TECHNIUM

Romanian Journal of Applied Sciences and Technology
ISSN: 2668-778X

vol. 16 / 2023

The 7th International Conference on Science Technology

organized by
Faculty of Social Science and
Law Universitas Negeri Manado and
Consortium of International Conference
on Science and Technology

The Innovation Breakthrough in Digital and Disruptive Era

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International
Communication & PR

*Technium: Romanian Journal of
Applied Sciences and Technology
Vol. 16, 430-435, October, 2023
ISSN: 2668-778X
www.techniumscience.com*

Enhancing Seawater Salinity through Spray-Assisted Evaporation: Investigating the Effect of Nozzle Sprayer Diameter and Feed Flowrate on Evaporation Rate using Multiple Regression Analysis

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Abstract. Salt production plays a vital role in life due to its essential minerals. Traditional salt production methods using direct solar rays are the most common in Indonesia. It needs a large area and several weeks extended to evaporate sea water into concentrated brine. It is very weather dependent. This study investigates the utilization of a spray-assisted evaporator to increase the salinity of seawater for salt production. The experimental setup consisted of a custom-designed spray evaporator that atomized seawater into fine droplets. A series of experiments were conducted to analyze the effect of different operational parameters, including feed flow rate (1000 ml/min; 1200 ml/min; 1400 ml/min; 1600ml/min; 1800ml/min) and diameter of nozzle sprayer (1 mm; 2 mm; 3 mm) on the average of evaporation rate. The results demonstrated that Higher spray flow rates and smaller droplet sizes positively correlated with increased evaporation rates, leading to higher salt concentrations in the collected brine. Optimizing the Impact of nozzle sprayer diameter and flow rate on the average evaporation rate utilizing multiple linear regression and deriving the Equation $y = 15.687 + 0.0038X_1 - 3.5327X_2$,where x_1 represents the seawater feed flow rate, and X_2 represents the nozzle sprayer diameter.

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1 Introduction

Salt is an essential commodity in daily life. Beyond its role in food preservation, salt is a fundamental ingredient in various food processing[1-2]. Salt is also widely used in chemical manufacturing and water treatment[3]. Furthermore, salt is essential for the creation of products ranging from plastics and detergents to pharmaceuticals and textiles [4][5][6].

The primary method of obtaining salt is through the natural evaporation of seawater, followed by the crystallization process. For a hundred years, evaporation by harnessing direct sunlight has been used in salt production because of its simple way. Using evaporation ponds for treating brine from a desalination facility holds three primary benefits. Initially, their construction is simple. Secondly, they are easy to maintain, and their preservation is less complicated than other mechanical regulatory methods. Lastly, the pond is one of the most economical management choices, particularly for handling small quantities in regions with high evaporation rates and low land expenses[7]. However, Solar thermal power is often perceived as a less potent energy source, presenting complexities in its transformation into alternative energy forms. As a result, obtaining salt from brine usually entails a highly time-consuming procedure. It needs approximately six months to prepare solid salt deposits through evaporation in salt pounds [8]. Weather also dramatically affects the salt-making process's duration and the quality of seawater and crystallization ponds[9].

The previous research investigated multi-level sprinkle methods to speed up the evaporation of brine in salt pounds. The multi-level sprinkling technique enhances the rate of salt production compared to traditional methods. This apparatus disperses seawater into the atmosphere, facilitating the swift separation of H_2O from the seawater and expediting the generation of salt crystals. In contrast to the conventional salt production process that relies on seawater evaporation, taking around 20 days per harvest, the multi-level sprinkling technique, with its technological enhancements, achieves the crystallization of salt within a mere six days per harvest[10]. Although this technology can reduce the time consumption of salt production still, the length of the dry season and the distribution of rainfall throughout the year play a crucial role in determining the production time and yield of salt.

One such approach that has garnered attention is the utilization of a spray-assisted evaporator. This cutting-edge technology harnesses the principles of atomization and droplet evaporation to enhance the seawater concentration process. By creating a fine mist or spray of seawater, the evaporator increases the surface area of interaction between water and air, accelerating the evaporation rate and promoting salt crystallization[11].

El-agouz et al. [12] presented an experimental investigation of a solar desalination system that uses spray evaporation to produce fresh water from salty water. They were involved in designing and constructing a pilot plant for a solar desalination system using spray evaporation. The setup comprised an evaporation tower, a condensation tower, a solar water collector, and a thermal storage tank. The saline water was pumped into the solar water collector, heated, and cycled back to the thermal storage tank. The spraying of water amplified both the evaporation and condensation procedures. The researchers studied the effect of parameters such as inlet hot water temperature and flow rate on the productivity and efficiency of the system. They discovered that the temperature and flow rate of the incoming hot water significantly influenced the spray evaporation process. Since this method uses solar as the thermal energy, the weather did affect the experiment. The system's productivity was higher on hot days with higher solar intensity than on cold days with lower solar intensity. The system’s effectiveness was contingent upon the hot water temperature within the storage tank, a factor influenced by solar radiation. Another investigation on the spray evaporator has been done by Alrowais et al. They discussed developing and evaluating a greener, cost-effective seawater desalination method called direct-contact spray evaporation and condensation (DCSEC)[13]. The study focuses on conducting experiments using a lab-scale DCSEC system to investigate the performance of single-stage and multi-stage configurations. Direct contact spray evaporation and condensation (DCSEC) is a desalination method that involves direct contact between a liquid feed (such as seawater) and a vapor (such as water vapor) to separate the pure water from the impurities. In DCSEC, the liquid feed is sprayed into an evaporator chamber, which comes into direct contact with a vapor, causing the liquid to evaporate. The vapor produced then moves to a condenser chamber, which comes into contact with a cooler surface, causing the vapor to condense and form pure water droplets. These droplets are collected as the distillate[14]. However, the DCSEC method utilizes concentrated solar power (CSP) as a heat source for generating the vapor. The availability of solar energy, which is influenced by weather conditions, can indirectly impact the operation of the CSP system.

The articles explore techniques and technologies employed in modern salt production, highlighting the balance between traditional practices and contemporary advancements. The spray-assisted evaporator can address key challenges in salt production from seawater. By optimizing evaporation efficiency, it offers the prospect of reducing time consumption, thereby minimizing the environmental impact of salt production processes.

Despite the promising outlook, several aspects of the spray-assisted evaporator technology still need further investigation. Understanding its performance under different weather, evaluating its environmental implications, and comparing its effectiveness to conventional methods are essential for determining its viability as a sustainable solution for salt production from concentrated seawater.

This article presents a comprehensive study that experimentally explores the spray-assisted evaporator's potential for concentrating seawater in salt production.

Weaknesses in previous studies include the requirement of sunlight in the seawater concentration process and the relatively long time needed for seawater concentration. Therefore, in this research, equipment in the form of a spray evaporator with electric heating plates inside the spray evaporator is utilized. The advantage of these electric heating plates inside the spray evaporator is their ability to substitute for the role of solar energy in the seawater evaporation process. This study hopes to accelerate the rate of seawater evaporation by examining the influence of the seawater feed flow rate and the diameter of the sprayer nozzle in the spray evaporator.

By investigating various operational parameters, analyzing the effects on evaporation rates, and assessing its environmental Impact, this research aims to contribute valuable insights into the feasibility and sustainability of using the spray-assisted evaporator for salt production. The findings from this study will serve as a foundation for future advancements and the potential integration of this innovative technology into the realm of seawater desalination and salt production,

2 Research methods

2.1 Equipment setup

The schematic diagram of the experimental setup of the spray evaporator is shown in Figure 1. The system mainly consists of a cylindrical evaporator chamber with a diameter of 80 cm. The heating element is a circle plate with a diameter of 50 cm placed inside the tank to face the feed seawater sprayer. The nozzle on the spray evaporator is installed according to diameter variables, which are 1 mm, 2 mm, and 3 mm. The feed flow rate is adjusted with variables 1000 ml/minute, 1200 ml/minute, 1400 ml/minute, 1600 ml/minute, and 1800 ml/minute. Before commencing the evaporation process, the temperature on the electric heating plate is set to 180^{o}C.

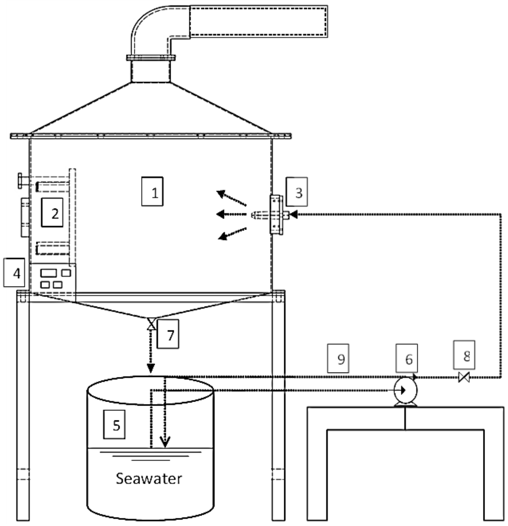


Figure 1 Schematic diagram of the spray-assisted evaporator with components : (1) Evaporator Chamber, (2) Electrical plate heater, (3) Nozzle Sprayer, (4)Thermo-control, (5) Sea water storage tank (6) Diaphragms pump(7&8) Valve (9) Overflow pipe

2.2 Experimental Procedure

The seawater used in this research is obtained from Kenjeran Beach in Surabaya City. The seawater has initial salinity of 2.5%. The experiment was initiated by filling the storage tank with 5 liters of seawater. Once activated, the pump propelled the seawater from the storage tank and directed it toward the evaporator chamber. Within the evaporator chamber, the seawater passed through the sprayer's nozzle. The seawater passing through the sprayer will be converted into tiny droplets. Subsequently, these droplets will come into contact with the surface of the electric heating plate and undergo evaporation. As the water vaporizes, it ascends to the chamber's top and exits through the exhaust. At the same time, the remaining unvaporized seawater descends to the base of the evaporator chamber and returns to the storage tank. The evaporation process operates continuously, wherein the unevaporated seawater is recycled and subjected to evaporation again in the evaporator tank. After 4 hours, the process is stopped, and the remaining unevaporated seawater, which becomes concentrated brine, is measured for its salinity using a refractometer.

2.3 The Average Evaporation Rate Calculation

The average evaporation rate is obtained by calculating the water evaporated at a certain time.

$$J = \frac{m}{t} \qquad (1)$$

Where, J : evaporation rate (gram/min)
m: the mass of water evaporated
t: evaporation time

The evaporated seawater mass is calculated by subtracting the mass of seawater before the evaporation process from the mass after evaporation. The mass of water is obtained by calculating brine concentration before and after the evaporation process. The mass of the brine is calculated by using a simple equation

$$m_b = \rho \; x \; V \tag{2}$$

Where,

m_b = mass of brine solution (gr)

ρ = brine density (gr/ml)

V = volume (ml)

The mass of water before and after the evaporation process was calculated by multiplying the water concentration and mass of the brine

$$m_w = C_w x \; m_b \tag{3}$$

Where,

m_w = mass of the water

C_w = water concentration

The water concentration is calculated by subtracting the total concentration from the salt concentration using a refractometer.

$$C_w = 100\% - C_s \tag{4}$$

Where,

C_w = water concentration (%)

C_s = salt concentration (%)

3 Result and Discussion

3.1 The Influence of Seawater Feed Flow Rate on the Average Evaporation Rate

The experiments were conducted at various seawater feed flow rates, 1000 ml/min, 1200 ml/min, 1400 ml/min, 1600 ml/ min, and 1800 ml/min. The effect of feed flow rate on the average seawater evaporation at various diameter nozzle sprayers is shown in Figure 2.

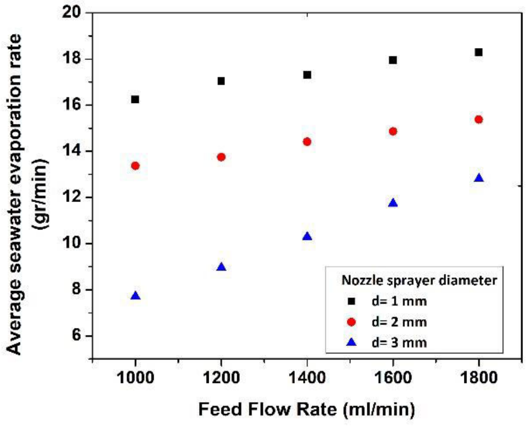


Figure 2 The effect of Feed flow rate on average seawater evaporation rate with various diameter nozzle sprayer

Figure 2 shows that the feed flow rate significantly influences the average seawater evaporation rate. The average seawater evaporation rate at a seawater feed flow rate of 1800 ml/minute is higher compared to a seawater feed flow rate of 1000 ml/minute with the same sprayer nozzle diameter. In this study, the seawater feed flow rate is directly proportional to the average seawater evaporation rate, meaning that higher seawater feed flow rates result in higher average evaporation rates. A higher seawater flow rate allows more contact with the heating plate, while a lower flow rate results in less contact. The larger the contact surface area between the liquid and the heating plate, the more water molecules can be evaporated, leading to a faster evaporation rate [15]. Seawater evaporation in the spray evaporator with a higher seawater feed flow rate yields a higher evaporation rate, meaning that the larger the feed rate introduced into the evaporator, the higher the resulting seawater evaporation rate.

3.2 The Influence of Seawater Nozzle Sprayer Diameter on the Average Evaporation Rate

The nozzle sprayer diameters used in this study were 1 mm, 2 mm, and 3 mm. The dimensions of the droplets formed through the nozzle sprayers were managed by modifying the nozzle sprayers' diameter by the predetermined parameters. The influence of the nozzle sprayer diameter on the average seawater evaporation rate is presented in Figure 3

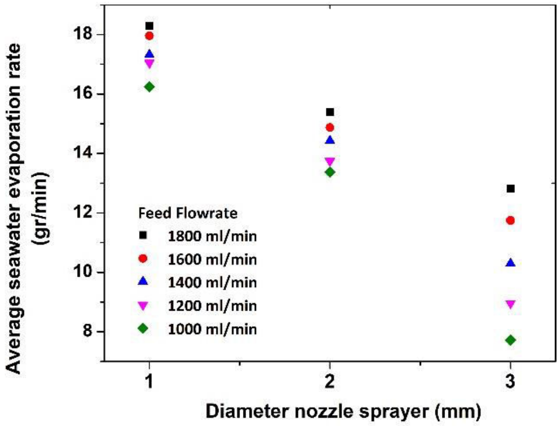


Figure 3 The effect of the diameter nozzle sprayer on the average evaporation rate at various feed flow rates

Figure 3 shows that the nozzle's diameter significantly impacts the average seawater evaporation rate. The average seawater evaporation rate with a 1 mm diameter nozzle sprayer is the highest compared to the average evaporation rates with 2 mm and 3 mm diameter nozzle sprayers at the same seawater feed flow rate. This study indicates an inverse relationship between the nozzle sprayer diameter and the average seawater evaporation rate, meaning that smaller nozzle sprayer diameters result in higher average evaporation rates. Smaller nozzle sprayer diameters produce smaller droplet sizes, and with smaller droplets and higher temperatures, the seawater evaporation rate is accelerated [16].

Nozzle sprayers in the spray evaporator greatly facilitate evaporation because the nozzle sprayer diameter can transform the feed into small droplets, rapidly increasing the feed temperature and enhancing the evaporation rate[17]. The evaporation rate of a solution depends on the droplet size, where smaller droplets lead to higher evaporation rates [18].

3.3 The Estimation of evaporation rate by Multiple Linear regression

The relationship between nozzle sprayer diameter and feed flow rate to the average evaporation rate of seawater is predicted using multiple linear regression (MLR). The data used in the plot of the multiple linear regression equation consists of the average evaporation rate from the research results (y), the seawater feed flow rate x_1, and the diameter of the nozzle sprayer x_2. The equation of the multiple linear regression will be expressed as

$$y = \alpha + \beta_1 x_1 + \beta_2 x_2 \tag{5}$$

Where:

α : Constant

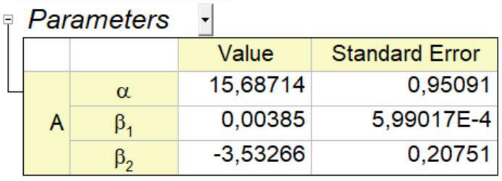
β_1,β_2 :Regression coefficients of the independent variables [19]

The experimental data plot for multiple regression is shown in Table 1

Table 1 Plot data for MLR

Y	x_1	x_2
18,2850	1800	1
17,9559	1600	1
17,3179	1400	1
17,0507	1200	1
16,2419	1000	1
15,3813	1800	2
14,8690	1600	2
14,4187	1400	2
13,7488	1200	2
13,3700	1000	2
12,8118	1800	3
11,7388	1600	3
10,2934	1400	3
8,9612	1200	3
7,7196	1000	3

The data is plotted using origin software, and obtained parameters as follows.



Parameters

		Value	Standard Error
A	α	15,68714	0,95091
	β_1	0,00385	5,99017E-4
	β_2	-3,53266	0,20751

Figure 4 Parameters for Multiple Linear Regression Analysis

From Figure 4, we can get the parameter α, β1, and β2 values. The evaporation rate formula becomes

$$y = 15.6871 + 0.0038x_1 - 3.532x_2 \tag{6}$$

Equation (6) is validated by fitting the curve between experimental data and calculated results. The variable seawater feed flow rate x_1 and the diameter of the nozzle sprayer x_2 are substituted to equation (6) to find the calculated evaporation rate. The curve-fitting result between the experimental data and the calculated result is shown in Figure 5.

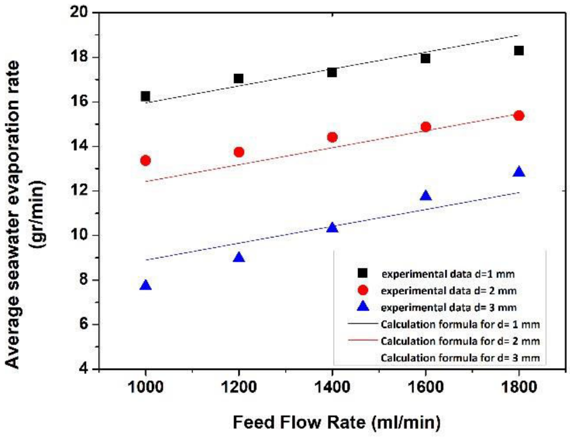


Figure 5 The Influence of Seawater Feed Flow Rate on the Average Evaporation Rate of Research Results and the Average Evaporation Rate Based on the Equation at Each Nozzle Sprayer Diameter.

Figure 5 shows that the comparison of the average evaporation rate values from the experimental data and the average evaporation rate values from the formula exhibit a small average percentage error of 4.1326%. The average evaporative rate values from the research closely align with the curve-fitting outcomes. The curve mentioned above fitting aids in identifying the function with parameters that best match a specific set of data points[20]. The smallest percentage error in the curve fitting is observed at the point of seawater feed flow rate of 1600 ml/minute with a nozzle sprayer diameter of 2 mm. At this point, the average evaporative rate from the research stands at 14.8690 grams/minute. In comparison, the curve fitting line corresponds to an average evaporative rate value of 14.7808 grams/minute based on the equation. This small discrepancy results in an extremely low percentage error of 0.5928%

4 Conclusion

The seawater feed flow rate affects the average seawater evaporation rate, where a larger seawater feed flow rate results in a faster average seawater evaporation rate. The diameter of the sprayer nozzle affects the average seawater evaporation rate; a smaller nozzle diameter leads to a faster average seawater evaporation rate.

The multiple linear regression equation obtained for the average evaporation rate of the spray evaporator is Y' = 15.6871 + 0.0038X1 - 3.5327X2. When comparing the average evaporation rate values from the research to the values calculated by the equation, there is a small average percentage error of 4.1326%.

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