International Journal of Design & Nature and Ecodynamics
Vol. 21, No. 3, March, 2026, pp. 795-803
Journal homepage: http://iieta.org/journals/ijdne

Integrating the Salt Suitability Index (SSI) and Sensitivity Analysis for Evaluating and Optimizing Salt Production Sites: A Case Study from South Malang, Indonesia

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https://doi.org/10.18280/ijdne.210317

Received: 3 December 2025
Revised: 20 January 2026
Accepted: 27 January 2026
Available online: 31 March 2026

Keywords:
coastal ecosystem, Malang Regency, salt production, salt suitability index, sensitivity analysis, site suitability

ABSTRACT

Salt is a strategic commodity with significant economic and ecological importance; however, Indonesia continues to face a deficit in high-quality salt production, particularly for industrial needs. This study evaluates the suitability of the southern coast of Malang Regency, East Java, as a potential new solar salt production area using the Salt Suitability Index (SSI). Field observations and secondary climate data were used to assess ten key parameters, including rainfall, soil permeability, soil type, sun exposure, air humidity, wind speed, air temperature, evaporation rate, water saturation, and road access. The results indicate that most environmental parameters fall into the very suitable (S1) category, yielding an overall SSI value of 82.5%, which corresponds to the quite suitable (S2) class. Wind speed, road access, and air humidity were identified as the primary limiting factors. Sensitivity analysis demonstrates that targeted improvements in these parameters could increase the SSI to 95%, shifting the site classification to very suitable (S1). These findings confirm that the southern coast of Malang has strong potential for salt production development, provided that technological interventions and infrastructure enhancements are implemented. The proposed SSI-based framework supports evidence-based site selection and optimization, contributing to more resilient and regionally diversified salt production in Indonesia, while promoting sustainable coastal resource management aligned with Sustainable Development Goals (SDGs) 8, 9, and 12.

1. INTRODUCTION

Salt is a strategic commodity that plays an essential role in daily life, both for household consumption and industrial applications [1]. Global salt demand continues to increase in parallel with population growth, food processing expansion, and industrial development. Consequently, more than 100 countries are actively engaged in salt production using various raw materials and production systems. Currently, the world's largest salt producer is China, with an estimated production of 62.7 million tons, followed by the United States (45 million tons), India (18.6 million tons), Germany (16.6 million tons), and Australia (12 million tons) [2]. This growing demand highlights the importance of ensuring stable and regionally diversified salt production systems, particularly in countries with extensive coastal resources such as Indonesia.

In Indonesia, salt production remains a critical national issue because domestic supply is still insufficient to meet the demand for high-quality salt, particularly for industrial purposes. East Java Province is one of the most significant salt-producing regions, contributing around 50% of national production. In 2017, East Java's total salt production reached 410.9 thousand tons [3]. Major production centers include Sumenep, Lamongan, Sampang, Probolinggo, Tuban, and Gresik, most of which are concentrated along the northern coast of Java, especially Madura Island. This spatial concentration creates regional dependency and vulnerability to climatic variability, particularly during prolonged rainy seasons. In contrast, the southern coast of East Java remains underutilized despite possessing coastal areas that may potentially support solar salt development [4, 5]. One promising area is the southern coast of Malang Regency, where the identification of new salt production sites could contribute to reducing dependency on traditional northern production zones and strengthening regional production resilience.

The expansion of salt production into new coastal areas requires a systematic and scientifically grounded site assessment. Solar salt production is highly sensitive to environmental conditions, as the efficiency of seawater evaporation and salt crystallization depends on climatic and physical parameters such as rainfall, evaporation rate, humidity, wind speed, temperature, and soil permeability [6]. In addition to environmental suitability, logistical aspects such as road accessibility influence transportation efficiency, production costs, and overall economic feasibility. Therefore, an integrated evaluation framework is necessary to assess both natural and infrastructural factors that determine site viability.

One widely applied approach for evaluating potential salt pond locations in Indonesia is the Salt Suitability Index (SSI). The SSI is a multi-criteria scoring method that integrates key climatic, hydrological, soil, and infrastructural parameters into a standardized evaluation framework. Each parameter is classified into suitability levels ranging from very suitable (S1) to not suitable (N), and the aggregated score determines the overall site classification [7]. The method is grounded in the principle that salt production performance is controlled by the interaction of evaporation drivers, soil characteristics, and operational accessibility. Previous studies have successfully applied SSI in several coastal regions of East Java, including Tuban Regency and other salt production centers [8], demonstrating its effectiveness in identifying limiting factors and guiding technological interventions for salt development planning. By consolidating multiple environmental variables into a single quantitative index, SSI provides a practical and transparent decision-support tool for spatial planning and optimization of salt production sites.

Beyond technical feasibility, the development of new salt production areas is closely linked to broader sustainability agendas. The parameters assessed within the SSI framework have direct implications for several Sustainable Development Goals (SDGs). For instance, infrastructure-related variables such as road access are aligned with SDG 9 (Industry, Innovation and Infrastructure), while improving production efficiency through optimized climatic and environmental conditions supports SDG 12 (Responsible Consumption and Production). Furthermore, expanding salt production into underutilized coastal regions can diversify local livelihoods and generate employment opportunities, contributing to SDG 8 (Decent Work and Economic Growth). By incorporating environmental suitability analysis into site selection, SSI-based planning also promotes more responsible coastal resource management.

Therefore, this study aims to evaluate the suitability of the southern coast of Malang Regency, East Java, as a potential new solar salt production area using the SSI. In addition, sensitivity analysis is conducted to identify the most influential limiting parameters and to simulate improvement scenarios that could optimize site suitability. The findings are expected to provide empirical evidence and quantitative decision support for regionally diversified and sustainable salt production development in Indonesia, particularly in supporting SDGs 8, 9, and 12 through evidence-based site evaluation and optimization strategies.

2. METHODOLOGY

2.1 Study area

The study was conducted in Sumberoto Village, Donomulyo Subdistrict, Malang Regency, East Java, Indonesia, located along the southern coast of Java (8°20′51.92″ S; 112°21′31.67″ E). The area directly faces the Indian Ocean and is characterized by a tropical monsoonal climate, seasonal rainfall variability, and relatively undeveloped coastal infrastructure (Figure 1).

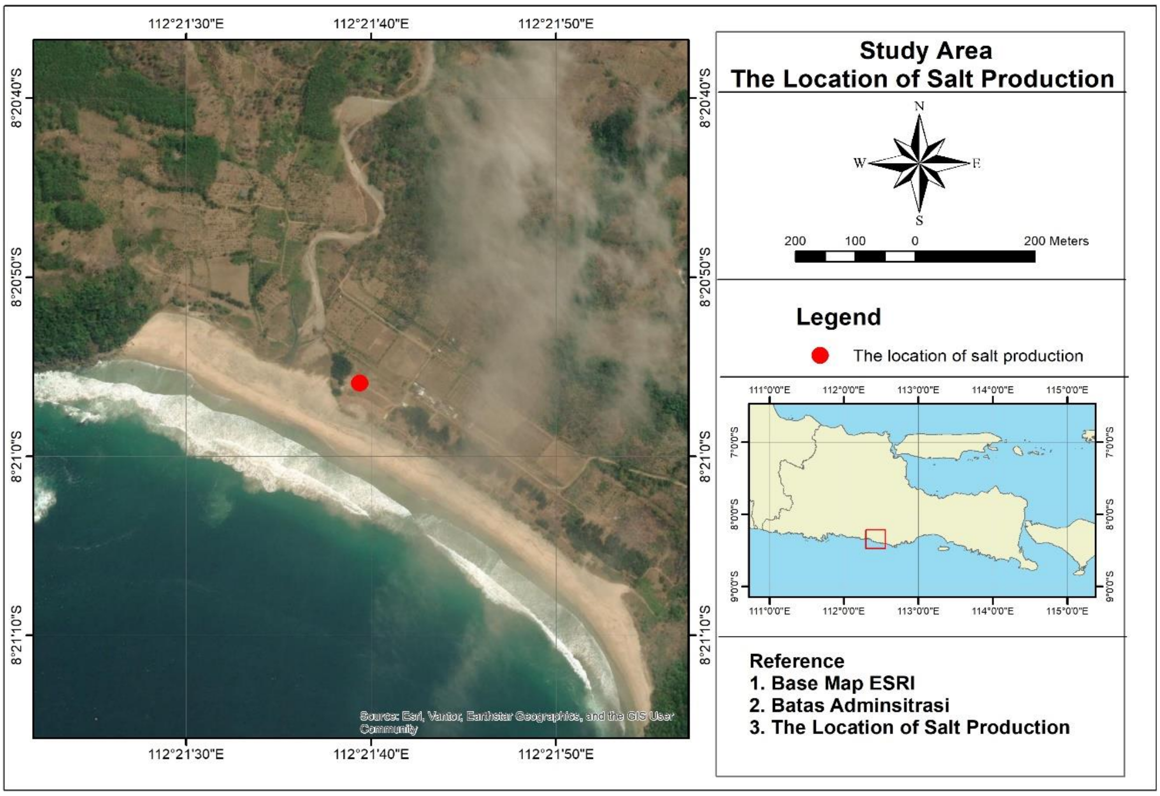

Figure 1. Study area location on the southern coast of Malang Regency, East Java, Indonesia

Geomorphologically, the coastal zone consists of narrow coastal plains bordered by limestone hills. Geologically, the region is dominated by limestone formations with impermeable clay soils, which are favorable for salt pond construction due to their ability to retain water. Current land use is primarily small-scale agriculture and open coastal land, with large areas remaining underutilized. This provides opportunities for new salt production development.

The coastal system is influenced by semi-diurnal tides, with two high tides and two low tides occurring daily, ensuring a stable supply of seawater for salt crystallization. With land use dominated by small-scale agriculture and open coastal land. Unlike the northern coast of East Java, this region has not been previously utilized for salt farming, making it a suitable case for evaluating new production site expansion.

A descriptive analytical approach was adopted in this study to systematically evaluate the feasibility of the proposed site for salt production development. The assessment of site suitability was conducted using the SSI framework [7, 8], which integrates multiple environmental, climatic, soil, hydrological, and infrastructural parameters into a structured and quantitative evaluation model. Through this framework, each parameter was classified according to predefined suitability criteria and subsequently aggregated to determine the overall suitability level of the study area. The application of SSI allows for a comprehensive and objective assessment by considering both natural conditions and supporting infrastructure, thereby providing a scientific basis for identifying limiting factors and potential improvement strategies. This methodological approach ensures that the evaluation of Sumberoto Village as a prospective salt production site is grounded in measurable indicators and reproducible criteria, supporting evidence-based decision-making for coastal resource development.

Table 1. Parameters and scoring criteria for the Salt Suitability Index (SSI)

No.	Parameter	Rating	S1 Category		S2 Category		S3 Category		N Category	
			Value	Score	Value	Score	Value	Score	Value	Score
1	Rainfall (mm)	5	<10	4	10–100	3	100–200	2	>200	1
2	Soil Permeability (k)	5	1×10^{-4}	4	1×10^{-3}	3	1×10^{-2}	2	1×10^{-1}	1
3	Soil Type	5	Clay	4	Sandy Clay	3	Loam	2	Silty	1
4	Sun Exposure (hours day^{-1})	5	>8.7	4	5.5–8.6	3	2.3–5.4	2	<2.3	1
5	Air Humidity (%)	5	<45–59	4	60–74	3	75–90	2	>90	1
6	Wind Speed (m s^{-1})	5	>5.7	4	4.1–5.7	3	2.4–4.0	2	<2.4	1
7	Air Temperature (°C)	5	>32	4	28.5–32	3	25–28.4	2	<25	1
8	Evaporation (mm day^{-1})	5	>2.0	4	1.5–2.0	3	1.0–1.4	2	<1.0	1
9	Water Saturation (°Be)	5	≥2	4	1.5–1.9	3	1.0–1.4	2	<1.1	1
10	Road Access	5	Paved	4	Unpaved but relatively good	3	Unpaved road	2	Broken road	1

Each parameter is categorized into four suitability classes (S1 = very suitable, S2 = quite suitable, S3 = conditionally suitable, N = not suitable) with corresponding scores used to calculate the overall SSI [8].

2.2 Salt suitability index

The variables included in the SSI were shown in Table 1, which include rainfall (mm), soil type, soil permeability (k), exposure time (hours day^{-1}), humidity (%), wind speed (m/s), air temperature (°C), evaporation rate (mm day^{-1}), and a saturation level of raw material water (°Be). Rainfall, wind speed, sunshine duration, and evaporation data were sourced from the Meteorology, Climatology, and Geophysics Agency (BMKG). Climate records were obtained from the nearest official BMKG meteorological station to the study area (Malang Station, approximately 75 km from the site). To enhance temporal representativeness and reduce the influence of short-term climatic variability, a 10-year dataset (2014–2023) was utilized. The dataset comprised monthly observations, which were aggregated to produce mean annual values for rainfall, air temperature, wind speed, humidity, and evaporation.

Soil samples were collected to determine soil texture and permeability characteristics relevant to salt pond development. A purposive sampling approach was applied to ensure that the samples represented the soil conditions of the proposed production area. Sampling locations were selected based on field observations, emphasizing relatively homogeneous surface conditions, proximity to the planned salt ponds, and absence of visible disturbances. Samples were taken from the surface layer (0–30 cm depth), corresponding to the active construction layer of traditional salt ponds. At each sampling point, three replicates were collected to account for small-scale spatial variability and enhance data reliability. Soil texture was classified using the Soil Texture Triangle method, and was measured using the Falling Head Permeameter method. Replicate results were averaged and subsequently used as input parameters in the SSI. Air temperature, humidity, and water saturation were measured by using. Digital Anemometer (GM8902, Benetech), Digital Hygrometer (HTC-2), and Boumehydrometer (Alla France, 0-30) in order. Those parameters were processed in Table 1. The standards in Table 1 guide the suitability of the parameters to support the production of salt through the evaporation method (solar salt).

2.3 Sensitivity analysis

To identify the most influential parameters on the SSI, a sensitivity analysis was conducted. This method simulated improvements in limiting parameters by changing their category scores according to the SSI criteria (from N, S3, S2 to S1).

Each scenario adjusted one or more parameters, recalculated the total B×S (rating × score), and then converted it into a percentage of SSI using the formula:

$$SSI(\%) = \frac{\Sigma(B \times S)}{N_{\max}} \times 100$$

$\Sigma(B \times S)$ is the total weighted score from all parameters, and N_{max} is the maximum possible score (200). By comparing SSI values across different scenarios, this analysis highlights which parameters contribute most significantly to location suitability and how targeted interventions could improve the overall site classification.

The results of this sensitivity analysis were then used to identify the key limiting factors and to evaluate the potential effectiveness of targeted interventions in improving the overall SSI classification of the study area.

3. RESULT AND DISCUSSION

3.1 Salt suitability index

Before analyzing the suitability level of potential salt pond locations in Sumberoto Village, which is used as a salt production area using the SSI has been carried out. SSI uses a standard of 10 parameters to analyze the location of salt production in Sumberoto Village. The results of this study will be described in Table 2.

3.1.1 rainfall

From the results of observations at the location of salt production in Sumberoto Village, the rainfall value is 10 mm. The observation results represent the rainfall value in Sumberoto Village, which has an index value of 15 and is included in the S2 class category. Based on the rainfall value, it is very suitable and ideal as a salt production location. The main problem in salt production lies in rainfall, which affects the evaporation process of brackish water into salt [8]. Therefore, the potential period for brackish water salt production to produce salt crystals is influenced by meteorological parameters, such as rainfall [6].

Table 2. Observation data and scoring results for Salt Suitability Index (SSI) parameters at Sumberoto Village, Malang Regency

No.	Parameter	Observation Data	Category	Rating (B)	Score (S)	B × S
1	Rainfall (mm)	10	S2	5	3	15
2	Soil Permeability (k)	1×10^{-4}	S1	5	4	20
3	Soil Type	Clay	S1	5	4	20
4	Sun Exposure (hours day^{-1})	10.5	S1	5	4	20
5	Air Humidity (%)	60	S1	5	3	15
6	Wind Speed (m s^{-1})	1.3	N	5	1	5
7	Air Temperatue(°C)	32.1	S1	5	4	20
8	Evaporation (mm day^{-1})	2	S1	5	4	20
9	Water Saturation (°Be)	3	S1	5	4	20
10	Road Access	Rocky road	S3	5	2	10

The table presents the observed values of ten parameters, their suitability categories (S1–N), and the corresponding rating (B), score (S), and weighted value (B×S) used to calculate the overall SSI.

Rainfall should be considered a strategic climatic parameter in evaluating and optimizing salt production areas due to its direct influence on evaporation dynamics and production continuity. Variations in rainfall patterns can alter salinity concentration levels, disrupt crystallization cycles, and shorten effective harvesting periods. Therefore, integrating rainfall into the SSI framework strengthens the robustness of site suitability assessments, while sensitivity analysis helps identify the degree to which salt production performance is vulnerable to climatic fluctuations. This approach ensures that site evaluation is not solely based on static environmental conditions but also accounts for potential meteorological variability that may affect long-term productivity and sustainability.

3.1.2 Soil permeability

Based on the data from the measurement of soil permeability in salt ponds in Sumberoto Village, the amount is 1×10^{-4} (k). From the measurement of soil permeability in Sumberoto Village, it is included in the S1 category (very suitable). This result shows that the location of salt production in Sumberoto Village is suitable for salt production. Soil permeability in salt ponds should be very low and crack in humid conditions. Soil type is primarily determined by the amount of sand, silt, and clay composition [9]. The type of soil in both locations of the salt business has an impermeable character (non-porous). It has very low permeability, so it is suitable as a location for salt production [10].

Soil permeability is a crucial parameter in determining the effectiveness of salt pond operations because it directly controls water retention and evaporation efficiency. Low-permeability soils reduce seepage losses, maintain stable brine levels, and support consistent salinity concentration during the crystallization process. Therefore, integrating permeability into the SSI strengthens the reliability of site suitability evaluation, while sensitivity analysis can clarify how changes in soil physical properties may influence overall production performance and long-term pond sustainability.

3.1.3 Soil type

Observation of soil types at the location of salt ponds in Sumberoto Village shows that the type of soil is clay. The soil type is determined mainly by sand, mud, and clay composition. The type of soil selected for the pond must be impermeable (not porous), with very low permeability [7]. The soil pore system is strongly influenced by soil type [11]. The IKG values for soil types at both locations are included in the S1 value category (very suitable). The clay soil is excellent and suitable for ponds because such soil is tough and will crack when dried. At the same time, it has an excellent ability to hold water [12].

Moreover, soil type is a fundamental factor in salt pond development because it determines the structural stability of the pond base and the efficiency of brine retention during the evaporation process. Clay-dominated soils are particularly advantageous due to their compact texture, low porosity, and strong water-holding capacity, which minimize seepage and help maintain optimal brine depth. Consequently, incorporating soil type into the SSI provides a stronger basis for assessing long-term site feasibility, while sensitivity analysis can highlight how variations in soil characteristics may affect the overall suitability and sustainability of salt production systems.

3.1.4 Exposure time

The duration of sunlight is a factor in salt production, which also affects the rate of water evaporation [3]. The observation results show that the location of salt production in Malang Regency at the sampling location in Sumberoto Village has a value of 10.5 hours of sunshine per day. This result shows that the location of salt production in Sumberoto has an index value of 20 and is included in the S1 category (very suitable). Therefore, Malang Regency is still suitable as a location for salt production.

Sunshine duration is one of the most influential meteorological parameters in salt production because it directly controls the intensity and continuity of solar evaporation, which is essential for accelerating brine concentration and salt crystallization. Longer sunshine hours generally increase evaporation rates, shorten the crystallization period, and improve harvesting efficiency. Therefore, incorporating sunshine duration into the SSI strengthens the accuracy of suitability assessments, while sensitivity analysis helps determine how fluctuations in solar exposure may affect productivity and operational reliability across different seasons.

3.1.5 Air humidity

The results of observations of air humidity in Malang Regency, Sumberoto Village, at sampling locations showed a value of 60%. Based on the IKG analysis, it is shown that the results of the observation of air humidity at the salt production site have an index value of 20 and are included in the S2 category (quite suitable). This result shows that Sumberoto Village has high air humidity, which is a very suitable location for salt production. The level of humidity affects the rate of evaporation. The lower the humidity, the higher the evaporation of the average air humidity will affect the quality of the salt produced [8].

Furthermore, air humidity is an important climatic parameter in salt production because it influences the evaporation gradient between the brine surface and the surrounding atmosphere. High humidity generally reduces evaporation efficiency, potentially prolonging the concentration and crystallization stages, while lower humidity supports faster water loss and more stable salt formation. Therefore, integrating humidity into the SSI improves the reliability of suitability classification by accounting for atmospheric conditions that affect production performance. In addition, sensitivity analysis is useful to evaluate how variations in humidity levels may impact evaporation rates and salt quality, particularly under seasonal and interannual climate fluctuations.

3.1.6 Wind speed

The results of observations of wind speed levels in Sumberoto Village at the sampling location showed a wind speed of 1.3 m/s. According to the assessment of wind speed parameters, the location of salt production in Sumberoto Village has an index value of 10. Therefore, it is in the S3 category (conditionally). Wind speed is one of the essential factors in the evaporation process in salt production. The higher the wind speed in the salt-making process, the faster the evaporation rate [2]. The supporting factors for making salt are climatological components such as rainfall, number of rainy days, and wind speed.

Moreover, wind speed plays a dynamic role in enhancing the evaporation process by facilitating air circulation above the brine surface and accelerating moisture removal. Adequate wind movement helps maintain a stable evaporation gradient, thereby supporting more efficient salt crystallization. Although it may function as a limiting factor under certain conditions, incorporating wind speed into the SSI framework ensures that atmospheric dynamics are adequately considered in site evaluation. Sensitivity analysis further strengthens this assessment by identifying how variations in wind intensity may influence evaporation efficiency and overall salt production performance, particularly in relation to other climatological parameters such as rainfall and humidity.

3.1.7 Air temperature

The results of observations of air temperature in the salt production area in Sumberoto Village have a temperature parameter value of 32.1 °C. According to the air temperature parameter assessment, the salt production location in Sumberoto Village has an index value of 20. Therefore, it is included in the S1 class category (very suitable). This result shows that the location of salt production in Sumberoto Village is very suitable for salt production. The ideal temperature for salt production is above 32 °C, increasing the evaporation and crystallization rate of salt [13].

Furthermore, air temperature is a primary driver of the evaporation and crystallization processes in salt production because higher temperatures increase the rate of water loss from brine and accelerate salt formation. Temperature also contributes to stabilizing production cycles by shortening the time required for concentration stages and improving overall operational efficiency. Therefore, incorporating air temperature into the SSI enhances the robustness of land suitability evaluation by capturing key thermal conditions that directly influence productivity. In addition, sensitivity analysis is essential to assess how fluctuations in temperature may affect evaporation performance and salt yield, particularly under seasonal variability and changing climatic patterns.

3.1.8 Evaporation rate

The results of observations of evaporation rates at salt production sites in Sumberoto Village have an evaporation parameter value of 2 mm per day. According to the evaporation rate parameter evaluation, the salt production location in Sumberoto Village has an index value of 20. Therefore, it is included in the S1 class category (very suitable). This result shows that salt production in Malang Regency, Sumberoto Village, is very suitable for salt production locations based on water evaporation parameters. The ideal evaporation rate for salt production is 1.7 mm per day, strongly influenced by wind speed, temperature, and air humidity levels [8, 14].

Moreover, the evaporation rate represents an integrated indicator of climatic suitability, as it reflects the combined effects of temperature, wind speed, solar radiation, and air humidity on the salt production process. A stable and optimal evaporation rate is essential to ensure efficient brine concentration and consistent crystal formation. Therefore, incorporating evaporation parameters into the SSI framework strengthens the overall evaluation by directly capturing the effectiveness of the physical processes underlying salt production. Sensitivity analysis further enhances this assessment by identifying how variations in climatic drivers may alter evaporation performance and, consequently, influence production sustainability and yield stability over time.

3.1.9 Water saturation

The process of forming salt crystals is influenced by many factors, including the level of water saturation of the salt raw material. This level of saturation will determine how long it takes to produce salt. The level of saturation of the raw saltwater in this study was analyzed based on the degree of the Baumé Scale (°Be) [3]. Observation of raw material saturation was carried out at prospective salt pond locations. A sampling of raw material water was carried out at the location of the salt pond in Sumberoto Village. The observations showed that the Baume Scale or saturation of the raw materials at that location is 3°Be. Therefore, according to the SSI analysis, it is included in the S1 category. The time of salt production from salt raw material water to produce salt crystals is influenced by meteorological parameters, such as rainfall, evaporation, cloud cover, surface winds, and the saturation level of the raw material water itself [15].

Furthermore, the saturation level of raw brine is a fundamental parameter in determining the efficiency of the crystallization process, as it directly reflects the concentration of dissolved salts prior to evaporation. A higher initial saturation level reduces the time required to reach supersaturation, thereby accelerating crystal formation and improving production efficiency. For this reason, incorporating the Baumé degree (°Be) into the SSI strengthens the technical accuracy of site evaluation by linking physicochemical conditions with meteorological influences. In addition, sensitivity analysis is essential to assess how variations in brine saturation, in combination with climatic factors such as rainfall and evaporation, may affect the stability, duration, and overall productivity of salt production systems.

3.1.10 Road access

The road access conditions in Sumberoto Village are characterized by rocky (macadam) roads and are classified as S3 (conditionally suitable). This classification is primarily due to the considerable distance between the prospective salt production site and nearby settlements, as well as the transportation constraints associated with distributing production outputs. The rocky road surface limits accessibility, increases transportation costs, and reduces the efficiency of moving raw materials, equipment, and harvested salt.

The suitability level could improve if the access road were upgraded and better connected to the main transportation routes, including the causeway, and supported by closer residential areas. Infrastructure improvements to and from the salt pond locations would significantly enhance production quality and distribution efficiency. Improved road conditions would accelerate the transportation process from the pond area to major transport networks, thereby supporting more efficient supply chain management [16].

Moreover, accessibility and transportation infrastructure are important non-climatic factors influencing the overall feasibility and sustainability of salt production sites. Adequate road conditions facilitate efficient logistics, reduce post-harvest losses, and strengthen market access. Therefore, incorporating road access parameters into the SSI ensures a more comprehensive evaluation that integrates both environmental and infrastructural considerations. Sensitivity analysis further demonstrates how improvements in road infrastructure could elevate the site's suitability classification and enhance the long-term competitiveness of local salt production.

3.2 Analysis of parameter contribution in SSI

The contribution analysis of parameters to the SSI, as illustrated in Figure 2, reveals that six primary parameters, soil permeability, soil type, solar radiation, air temperature, evaporation rate, and brine saturation, each contribute 12.1% to the overall SSI score. This indicates that the fundamental physical and climatic conditions in Sumberoto Village are generally favorable for salt crystallization through natural evaporation methods. Rainfall and air humidity contribute around 9.1%, suggesting a moderate influence on site suitability.

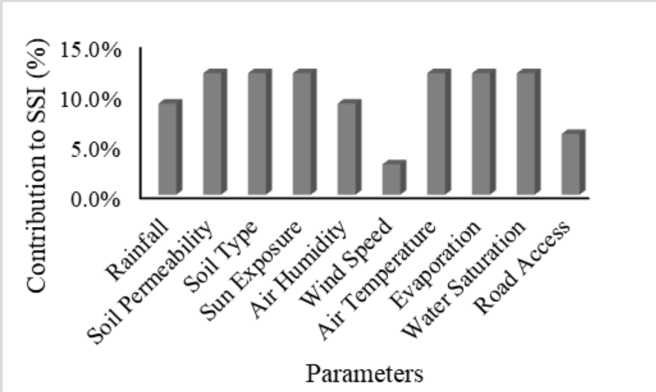

Figure 2. Contribution of each parameter to the Salt Suitability Index (SSI) at Sumberoto Village, Malang Regency

The analysis shows that soil permeability, soil type, sun exposure, air temperature, evaporation, and water saturation contributed the highest proportion (12.1%), while wind speed (3.0%) and road access (6.1%) were the lowest contributors, indicating the main limiting factors in the study area.

Nevertheless, the analysis also identifies key limiting factors, namely wind speed and road access. The recorded wind speed of only 1.3 m/s contributes the lowest share, at 3.0%, and falls into the unsuitable (N) category. This condition slows down the evaporation process, thereby reducing the efficiency of salt crystallization [17]. In parallel, road access is still limited to rocky paths, which accounts for just 6.1%, hindering the effectiveness of distribution and production logistics. These two factors are the primary reasons why the overall SSI score remains at 82.5%, placing the site in the quite suitable (S2) category.

The limited contribution of wind speed to the SSI score reflects not only its measured value but also the influence of local geographic conditions. In the southern coastal zone of Malang Regency, wind circulation is primarily shaped by the monsoonal system over Java, with southeasterly winds prevailing in the dry season and northwesterly winds in the wet season. Nevertheless, despite the area's proximity to the Indian Ocean, near-surface airflow in Sumberoto Village is likely weakened by surrounding limestone hills and elevated coastal terrain, which act as natural barriers and restrict horizontal wind penetration across salt pond surfaces. Similar topographic constraints have been documented in other southern coastal regions of East Java, explaining why wind speed emerged as the most critical limiting factor in the SSI evaluation.

From an engineering standpoint, the challenges posed by low ambient wind speed can be addressed through localized technological solutions. The use of greenhouse salt tunnel (GST) systems and continuously dynamic mixing (CDM) methods has proven effective in enhancing evaporation efficiency under conditions of weak wind and high humidity, primarily by improving heat retention and promoting brine circulation [3]. Furthermore, adjusting pond orientation to align with prevailing seasonal winds and reducing artificial obstructions can improve micro-scale airflow. These interventions are consistent with sensitivity analysis findings, which indicate that improvements in wind-related parameters significantly increase SSI values and strengthen overall site suitability.

These findings emphasize that although most environmental parameters at the study site are supportive of salt production, optimal productivity cannot be achieved without technological intervention and infrastructure improvement. The adoption of technologies such as the GST or the continuous dynamic mixing method may help address the constraints of low wind speed and high humidity, while road infrastructure development would enhance the speed and efficiency of salt distribution [18]. Accordingly, salt development strategies in the southern Malang coast should prioritize the mitigation of these limiting factors to elevate the site's suitability to the very suitable (S1) category.

3.3 Sensitivity analysis of Salt Suitability Index

Sensitivity analysis indicates that improvements in limiting parameters can significantly enhance the SSI. In the baseline condition, the SSI value at the study site was 82.5% (classified as S2, quite suitable). When wind speed increased from category N to S3 (2.4–4.0 m/s), the SSI rose to 85.0%. A further increase to category S2 (4.1–5.7 m/s) and S1 (>5.7 m/s) elevated the SSI to 87.5% and 90.0%, respectively. Similarly, upgrading road access from rocky (S3) to paved (S1) increased the SSI to 87.5%, while reducing relative humidity from category S2 to S1 resulted in an SSI of 85.0%.

Table 3. Sensitivity analysis of the Salt Suitability Index (SSI) under different improvement scenarios

Scenario	Total B×S	SSI (%)
Base Condition (Current)	165	82.5
Improved Wind → S3 (B × S = 10)	170	85
Improved Wind → S2 (B × S = 15)	175	87.5
Improved Wind → S1 (B × S = 20)	180	90
Road Access → S1 (B × S = 20)	175	87.5
Humidity → S1 (B × S = 20)	170	85
Wind S2 + Road S1	185	92.5
Wind S2 + Road S1 + Humidity S1	190	95

Improvements in wind speed, road access, and humidity increase SSI from 82.5% (base condition) to a maximum of 95.0% under combined interventions.

Combined improvement scenarios demonstrate an even stronger effect (Table 3). For instance, when wind speed was raised to category S2 and road access improved to S1, the SSI increased to 92.5%. Adding a reduction in humidity to category S1 further boosted the SSI to 95.0%. These findings highlight that wind speed, air humidity, and road access are critical variables to consider in the development of salt production areas in South Malang [19].

From a practical perspective, interventions such as the application of GST technology or the continuous dynamic mixing method can mitigate the limitations of microclimatic factors, particularly wind speed and humidity. At the same time, improving road infrastructure would enhance efficiency in salt distribution and marketing [20, 21]. With such strategies, areas initially categorized as quite suitable (S2) could potentially be upgraded to very suitable (S1), thereby increasing the likelihood of successful salt production development along the southern coast of Malang.

3.4 Implications for Sustainable Development Goals

The identification of wind speed, road access, and air humidity as critical limiting factors provides a clear framework for aligning salt industry development in South Malang with the SDGs. Enhancing road infrastructure directly supports SDG 9 (Industry, Innovation, and Infrastructure) by reducing logistical inefficiencies, lowering production costs, and improving market access for local salt producers. Such improvements also contribute to SDG 8 (Decent Work and Economic Growth) through the expansion of salt-related economic activities and the creation of employment opportunities in coastal regions that remain underutilized.

From an environmental and efficiency standpoint, addressing climatic constraints such as low wind speed and high humidity through technological innovation advances SDG 12 (Responsible Consumption and Production). Engineering solutions like GST systems and CDM methods enhance evaporation efficiency and productivity without expanding land use or increasing ecological stress [3]. By optimizing existing coastal resources rather than exploiting new areas, these strategies foster more sustainable and resilient salt production systems. Integrating SSI-based site evaluation with targeted technological and infrastructural interventions thus offers a practical pathway to strengthen economic growth, infrastructure development, and sustainable resource management in line with the SDGs.

4. CONCLUSIONS

This study demonstrated that the southern coast of Malang Regency, particularly Sumberoto Village, is suitable for salt pan development under current conditions, as indicated by an SSI value of 82.5%, which corresponds to the quite suitable (S2) category. Most key environmental parameters—including soil type and permeability, sun exposure, air temperature, evaporation rate, and brine saturation—were classified as very suitable (S1), confirming that the fundamental physical and climatic setting supports solar salt production. However, the site is not yet categorized as very suitable (S1) due to several limiting factors, particularly low wind speed, suboptimal road access, and relatively high air humidity, which constrain evaporation efficiency and operational logistics. Sensitivity analysis further showed that the site could become very suitable (S1) if targeted improvements are implemented, especially increasing effective wind-driven evaporation through technological interventions (e.g., GSTs or continuous dynamic mixing), upgrading road infrastructure, and reducing humidity-related constraints. Under combined improvement scenarios, the SSI increased to 95%, indicating that Sumberoto Village has strong potential to be upgraded into a highly suitable salt production area through focused, evidence-based interventions. Future research should complement this suitability analysis with ecological monitoring, socio-economic feasibility evaluation, and climate variability assessment to ensure sustainable and resilient salt development in the region.

ACKNOWLEDGEMENT

This study was supported by the Research and Innovation Programs for Advanced Indonesia under the National Research and Innovation Agency (BRIN), funded by the Indonesia Endowment Fund for Education (LPDP), Ministry of Finance of the Republic of Indonesia, through contract numbers 32/IV/KS/06/2022 and 1612.1/UN10.C10/TU/2022. The authors also wish to thank the Department of Fisheries of Malang Regency for their valuable support of this research.

REFERENCES

[1] Kurniawan, A., Amin, A.A., Ardian, G., Mahasin, M.Z., Kuncoro, R.D. (2021). Analysis of salt production location using the salt location suitability index to apply the continuously dynamic mixing in the greenhouse salt tunnel in North Aceh and East Aceh. Jurnal Segara, 17(2): 97-106. https://doi.org/10.15578/segara.v17i2.8529

[2] Kurniawan, A., Lestariadi, R.A., Kurniaty, R., Prayodo, T.B., Dewi, C.S.U., Amin, A.A., Yanuar, A.T., Salamah, L.N. (2020). Analisis indeks kesesuaian lokasi garam (IKG) di kawasan sentra produksi garam Jawa Timur. Journal of Science and Technology, 13(3): 225-233. https://doi.org/10.21107/rekayasa.v13i3.9130

[3] Kurniawan, A., Syafi'i, M.I., Ardian, G., Jaziri, A.A., Amin, A.A., Budiyanto, B., Amenan, M., Salamah, L.N., Setiawan, W.B. (2019). Continuously dynamic mixing (CDM) method and greenhouse salt tunnel (GST) technology for sea salt production throughout the year. Jurnal Ilmiah Perikanan dan Kelautan, 11(2): 82-90. https://doi.org/10.20473/jipk.v11i2.13480

[4] Li, X., Shi, F. (2021). Effects of evolving salt precipitation on the evaporation and temperature of sandy soil with a fixed groundwater table. Vadose Zone Journal, 20(3): e20122. https://doi.org/10.1002/vzj2.20122

[5] Pramudia, Z., Amin, A.A., Yanuar, A.T., Al Zamzami, I.M., Kurniaty, R., Lestariadi, R.A., Ulfa, S.M., Guntur, Kurniawan, A. (2023). Induction of the continuously dynamic mixing (CDM) method for optimizing salt production with greenhouse salt tunnel (GST) technology on the southern coast of Malang Regency. Journal of Innovation and Applied Technology, 9(1): 49-56. https://doi.org/10.21776/ub.jiat.2023.009.01.9

[6] Amin, A.A., Yanuar, A.T., Pramudia, Z., Susanti, Y.A.D., Al Zamzami, I.M., Salamah, L.N., Lestariadi, R.A., Hakim, L., Ardian, G., Hanifuddin, M., Kurniawan, A. (2025). Analysis of environmental dynamic factors during salt crystallization process in greenhouse salt tunnel (A case study in south and north coastal East Java, Indonesia). Jurnal Penelitian Pendidikan IPA, 11(4): 567-574. https://doi.org/10.29303/jppipa.v11i4.7131

[7] Kurniawan, A., Amin, A.A., Yanuar, A.T., Pramudia, Z., Susanti, Y.A.D., Zamzami, I.M., Kurniaty, R., Hakim, L., Ardian, G., Amenan, M. (2024). Exploring viability and innovation requirements for novel salt production: A case study of Kangen Beach, Malang Regency's south coast, Indonesia. Cogent Social Sciences, 10(1): 1-8.

[8] Amin, A.A., Yanuar, A.T., Kurniaty, R., Hakim, L., Ardian, G., Amenan, M., Kurniawan, A. (2023). Greenhouse Salt Tunnel as innovation to create salt production in the South Coast Malang Regency, Indonesia. Jurnal Pembangunan dan Alam Lestari, 14(1): 14-21. https://doi.org/10.21776/ub.jpal.2023.014.01.03

[9] Jaziri, A.A., Guntur, G., Setiawan, W., Prihanto, A.A., Kurniawan, A. (2018). Preliminary design of a low-cost greenhouse for salt production in Indonesia. IOP Conference Series: Earth and Environmental Science, 137(1): 012054. https://doi.org/10.1088/1755-1315/137/1/012054

[10] Kurniawan, A., Assafri, F., Munandar, M.A., Jaziri, A.A., Prihanto, A.A., Guntur, G. (2019). Analysis of salt quality produced by Prisma greenhouse in Sedayu Lawas Village, Lamongan Regency, East Java. Jurnal Kelautan Nasional, 14(2): 95-102. https://doi.org/10.15578/jkn.v14i2.7073

[11] Steponavičienė, V., Bogužas, V., Sinkevičienė, A., Skinulienė, L., Vaisvalavičius, R., Sinkevičius, A. (2022). Soil water capacity, pore size distribution, and CO_2 emission in different soil tillage systems and straw retention. Plants, 11(5): 614. https://doi.org/10.3390/plants11050614

[12] Dapieve, D.R., Maggi, M.F., Mercante, E., Francisco, H.R., Oliveira, D.D.D., Luiz Junior, O.J. (2023). Use of geotechnologies for aquaculture site selection: Suitability factors and constraints for production in ground-excavated ponds. Latin American Journal of Aquatic Research, 51(2): 160-194. https://doi.org/10.3856/vol51-issue2-fulltext-2981

[13] Amin, A.A., Yanuar, A.T., Salamah, L.N., Kurniawan, A. (2021). Analysis of salt location suitability in Tuban Regency, East Java using the salt suitability index (SSI). AIP Conference Proceedings, 2353: 020001. https://doi.org/10.1063/5.0053079

[14] Pambudi, N.A., Yusafiadi, J., Biddinika, M.K., Estriyanto, Y., Sarifudin, A. (2022). An experimental investigation of salt production improvement by spraying and heating. Case Studies in Thermal Engineering, 30: 101739. https://doi.org/10.1016/j.csite.2021.101739

[15] Guntur, G., Jaziri, A.A., Prihanto, A.A., Arisandi, D.M., Kurniawan, A. (2018). Development of salt production technology using prism greenhouse method. IOP Conference Series: Earth and Environmental Science, 106(1): 012082. https://doi.org/10.1088/1755-1315/106/1/012082

[16] Tu, N., Adiputranto, D., Fu, X., Li, Z.C. (2018). Shipping network design in a growth market: The case of Indonesia. Transportation Research Part E: Logistics and Transportation Review, 117: 108-125. https://doi.org/10.1016/j.tre.2017.10.001

[17] Ramly, Z.A., Ahmad, N., Juhaseng, N.A. (2023). Geomembrane filter thread technique's potential to increase salt production in Jeneponto Regency. Indonesian Journal of Environmental Management and Sustainability, 6(3): 76-81. https://doi.org/10.26554/ijems.2022.6.3.76-81

[18] Yin, Q., Kong, F., Wang, S., Du, J., Pan, L., Tao, Y., Li, P. (2023). 3D printing of solar crystallizer with polylactic acid/carbon composites for zero liquid discharge of high-

salinity brine. Polymers, 15(7): 1656. https://doi.org/10.3390/polym15071656
[19] Al-Handawi, M.B., Commins, P., Dinnebier, R.E., Abdellatief, M., Li, L., Naumov, P. (2023). Harvesting of aerial humidity with natural hygroscopic salt excretions. Proceedings of the National Academy of Sciences, 120(45): e2313134120. https://doi.org/10.1073/pnas.2313134120
[20] Kuswanto, D., Solihin, F., Ardinata, A. (2024). Utilization of the Internet of Things for monitoring salt houses with fuzzy logic rule-based model. E3S Web of Conferences, 499: 01029.
[21] Mahasin, M.Z., Rochwulaningsih, Y., Sulistiyono, S.T. (2021). Ecological mapping for the development of salt production centres in Indonesia during the Dutch colonial era. E3S Web of Conferences, 317: 04024.