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Enhancement of Seawater NaCl Concentration Using Spray-Assisted Evaporation and Ion Exchange Pretreatment

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A B S T R A C T

This study investigates the enhancement of seawater NaCl concentration using a combination of ion exchange pretreatment and spray-assisted heating as an alternative method for a more efficient and sustainable salt concentration process. The novelty of this study lies in the utilization of Dowex cation and anion exchange resin pretreatment prior to the spray heating process to reduce impurity ions that may affect the NaCl concentration process. This study aims to analyze the effect of nozzle-to-heating plate distance variations (16, 18, 20, 22, and 24 cm) and spraying flow rates (25, 30, 35, 40, 45, 60, and 70 L/h) on the increase of seawater %Brix values. Before the concentration process, seawater was pretreated using Dowex cation and anion exchange resins for 25 minutes to reduce impurity ion content. The results showed that the optimum operating condition was achieved at a nozzle distance of 16 cm and a spraying flow rate of 45 L/h for 5 hours, resulting in a maximum concentration of 15 %Brix. The concentration enhancement was also indicated by the darker color of the solution due to the increase in dissolved solids content. Scientifically, this study demonstrates that ion exchange pretreatment followed by spray heating can improve the effectiveness of seawater concentration. Furthermore, this method has the potential to be applied in the salt industry as a more energy-efficient alternative technology, supporting the improvement of national salt raw material quality and contributing to the development of more sustainable salt production processes.

Contribution to Sustainable Development Goals (SDGs):

SDG 6: Clean Water and Sanitation

SDG 9: Industry, Innovation and Infrastructure

SDG 12: Responsible Consumption and Production

SDG 13: Climate Action

1. INTRODUCTION

1.1. Research Background

Indonesia is a maritime nation comprising numerous islands, with nearly 70% of its territory being ocean. This strategic location offers significant potential to develop Indonesia's salt industry and meet domestic demand. Despite its vast maritime territory, Indonesia has not yet been able to fully utilize this potential, as evidenced by the fact that the quantity and quality of salt products

currently fall short of standards. The quality of current salt products contains only approximately 90–93% sodium chloride (NaCl), with ± 7 –10% impurities consisting of calcium (Ca), magnesium (Mg), potassium (K), and sulfate (SO_4) ions [1]. Salt production in Indonesia has not been maximized because the salt industry in Indonesia still relies on technology that is dependent on climate and weather conditions.

One method that can improve the quality of salt is washing and evaporation. Washing a salt solution near saturation can yield salt with a sodium chloride (NaCl) content of 94.85–98.14%, and partial evaporation can yield salt with a sodium chloride (NaCl)



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content of 99.34–99.73% [2]. Salt production via evaporation is carried out using the spray method, which accelerates water evaporation, resulting in a salt solution with a higher Boume degree (°Be) [3]. The evaporation process requires precise control of the feed seawater temperature and flow rate to accelerate evaporation and increase the seawater's NaCl concentration [4].

Another method for improving salt quality, more efficient than washing, is ion exchange in a salt solution. This method focuses on improving salt quality by using resin to bind calcium (Ca), magnesium (Mg), potassium (K), and sulfate (SO₄) ions. Using cationic resin can remove Ca ions: 82.86%, Mg: 62.22%, K: 25.00%, and SO₄: 72.50% under conditions of 100 grams/liter and a contact time of 25 minutes [5]. Ion exchange is influenced by flow rate and process time; that is, the longer the process time, the more ions are absorbed by the resin [6].

Based on this, we propose research on the Spontaneous Heating Method to Increase the NaCl Content of Seawater as a Raw Material for Salt, as a modern method of increasing the salt concentration in seawater that has not yet been implemented. In addition, the reason for choosing this heating method is because many salt farmers still use traditional methods with solar heat, which is inefficient during the rainy season. The NaCl concentration in the heated seawater will be analyzed using a refractometer and its density will be calculated.

1.2. Literature Review

Evaporation is a method of purifying a substance from its impurities through a dissolution process based on the substance's solubility in a solvent, wherein solubility increases with rising temperature and decreases at low temperatures. Impurities have different properties; their solubility is low at high temperatures and high at low temperatures. This evaporation process can produce pure, crystalline products free of impurities; for example, salt is obtained by evaporating seawater [7]. Seawater is a mixture of 96.5% water and 3.5% dissolved and suspended materials, such as salts, dissolved gases, organic substances, and insoluble particles [8]. When salts dissolve in water, they react with the water and break down into ions consisting of six ions: four cations—sodium (Na⁺), magnesium (Mg²⁺), calcium (Ca²⁺), and potassium (K⁺)—and two anions—chloride (Cl⁻) and sulfate (SO₄²⁻) [9].

Table 1. Ionic composition of seawater

No	Composition	Massa (%)
1	Cl ⁻	55%
2	Na ⁺	30.6%
3	SO ₄ ²⁻	7.7%
4	Mg ²⁺	3.7%
5	Ca ²⁺	1.2%
6	K ⁺	1.1%

High-quality salt typically contains 99% sodium chloride (NaCl), along with impurities such as calcium, magnesium, potassium, and sulfate. To produce high-quality salt, five salt production technologies can be used: conventional salt production, geomembrane spiral filters, multi-effect evaporation, seawater desalination, and pyramid desalinators

1.2.1. Salt production technology

1. Conventional salt production

A specially designed and well-structured system in which each salting plot functions as a complete salting unit, consisting of settling ponds and salt tables equipped with stairs, allowing water to flow naturally (by gravity) [10]

2. Geomembrane Filter Coils

The primary principle of this salt production technique involves the evaporation of seawater using solar energy, which is channelled through a series of basins during the maturation process. Additionally, natural materials are added to serve as filters for purifying the brine [11]

3. Multi-Effect Evaporation

The feed, typically a 26% NaCl solution, is first heated in a preheater. The heated NaCl solution is then fed into the first evaporator of a five-stage evaporator system. The second through fifth evaporators are vacuumed, causing the boiling point to decrease progressively from one evaporator to the next. The evaporators produce a salt slurry, which is then fed into a centrifuge [12]

4. Seawater Desalination

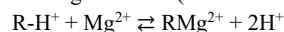
Desalination is the process of treating seawater to produce freshwater and brine using membranes. One of the most widely used desalination technologies is Seawater Reverse Osmosis. In this reverse osmosis process, pressure is applied to the seawater to cause the opposite effect: the freshwater contained within the seawater passes through the membrane, which acts as a separating barrier. The salt concentration in seawater, the type of membrane, and the pressure are factors that influence the output from the membrane [13]

5. Pyramid Desalination Unit

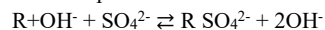
Pyramid desalination technology is a seawater evaporation method that produces salt while simultaneously yielding freshwater. This technology involves a series of processes for salt production and its derivatives, which are beneficial for arid regions and areas facing clean water shortages. Prism-shaped structures have been developed in several salt production centers. Salt crystallization plots are constructed as structures with prism-shaped roofs made of geothermal plastic [14].

1.2.2. Exchange of Positive and Negative Ions

The process of reducing impurities in seawater can be achieved by exchanging positive and negative ions with cation- and anion-exchange resins. This process combines physical and chemical processes (ion exchange), positive ions (Mg²⁺, Ca²⁺, K⁺ dan Na⁺) present in the salt solution are exchanged for hydrogen ions (H⁺ or Na⁺) in the ion exchange medium (cation resin), while the negative ions (Cl⁻ and SO₄²⁻) are exchanged for hydroxide ions (OH⁻) in the ion exchange medium (anion resin).



In this cation-exchange resin, positively charged Mg²⁺ ions are bound to the resin, while the resin releases H⁺ ions; this release can lower the solution's pH.



In this anion exchange resin, negatively charged SO₄²⁻ ions are bound to the resin, while the resin itself releases OH⁻ ions; the release of OH⁻ ions can cause an increase in the solution's Ph.

1.3. Research Objective

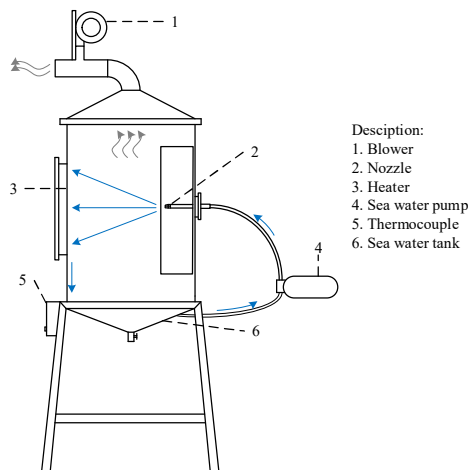
This study aims to determine the quality of salt produced from seawater as a raw material through ion exchange and spontaneous heating using an evaporator

2. MATERIALS AND METHODS

2.1. Raw materials

This study aims to investigate the effects of nozzle distance and spray flow rate on enhancing seawater NaCl concentration via spray heating after ion-exchange pretreatment.

2.2. Set of tools



2.3. Preparation of raw materials

Seawater with a salinity of 3% was collected to determine the initial impurity level. Stir the mixture by adding 8 liters of seawater to a bucket containing 1.2 kg of cation exchange resin for 25 minutes. Then, filter the mixture to separate the cation exchange resin from the seawater. Add 1.2 kg of anion exchange resin to the filtered seawater and stir for 25 minutes. Filter the mixture to separate the anion exchange resin from the seawater. Take a sample to test for impurity levels.

2.4. Research methods

Eight liters of pre-treated seawater were placed in a container. Adjust the distance between the nozzle and the heater (16, 18, 20, 22, and 24 cm). The heating plate was operated at 90°C and spray the seawater at flow rates of (25, 30, 35, 40, 45, 60, and 70 liters/hour). Collect the samples after 5 hours for NaCl and density analysis.

2.5. Salt content analysis

A salinity test is used to measure the amount of salt in seawater. The steps involved are as follows: Use a pipette to place a sample drop onto the prism of the refractometer. Then, read the salinity value through the lens. Next, calculate the salinity using the following formula :

$$\text{gram/ml} = \frac{\frac{\text{Brix}}{100\%} \times 100 \text{ gram}}{100 \text{ ml}}$$

2.6. Seawater density analysis

The density of seawater is determined using a pycnometer. The steps are as follows: first, record the weight of the empty pycnometer. Using a pipette, add the sample to a 10-ml pycnometer, then record the weight. Next, calculate the density of the seawater using the formula :

$$\rho = \frac{(\text{Pycnometer capacity} - \text{Pycnometer empty})}{\text{Pycnometer volume}}$$

2.7. Evaporation Rate Analysis

he evaporation rate was calculated based on the difference between the seawater mass before and after the heating process over a certain operating time. Evaporation occurred due to heat transfer causing the phase change of water from liquid to vapor. The evaporation rate was calculated using the following equation:

$$\text{Evaporation Rate} = \frac{\text{initial solution mass} - \text{final solution mass}}{\text{evaporation time}}$$

2.8. Statistical Analysis

The experimental data were analyzed descriptively based on the relationship between spraying flow rate, nozzle distance, and the resulting % Brix value. The obtained data were presented in tabular form to evaluate the effect of operating variables on seawater concentration enhancement.

3. RESULT AND DISCUSSION

3.1. Effect of Feed Water Flow Rate and Nozzle Distance

Table 2. Results for Brix (%), Evaporation Rate (L/h), and Density (g/ml) for various combinations of feed water flow rate (L/h) and nozzle distance (cm)

Spraying Speed (L/hour)	Distance (cm)	Brix %	NaCl (g/ml)	Density (g/ml)	Rate of evaporation (L/hour)
25	16	12.5	0.1250	1.1220	1.324
	18	12.1	0.1210	1.1162	1.306
	20	11.4	0.1140	1.1117	1.274
	22	10.4	0.1040	1.1042	1.240
	24	9.4	0.0940	1.0971	1.210
30	16	13.0	0.1300	1.1242	1.342
	18	12.6	0.1260	1.1208	1.328
	20	11.9	0.1190	1.1145	1.284
	22	11.3	0.1130	1.1087	1.266
	24	10.9	0.1090	1.1046	1.255
35	16	13.9	0.1390	1.1283	1.360
	18	12.8	0.1280	1.1226	1.336
	20	12.4	0.1240	1.1182	1.320
	22	11.4	0.1140	1.1117	1.274
	24	11.2	0.1120	1.1055	1.264
40	16	14.8	0.1480	1.1323	1.392
	18	13.8	0.1380	1.1255	1.350
	20	12.5	0.1250	1.1220	1.324
	22	12.2	0.1220	1.1169	1.310
	24	11.8	0.1180	1.1123	1.280
45	16	15.2	0.1520	1.1341	1.416
	18	14.7	0.1470	1.1316	1.380
	20	13.4	0.1340	1.1248	1.348

60	22	12.7	0.1270	1.1224	1.340
	24	12.2	0.1220	1.1169	1.312
	16	9.3	0.0930	1.0952	1.206
	18	9.6	0.0960	1.0980	1.224
	20	10.0	0.1000	1.1013	1.230
	22	10.7	0.1070	1.1047	1.250
70	24	11.2	0.1120	1.1055	1.264
	16	8.8	0.0880	1.0886	1.170
	18	9.0	0.0900	1.0913	1.180
	20	9.4	0.0940	1.0969	1.212
	22	9.8	0.0980	1.0991	1.222
	24	10.5	0.1050	1.1044	1.246

From the data table above, it can be seen that as the feed water flow rate (L/hr) increases, the resulting Brix (%) also increases, whereas increasing the distance between the nozzle and the heater yields a decreasing Brix (%). The table shows the Brix values for each seawater sample obtained; the highest Brix, 15.2%, was achieved at a flow rate of 45 L/hour and a nozzle-to-heater distance of 16 cm. Brix is the amount of total dissolved solids (in grams) per 100 grams of solution. The temperature in this study was set to 90°C because the evaporator temperature affects the evaporation rate; higher temperatures lead to faster evaporation. However, using high temperatures can damage heat-sensitive materials. Previous research has reported that a solution with a 12 B concentration evaporates at 94°C [15]. After the feed water evaporates, the temperature will remain constant. Because a phase change occurs, the heat supplied by the electric heater is used for the evaporation heat from the liquid phase to the vapor phase. At this point, the temperature will be constant, and the evaporation process proceeds continuously. The evaporation rate may decrease due to the temperature difference between the evaporator unit and the evaporator wall, which loses heat to the environment [16].

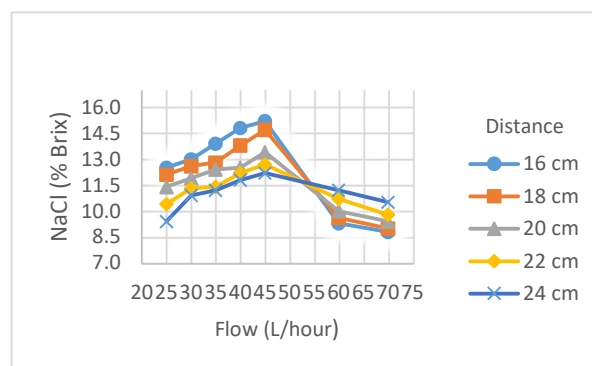


Fig. 1. The relationship between spray rate (L/h) and NaCl concentration (% Brix) at flow rates of 16, 18, 20, 22, and 24 L/h

Figure 1 shows that the NaCl concentration (%Brix) was inversely proportional to nozzle distance. The highest %Brix value, 15.2%, was obtained at a nozzle distance of 16 cm with a feed water flow rate of 45 L/h, while the lowest, 8.8%, was obtained at the same nozzle distance with a flow rate of 70 L/h. At shorter nozzle distances, seawater droplets received heat more effectively from the heating plate, resulting in higher evaporation rates and increased NaCl concentration. Similar findings have

been reported in previous studies, where shorter nozzle-to-surface distances improved heat transfer and evaporation performance [17]. However, excessively high spraying flow rates caused wider spray coverage and splash reflection toward the chamber walls, reducing droplet contact with the heating plate. The position of the heating center relative to the nozzle also affected spray distribution, where heat intensity was highest at the center of the spray area and gradually decreased toward the edge of the spray pattern [18].

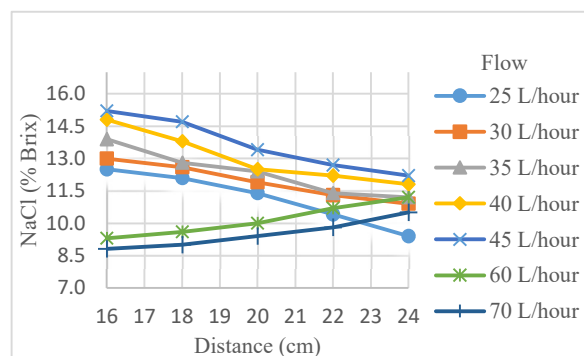


Fig. 2. The relationship between spray rate (L/h) and NaCl concentration (% Brix) at flow rates of 16, 18, 20, 22, and 24 L/h

Figure 2 shows that nozzle distance and spraying flow rate influenced evaporation behavior during the spray heating process. At flow rates of 25–45 L/h, the %Brix value decreased with increasing nozzle distance, whereas at 60 and 70 L/h, it increased. At shorter nozzle distances, droplets received heat more effectively, resulting in faster evaporation and higher NaCl concentration [19]. In addition, spraying flow rate affected droplet distribution and evaporation efficiency. At a flow rate of 45 L/h, the spray distribution became more optimal and produced the highest %Brix value. However, excessively high flow rates reduced droplet contact time with the heating plate, thereby decreasing evaporation efficiency [20].

3.2. Rate of Evaporation

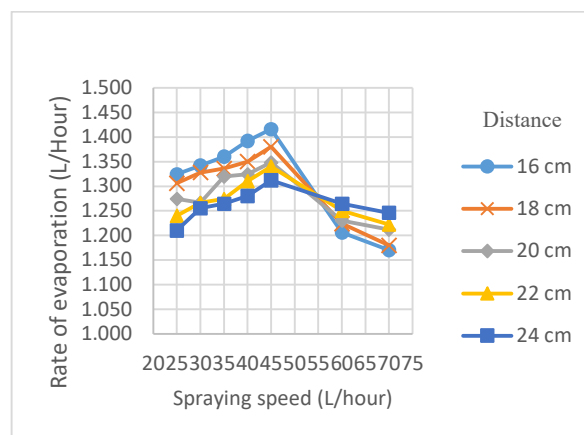


Fig. 3. The relationship between Spray Rate (L/h) and Evaporation Rate (L/h) at flow rates of 16, 18, 20, 22, and 24 L/h

Based on Figure 3, the evaporation rate increased with increasing %Brix. The evaporation rate increased from 25 to 45 L/h and decreased above 45 L/h. This behavior was influenced by

spray coverage and the evaporation area on the heating plate. At higher flow rates, part of the sprayed seawater did not come into direct contact with the heating surface, thereby reducing evaporation efficiency. In addition, higher NaCl concentrations reduced the amount of free water available on the droplet surface, thereby decreasing the evaporation rate [21]. Similar results were reported in previous studies, where optimized spray distribution improved heat and mass transfer during thermal evaporation processes [22].

3.3. Analysis of Impurities Sea Water

Table 3. Test results for impurities in seawater prior to processing

No.	Parameter	Unit	Test Results
1	Lead (Pb)	mg/L	< 0,016
2	Magnesium (Mg)	mg/L	726
3	Calcium (Ca)	mg/L	1390.5
4	Potassium (K)	mg/L	72,3
5	Sulfate (SO ₄)	mg/L	1936
6	NaCl	%	3

Table 4. Results of impurity content testing in seawater after processing

No.	Parameter	Unit	Test Results
1	Lead (Pb)	mg/L	< 0,016
2	Magnesium (Mg)	mg/L	468
3	Calcium (Ca)	mg/L	1097,8
4	Potassium (K)	mg/L	62
5	Sulfate (SO ₄)	mg/L	1511
6	NaCl	%	4,1

In this study, impurities in seawater will first be removed using cation resin and anion resin. Seawater impurities are removed using a batch method, whereby 8 liters of seawater is placed in a container and treated with 1.2 kg each of cation resin and anion resin, with stirring for 25 minutes. Samples of the purified seawater will then be taken for analysis. The data obtained showed decreases in the contents of Mg, Ca, K, and SO₄, and an increase in NaCl content from 3% to 4.1%. In previous studies, it was found that flow rate affects the decrease in Ca and Mg ions in seawater; the lower the flow rate, the greater the decrease.

Table 5. Salt crystal test results

No.	Parameter	Unit	Test results
1	Lead (Pb)	mg/kg	<0,076
2	Mercury (Hg)	mg/kg	<0,0004
2	Magnesium (Mg)	%	0,24
3	Calcium (Ca)	%	0,28
4	Potassium (K)	%	0,03
5	Sulfate (SO ₄)	%	1,97
6	NaCl	%	89,2

The results of the NaCl salt crystal test indicated an NaCl content of 89.2% and relatively low Ca, Mg, and K contents, despite the high sulfate content. The salt crystal content is higher than that of traditional salt (krosok salt), which is around 85%. These results are in accordance with SNI salt consumption regulations, based on the metal contamination category that has been met. Washing time of 45 minutes at a stirring speed of 200 rpm can increase the average NaCl content by 12.37% with an NaCl content of 94.85–98.14%.

Although the purity of the NaCl obtained was 89.2%, it was still below industrial-grade standards. This indicates that the ion-exchange pretreatment and spray-heating processes were not yet fully capable of removing impurity ions such as magnesium and calcium. In addition, impurity incorporation may still occur during crystallization and drying processes. Therefore, further optimization, such as adding a recrystallization stage or improving evaporation control, is required to enhance the final product purity.

4. CONCLUSION

This study demonstrated that ion-exchange pretreatment and spray heating significantly enhanced the removal of seawater NaCl. The use of cation and anion exchange resins successfully reduced impurity ions and increased the NaCl concentration of seawater from 3% to 4.1% after 25 minutes of contact time. Furthermore, the spray heating process enhanced heat transfer and evaporation efficiency, increasing the NaCl concentration from 4.1% to 15.2% at an optimal spraying flow rate of 45 L/h and a heating time of 5 hours. The spraying mechanism generated fine droplets with larger surface areas, thereby accelerating evaporation and improving seawater concentration. Subsequent solar drying for 7 days produced salt crystals with an NaCl purity of 89.2%. However, the obtained purity was still below industrial-grade salt standards, indicating that further purification and process optimization are required. Overall, this study demonstrates the potential of ion-exchange pretreatment and spray heating as an alternative, more sustainable seawater concentration technology for salt production.

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