processes [19]. Furthermore, this potential is also relevant for addressing the issue of freshwater scarcity commonly experienced in coastal regions, such as in salt production areas, through the implementation of renewable energy-based desalination systems [20].

5. 1. 2. Average humidity and solar radiation intensity from tests of multi-stage solar stills in different environments

Fig. 3 shows the relationship between relative humidity and average daily solar radiation intensity in Malang and Lamongan during the observation period. In general, an inverse relationship between the two parameters is observed, wherein an increase in solar radiation intensity is followed by a decrease in relative humidity. This phenomenon is consistent with physical processes in the atmosphere, where higher solar radiation increases air temperature and increases the air's capacity to hold water vapor, causing relative humidity to decrease [21].

During the testing in Malang, relative humidity showed fairly significant variation, ranging from approximately 78% to 84%, with a tendency to increase in the middle to late stages of the period. In contrast, solar radiation intensity at this location exhibited greater fluctuations. This pattern indicates the influence of local weather conditions, such as clouds and rain, which affect solar radiation while keeping humidity high. Variations in solar radiation due to cloud cover and rainfall are known to be one of the main factors affecting the performance of solar still systems in tropical regions [22].

Meanwhile, measurements in Lamongan show more stable patterns in terms of both humidity and solar radiation. Relative humidity in Lamongan tends to be high and constant, ranging from 84% to 87%, while solar radiation intensity remains relatively stable at 280–310 W/m^2/day. This stability reflects more consistent atmospheric conditions, likely influenced by the characteristics of coastal areas, which have more uniform thermal and humidity dynamics.

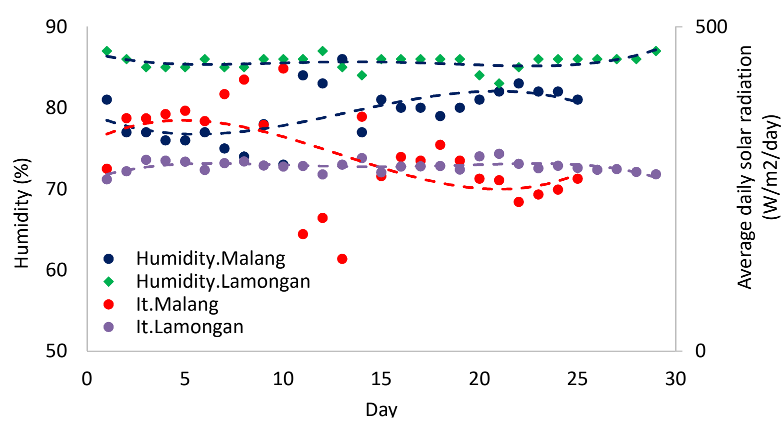


Fig. 3. Average humidity and solar radiation intensity during testing in Malang and Lamongan

A comparison of the two locations shows that Lamongan has more stable and predictable environmental conditions than Malang. This offers advantages for solar-based systems, as the stability of solar radiation supports continuous energy production. This technology is rapidly developing as an alternative solution for clean water supply in areas with limited freshwater sources and high humidity [23]. Thus, the combination of solar radiation and humidity characteristics in Lamongan not only supports the efficiency of renewable energy systems but also opens opportunities for the development of alternative solutions to address the limitations of freshwater and salt sources.

5. 1. 3. Test results for multi-stage solar stills in different environments

Temperatures in the solar still, such as the water temperature (T_w), fin temperature (T_f), cover glass temperature (T_g), and ambient temperature (T_a), were used to assess the performance of the solar still in different environments, namely in Malang and Lamongan. Temperature parameters are key indicators in the analysis of heat transfer and evaporation-condensation performance in solar still systems, as distillate productivity is significantly influenced by the temperature distribution among system components [19].

Fig. 4 shows symbols 1, 2, 3, and 4 corresponding to temperatures that indicate the stages or levels of the solar still. Testing was conducted from the first to the fourth level of the solar still in accordance with the experimental procedure. In Fig. 4, *a*, the temperatures of the solar still components including water temperature (T_w), cover glass temperature (T_g), fin temperature (T_f), and ambient air temperature (T_a) show relatively large fluctuations throughout the testing period. The fin temperature (T_f) reached a maximum of approximately 40–43°C, but with fairly sharp daily variations. This pattern indicates that the heating process is strongly influenced by changes in environmental conditions, particularly solar radiation intensity [24].

In addition, large temperature differences between the water and the glass ($T_w - T_g$) and between the fins and the glass ($T_f - T_g$) have the potential to increase the evaporation rate. Meanwhile, the temperature difference between the glass and the environment ($T_g - T_a$) plays a significant role in enhancing the condensation process on the glass surface [25]. Several studies have reported that an increased temperature gradient between the basin and the cover glass is a key factor in boosting distilled water productivity in solar stills [18].

In Fig. 4, *b*, all temperature parameters exhibit a more stable pattern. The fin temperature (T_f) ranges from 35–37°C, the water temperature (T_w) is around 29–31°C, and the glass temperature (T_g) ranges from 26–28°C, with relatively small fluctuations over time. However, the temperature gradient between the water and the glass ($T_w - T_g$), the temperature gradient between the fins and the glass ($T_f - T_g$), and the temperature gradient between the glass and the environment ($T_g - T_a$) in Lamongan are smaller than in Malang. These conditions result in lower distilled water productivity in Lamongan compared to Malang. This phenomenon is consistent with previous study showing that high ambient temperatures and humidity can reduce the effectiveness of evaporative-condensational heat transfer in solar stills [26].

The performance of a solar still is greatly influenced by the energy balance between incoming solar radiation, heat accumulation in the water and fins, and heat release through the condensation process on the cover glass [27]. In this study, the ambient temperature in Lamongan tended to be higher than in Malang, resulting in lower evaporation and condensation potential. High ambient temperatures can reduce the temperature difference between the glass and the surrounding air, making the heat release and condensation processes less effective [28]. Thus, it can be concluded that locations with higher ambient temperatures tend to result in lower solar still performance.

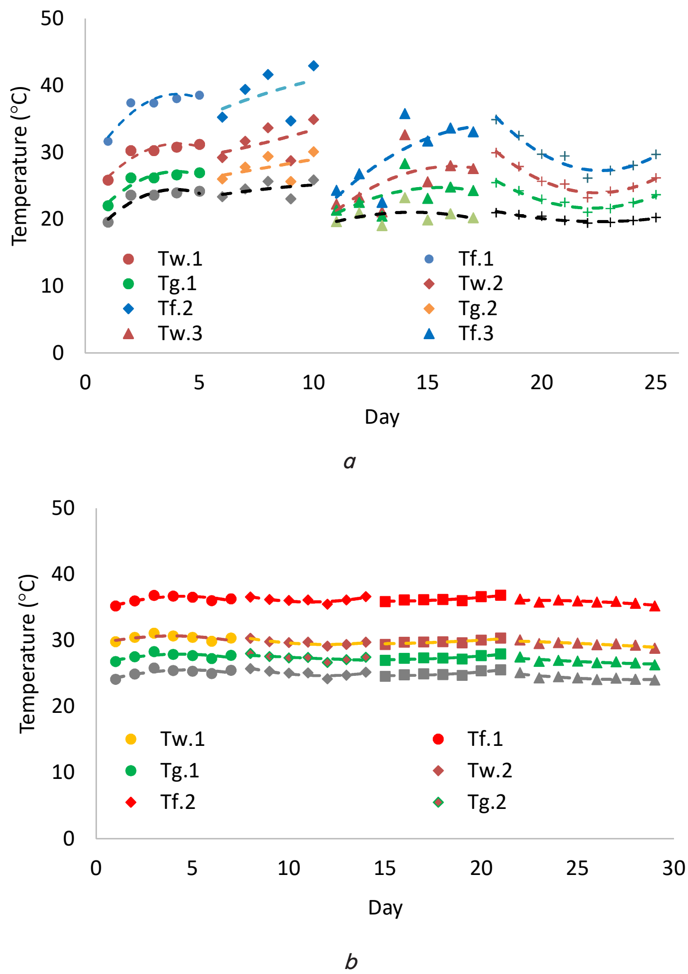


Fig. 4. Temperatures of the solar still and the surrounding environment during the experiment: *a* – Malang site; *b* – Lamongan site

5. 1. 4. Productivity and salinity of multi-stage solar stills in different environments

Fig. 5 shows the changes in salinity and productivity of the distilled water in the multi-stage solar still system during the testing period. In general, all curves show an upward trend in both salinity and productivity over time. The increase in salinity results from the continuous evaporation process, in which water evaporates and leaves behind dissolved salts, thereby increasing the solution's concentration [29]. This increase pattern is gradual and consistent with the research procedure, namely the transfer of seawater between solar still levels based on specific salinity thresholds (±5%, ±7.5%, ±13%, up to ±29%). In the early stages, the increase in salinity is relatively slow because the water volume is still large, but in the later stages, the rate of increase becomes faster due to the decreasing water volume and increasing solution concentration [30].

A comparison of test results from Malang and Lamongan reveals significant differences in performance. Test results from Malang tended to reach higher salinity levels in a shorter time compared to those from Lamongan, primarily due to higher distilled water productivity. Distilled water productivity is influenced by the rates of evaporation and condensation, which are closely related to the temperature gradient between the water and the cover glass ($T_w - T_g$), the temperature gradient between the fins and the glass ($T_f - T_g$), and the temperature gradient between the glass and the environment ($T_g - T_a$). Thus, ambient temperature significantly affects distilled water productivity and, consequently, influences the increase in seawater salinity.

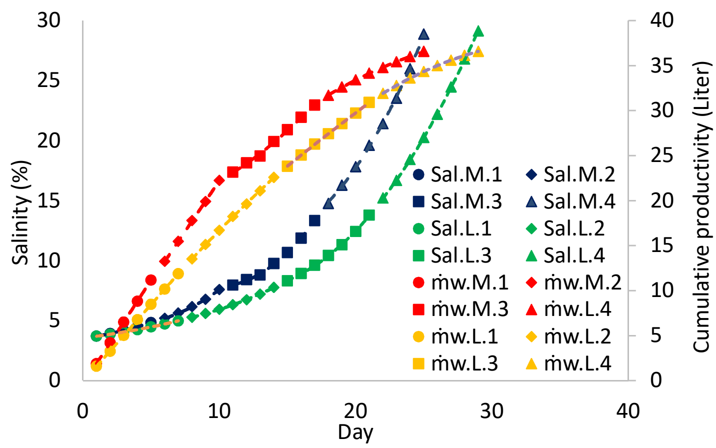


Fig. 5. Salinity and cumulative productivity in the solar stills tested in Malang and Lamongan

In addition to ambient temperature, air humidity and wind speed also affect the productivity of solar stills. The tests conducted in Lamongan were carried out under conditions of high air humidity and wind speed. These conditions should have aided the convection process on the cover glass and increased condensation; however, the high ambient temperature made convective heat transfer less effective. Furthermore, the wind direction coming from the sea and not directly opposing the east-west orientation of the solar still's cover glass resulted in suboptimal convective cooling on the glass.

Fig. 5 also shows that an increase in seawater salinity leads to a slower trend in freshwater productivity. Seawater with high salinity has a lower vapor pressure than water with low salinity, in accordance with Raoult's Law, resulting in a decrease in the evaporation rate. Additionally, increased salinity raises the boiling point of the solution and increases the energy required for the evaporation process. Salt ions such as Na^+ and Cl^- form a hydration layer that restricts the mobility of water molecules and increases mass transfer resistance during evaporation. Furthermore, an increase in salinity also increases the viscosity and density of the solution, thereby slowing the movement of water molecules toward the surface. This condition is exacerbated by the formation of a more stable boundary layer in high-concentration solutions, which slows the diffusion of water vapor into the environment. Overall, the combination of decreased vapor pressure, increased boiling point, increased viscosity, and mass transfer resistance causes the evaporation rate to decrease as salinity increases. This finding aligns with various recent studies indicating that meteorological parameters such as solar radiation, ambient temperature, air humidity, and wind speed significantly determine the efficiency of solar-powered desalination systems.

5. 1. 5. Efficiency of multi-stage solar stills in different environments

Fig. 6 provides information on the efficiency of the solar still during testing in Malang and Lamongan. Fig. 6 shows that the solar still efficiency exhibits a decreasing trend over time across all test variations. At the beginning of the testing (approximately days 1 through 5), efficiency was in a relatively high range, around 40–46%, and then gradually decreased to reach approximately 10–25% by the end of the observation period. This decline occurred consistently at both testing sites, though at different rates, with the testing in Malang tending to show a sharper decline compared to Lamongan. The decrease in solar still efficiency in Malang was caused by a shorter timeframe 25 days to reach seawater salinity of ±29%, which was then harvested, compared to Lamongan, which required a longer time of 29 days. The phenomenon of efficiency decline as salinity increases has been widely reported in previous studies, where salt accumulation during the desalination process causes a decrease in evaporation rate and distilled water productivity due to reduced vapor pressure and increased mass transfer resistance. In addition, solar still efficiency is also known to decrease over time due to changes in the thermophysical properties of the solution and the system's reduced ability to maintain the evaporation-condensation temperature gradient.

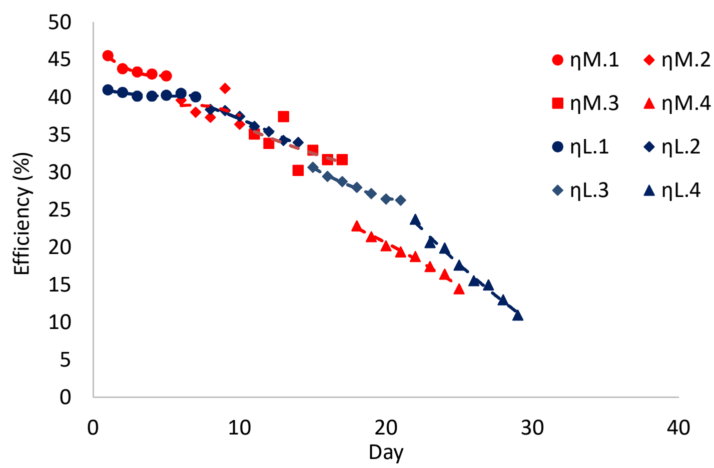


Fig. 6. Efficiency of solar stills tested in Malang and Lamongan

The decline in solar still efficiency is also caused by increased seawater salinity and reduced productivity. This increase in salinity has a direct impact on efficiency, as high salt concentrations lower the vapor pressure of water and increase the viscosity of the solution, thereby reducing the evaporation-condensation process and affecting distilled water productivity. Declining distilled water productivity leads to a corresponding decrease in solar still efficiency. Comparisons across locations show that ambient temperature, air humidity, and wind speed also affect solar still productivity. Testing in Lamongan, with high ambient temperature and air humidity, resulted in lower evaporation-condensation heat transfer compared to testing conditions in Malang, which had lower ambient temperature and air humidity. The test in Lamongan had higher wind speeds compared to the test in Malang. However, because the ambient temperature in Lamongan was higher, convective heat transfer through the cover glass played a lesser role in aiding the condensation process.

5. 2. Physicochemical characterization of salt produced by a multi-stage solar still

5. 2. 1. NaCl content of salt based on the argentometric test

The results of the multi-stage solar still experiments in Malang and Lamongan produced salt crystals. The salt was dried to reduce its moisture content, and then argentometric analysis was performed to determine the NaCl content, as shown in Table 1.

Table 1

Argentometry test

Argentometry	
Lamongan salt	86.95%
Malang salt	92.33%

The argentometric results show that the NaCl content of the salt tested in Lamongan was 86.95%, while that of the salt tested in Malang was 92.33%. These values indicate that the salt tested in Malang has a higher NaCl content compared to the salt tested in Lamongan. Chemically, these results suggest that the salt tested in Malang has a relatively higher purity of NaCl, whereas the salt tested in Lamongan still contains a larger fraction of non-NaCl impurities. The NaCl content is a primary parameter in determining the quality and purity of salt, where the presence of impurities such as Mg^{2+}, Ca^{2+}, sulfates, and other dissolved materials can reduce the percentage of NaCl in crystallized salt. The argentometric method is widely used to determine the chloride or NaCl content in salt because it offers good accuracy and sensitivity in the analysis of salt produced by evaporation or desalination.

5. 2. 2. Elemental composition of salt based on X-ray fluorescence analysis

The salt samples from the experiments in Malang and Lamongan were subjected to XRF analysis, and the results are presented in Table 2. The XRF analysis results indicate that the dominant element in both salt samples is Cl, accounting for 91.96% in the salt sample from Malang and 87.29% in the salt sample from Lamongan. The high Cl content indicates that both samples are dominated by chloride-based compounds associated with the presence of NaCl/halite as the primary component of the salt. However, the Cl value from XRF cannot be directly interpreted as the NaCl concentration because XRF measures elemental composition, not compounds. Therefore, the NaCl concentration still needs to be confirmed using argentometric analysis. The difference in Cl content indicates that the salt tested in Malang has a higher chloride composition compared to the salt tested in Lamongan. This condition may indicate that the salt tested in Malang has a higher NaCl content or lower mineral impurity content.

Another difference is evident in the Mg and S content, where the salt tested in Lamongan has higher values 4.15% Mg and 4.06% S, compared to the salt tested in Malang, which has values of 1.15% and 2.29%, respectively. The higher Mg and S content indicates the possible presence of impurity minerals such as magnesium and sulfate compounds that were carried over during the crystallization process. K and Ca were also detected in both samples with relatively similar values, suggesting they may be associated with natural minor minerals from seawater or the salt production environment. Additionally, minor elements such as V, Fe, Ni, and Cu were detected in small amounts and likely originate from seawater, sediments, or contact with production equipment. Bittern from sea salt production contains major elements such as Na, K, Mg, Cl, sulfate, and bromide, as well as minor elements and trace elements in lower concentrations. The high levels of Mg and S in the salt tested in Lamongan can be interpreted as an indication that residual bittern minerals or sulfate impurities were co-crystallized with the salt.

5. 2. 3. Salt functional groups based on Fourier transform infrared spectroscopy analysis

FTIR (Fourier Transform Infrared Spectroscopy) is used to identify functional groups in compounds, detect chemical bonds, analyze organic and inorganic content, and determine the presence of impurities in materials, including salt produced by solar stills. In this study, FTIR was used to identify compounds or impurities in salt crystals, determine the presence of specific functional groups, and compare the chemical characteristics of salt samples tested in Malang and Lamongan. The test results are shown in Fig. 7.

Fig. 7 shows that the FTIR spectra of the salt tested in Lamongan and the salt tested in Malang exhibit relatively similar absorption patterns, suggesting that both samples share the same primary chemical characteristics. In the 3600–3200 cm^{-1} region, a broad absorption band is observed in both samples. This band can be attributed to O-H vibrations from moisture absorbed onto the salt crystal surface. The presence of this bound water is further supported by the 1650–1600 cm^{-1} band, which is associated with H-O-H bending vibrations. These conditions indicate that both samples still contain water or moisture, which can affect the salt's purity value because the sample mass does not entirely consist of NaCl. The FTIR spectrum also shows absorption in the regions around 1450–1400 cm^{-1} and 1150–1000 cm^{-1}. This area can be attributed to the presence of inorganic minerals such as carbonates and sulfates. This interpretation is consistent with the XRF results, which indicate the presence of 5.58% SO_3, 2.74% CaO, 2.20% K_2O, 0.67% P_2O_5, and 0.37% Br. Thus, FTIR supports the XRF results that the salt samples contain not only NaCl but also minor minerals derived from seawater or the crystallization process. The use of XRF to assess the mineral composition of salt was also reported by Meng et al. in the analysis of several types of salt, where XRD was used to identify crystalline phases and XRF was used to determine elemental/mineral composition.

Table 2

Elemental composition of salt produced by a solar still based on XRF analysis

Element (%)	Mg	P	S	Cl	K	Ca	V	Fe	Ni	Cu
Malang salt	1.15	0.3	2.29	91.96	2.02	2.12	0.062	0.053	0.032	0.056
Lamongan salt	4.15	0.1	4.06	87.29	2.29	1.95	0.06	0.068	0.027	0.065

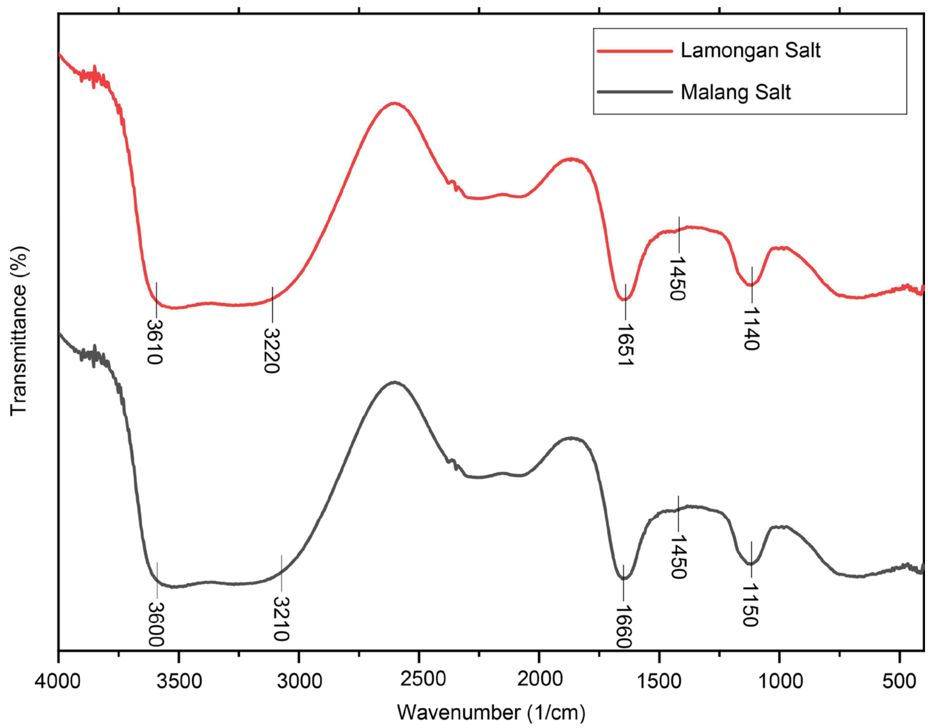


Fig. 7. Comparison of the Fourier transform infrared spectroscopy spectra of salt produced by the solar still in Lamongan and Malang

5. 2. 4. Salt crystal phases based on X-Ray diffraction analysis

XRD analysis is used to analyze the crystal structure, mineral phases, crystal size, and degree of crystallinity of a material. In this study, XRD was used to identify the crystal structure and mineral phases of salt produced by a solar still, as well as to compare the crystal characteristics of salt tested in Malang and Lamongan. The XRD results are presented in Fig. 8.

The XRD patterns of the salt samples tested in Lamongan and tested in Malang show nearly identical diffraction peaks, particularly at angles around 2θ, 31–32°, 45–46°, 56–57°, 66–67°, 75–76°, and 84–85°. These peaks are the primary characteristics of the crystalline phase of halite or sodium chloride (NaCl), indicating that both salt samples have a dominant crystalline phase of NaCl. The sharp main peak at 31–32° indicates that the NaCl in both samples possesses a well-defined crystalline structure. The similarity in peak positions between Lamongan salt and Malang salt indicates that both have the same main phase, namely NaCl. However, the intensity and sharpness of the peaks cannot be directly used to determine the quantitative NaCl content without further analysis such as Rietveld refinement.

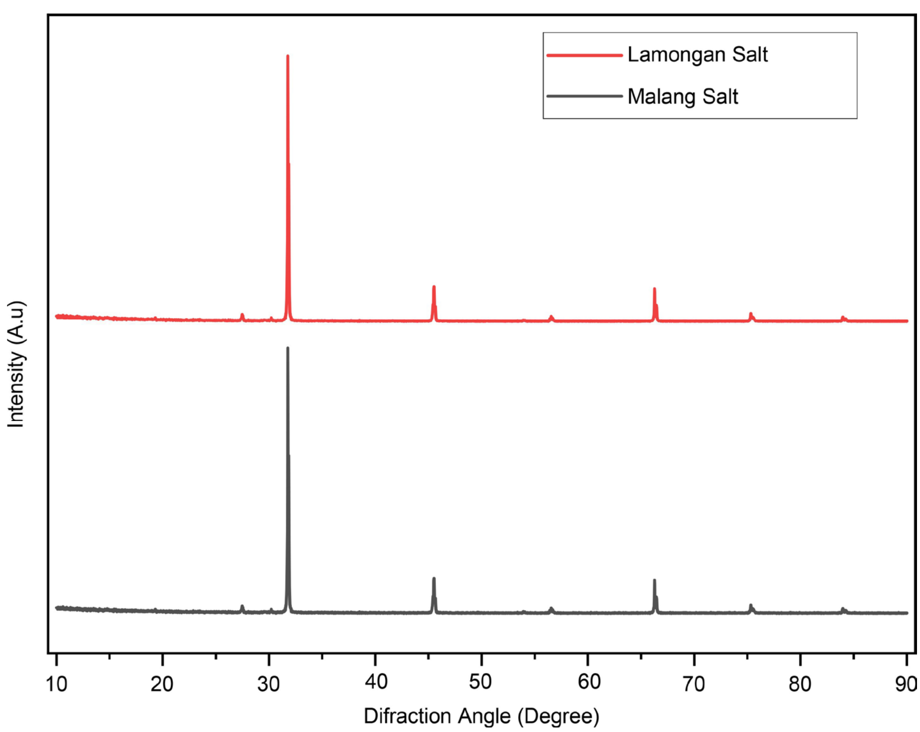


Fig. 8. Comparison of x-ray diffraction patterns of Lamongan salt and Malang salt produced by a solar still

5. 2. 5. Crystal morphology of salt based on macro photographs

The macro photographs are shown in Fig. 9. The Fig. 9 illustrates the differences in salt crystal morphology between the samples tested in Malang and Lamongan. In the salt samples tested in Malang, the crystals appear larger, denser, and some form more distinct crystal faces. This form indicates a tendency toward more ordered NaCl crystal growth, as salt crystals generally form cubic or cube-like morphologies depending on supersaturation conditions and the growth process. Conversely, the salt samples tested in Lamongan appear to have smaller, irregular crystal sizes and tend to form aggregates. This difference in shape suggests that the crystallization process in the samples tested in Lamongan likely proceeded more unevenly compared to the samples tested in Malang. Salt crystal morphology can change due to growth conditions such as the level of supersaturation and the evaporation dynamics of the salt solution.

a *b*

Fig. 9. Salt produced by a solar still: *a* – testing in Malang; *b* – testing in Lamongan

These morphological differences can also be linked to the XRF results, which show that the salt tested in Lamongan has higher Mg and S content compared to the salt tested in Malang. Higher Mg and S content indicates the presence of impurity minerals such as magnesium and sulfate that remain in the salt during the crystallization process. The presence of these impurities can affect the purity of halite and disrupt the growth of NaCl crystals, resulting in less uniform crystal formation. Halite purity is influenced by major impurities such as Ca, Mg, and sulfate species. Bittern, or the residue from the concentrated salt production solution, contains elements such as Mg, K, Cl, sulfates, and bromides that can be carried over during the final stage of crystallization. Therefore, the macro photographs support the XRF results, showing that the salt tested in Malang tends to have more ordered crystals, whereas the salt tested in Lamongan exhibits a greater influence of impurity minerals.

6. Discussion of the performance of a double-slope solar still in a multi-stage configuration and salt characteristics

The results obtained in this study can be explained by the interaction between solar radiation, temperature gradient, humidity, wind speed, and the gradual increase in brine concentration in the multi-stage double-slope solar still. The experimental setup shown in Fig. 1 confirms that four double-slope solar still units were arranged in a tiered configuration, allowing seawater to be transferred from one stage to the next according to salinity levels. This configuration explains why seawater salinity could increase gradually from 3.5% to approximately 29%. The meteorological data in Fig. 2, 3 show that wind speed, solar radiation, and relative humidity differed between Malang and Lamongan. These environmental differences affected the evaporation and condensation processes. In particular, the temperature distributions shown in Fig. 4 indicate that Malang had larger temperature gradients between water, fins, glass cover, and ambient air. These gradients enhanced evaporation from the basin and condensation on the glass cover. Therefore, the faster salinity increase in Malang, which reached the harvesting condition in 25 days compared with 29 days in Lamongan, is explained by more favorable heat and mass transfer conditions.

However, Fig. 5, explain the obtained results. During evaporation, water was extracted from brine, leaving dissolved salts in the slurry therefore increasing salinity. However, with rising salinity the evaporation rate will decrease since higher salts concentration leads to reduced vapor pressure in solution, raised viscosity and increased mass transfer resistance. This also explains the trend of decreasing efficiency as illustrated in Fig. 6. Equation for efficiency of solar still with respect to distilled water produced, solar radiation absorbed and effective area defined in equations given in Section 4.5. Thus, the estimated efficiency declined due to a decrease in net water output at greater salinity in pure-water productivity. This is supported by the salt quality results in Tables 1, 2. Malang salt had much higher NaCl content (92.33%, Table 1) than Lamongan salt (86.95%). This finding is consistent with Table 2, showing Malang salt containing greater Cl content and lower Mg and S contents than South Buru salt, suggesting fewer impurities other than NaCl. Fourier Transform Infrared Spectroscopy (FTIR) spectra in Fig. 7 further display the existence of O-H, carbonate, and sulfate groups in trace amounts confirmed that the obtained salt still contained some moisture and small inorganic impurities.

The uniqueness of the proposed method corresponds to simultaneous distilled water and crystallized salt production under the tropical rainy condition with a combination of a multi-stage arrangement along with a single and double sloping solar still. Different from the spraying-heating approaches reported in [4], which is limited to a nozzle with blower and heater using external heating to accelerate salt production, the proposed system uses solar energy in an evaporation-condensation close process without needing external heating. In contrast to the aforementioned laser-printing evaporator [5], which relies on precise regulation of water supply to evaporation capacity ratio, our technique employs a less complex staged saline transfer according thresholds in salinity. As compared with the four-stage Fresnel-lens solar distiller in [9], the presented system does not involve optical focusing and accurate positioning of the Fresnel lenses. In comparison with the multistage membrane distillation system in [11], the design does not use layered membranes, nor is there a specific confined saline layer; therefore, from a construction point of view, our method has formatted a much simpler system. Regarding salt quality, one of the main advantages over the mangrove-mimicked solar vapor generation device in [12] is that it uses argentometry analysis to assess qualitatively and quantitatively the recovered salt crystals. Unlike the thermal storage solar still in [14] and analytical active basin still model in [15], experimental validation at two real tropical climates during the rainy season is conducted as part of present study. Therefore, the common one does not only use a multi-stage solar still but is in continuous operation continuously producing salt and distilled water under high-humidity rainy weather.

These findings do have limitations regarding the applicability conditions and reproducibility range of the results. The results are more relevant to tropical regions with seawater salinity was around 3.5%, high humidity and daily solar radiation similar to those all experienced in Malang and Lamongan. Performance of this system may vary based on climatic conditions such as dry climate, subtropical climate, solar radiation much lower than that of the concerned region, seawater composition and others. Evaluation: The experiments were carried out with approximate fixed geometry, absorber material, number of stages and brine transfer thresholds (5%, 7.5%, 13% and 29%). Thus, the results are reproducible only in these design and operating conditions. The stability of the results across wider seasonal variation still needs additional confirmation as the study only tested two locations and one rainy-season period from each location. Moreover, the results are also influenced by the local environmental parameters including solar radiation, ambient temperature, humidity, wind speed and wind direction. Changes in these factors can change evaporation rate, condensation rate, salt crystallization time, distilled water productivity and salt purity.

The disadvantages of this study are not the same as its limitations. A limitation is the circumstances under which results hold true, while a disadvantage is an aspect of study design or system behavior that can be improved upon. A major disadvantage is that the system took rather long (25–29 d) to obtain the final salinity for salt harvesting. This can be enhanced by incorporating thermal energy storage, added insulation, absorber geometry optimization or enlarging the effective evaporation area. As also indicated by the x-ray fluorescence and Fourier transform infrared spectroscopy results, another drawback is that the salt produced still bore impurities (mainly Mg and S compounds). This is one being improved (in the future) by adding a washing, a recrystallisation or a controlled bittern separation step before final drying. Another disadvantage is that economic analysis, durability and maintenance were not assessed yet. These features should be tackled in future works by running the system over multiple production cycles, assessing material wear, and computing cost per kg of salt produced or liter distilled water.

This development of this study could lead in multiple directions. These systems can be optimized by designing the optimal stages number, absorber thickness, fin geometry, glass cover angle and insulation thickness & brine depth. It could also be studied the addition of phase change materials or sensible heat storage to sustain evaporation after solar radiation reduce. At a methodology level, longer testing durations, seasons and locations should be incorporated into future studies to enhance reproducibility. In mathematical terms, a heat and mass transfer model was devised in order to estimate the salinity increases, productivity of distilled water and efficiency for different environmental conditions. However, some challenges might arise. The greatest challenge for the experiment is the control of cloud cover, rain amount, dampness and air field. The main methodological challenge is to disentangle the impact of particular environmental variables because they do not change independently in real weather conditions. The main challenge mathematically is modelling transient evaporation, condensation, crystallization of salts, evolving properties of brine and heat losses at each stage. The future development should therefore integrate experimental tests, numerical modelling and economic assessment to provide a basis for application at coastal salt-production sites.

7. Conclusion

1. A double-sloped solar still arranged in tiers is capable of producing distilled water while simultaneously concentrating the solution to form salt during the rainy season under two different environmental conditions, with system performance influenced by temperature gradients, humidity, and heat-mass transfer mechanisms; the concentration process in Malang occurred more quickly (25 days) compared to Lamongan (29 days), although the distilled water productivity of both was relatively the same (±36.57–36.58 L/m^2).

2. Characterization indicates that salt quality is influenced by operational and environmental conditions, with Malang salt having a higher NaCl content (92.33%) compared to Lamongan (86.95%) based on argentometric and XRF analyses, FTIR revealed the presence of O-H, sulfate, and carbonate groups, indicating bound water and mineral impurities; XRD confirmed the dominant halite (NaCl) phase in both samples; and macro photographs showed that the crystal morphology of Malang salt was larger, more homogeneous, and more ordered than that of Lamongan salt due to differences in impurity content and crystallization conditions.

Conflict of interest

The authors declare that they have no conflict of interest in relation to this study, whether financial, personal, authorship or otherwise, that could affect the study and its results presented in this paper.

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Data availability

Manuscript has no associated data.

Use of artificial intelligence

The authors declare that generative artificial intelligence tools were used exclusively for language editing, grammar checking, and technical formatting of the manuscript under full human control. Artificial intelligence was not used to generate, process, or interpret scientific data, form conclusions, or other elements of the scientific results in the paper. Tool used: ChatGPT (OpenAI GPT-5.2, version 2026). The authors bear full responsibility for the content, reliability, and scientific correctness of the submitted material.

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Authors' contributions

Nova Risdiyanto Ismail: Conceptualization, Methodology, Investigation, Resources, Project administration; **Purbo Suwandono**: Formal analysis, Data Curation, Writing – original draft, Visualization, Writing – review & editing; **Dadang Hermawan**: Supervision, Validation, Resources, Project administration; **Frida Dwi Anggraeni**: Investigation, Formal analysis, Validation, Data Curation, Visualization; **Dzulfikar Johan Akbar**: Writing – review & editing, Validation, Visualization, Project administration.

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