JPPIPA 11(4) (2025)

Jurnal Penelitian Pendidikan IPA

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Analysis of Environmental Dynamic Factors During Salt Crystallization Process in Greenhouse Salt Tunnel (A Case Study in South Coastal and North Coastal East Java, Indonesia)

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Received: November 22, 2024
Revised: January 31, 2025
Accepted: April 25, 2025
Published: April 30, 2025

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DOI: 10.29303/jppipa.v11i4.7131

Abstract: Salt is an essential commodity for both domestic use and industrial applications, with East Java Province in Indonesia playing a crucial role in national salt production. Traditional salt production methods, primarily based on natural evaporation, face challenges due to seasonal factors, particularly during the rainy season. This study investigates the environmental conditions affecting the salt crystallization process in the Greenhouse Salt Tunnel (GST) technology. Field experiments were conducted at two sites, Tuban Regency on the North Coast and Malang Regency on the South Coast, where key parameters such as air temperature, water temperature, humidity, wind speed, and evaporation rates were monitored three times daily. The findings showed that water temperatures within the GST ranged from 31 to 38°C on the North Coast and 26 to 38°C on the South Coast. Wind speeds varied between 1.5–2.4 m/s on the North Coast and 0.4–1.0 m/s on the South Coast, while humidity levels ranged from 54 to 80%. The GST system achieved a salt production rate of 6.4 kg/m² with NaCl content exceeding 94%, a significant improvement over traditional methods, which yield less than 70% NaCl. These results demonstrate that GST technology enhances both the quality and quantity of salt production, though design modifications are needed to address the dynamic coastal environment.

Keywords: Greenhouse Salt Tunnel (GST); Salt; Strategic commodity; Traditional salt production

Introduction

Coastal and marine resources, epitomized by seawater, stand as invaluable assets ripe for optimal utilization (Ghalidza, 2020; Wolters, 2011; Witomo et al., 2020). Among its multifaceted applications, seawater serves as a pivotal raw material for salt production, an indispensable resource with strategic significance for both daily consumption and industrial processes (Adachi & Buseck, 2015; Bueger, 2015; Chapsos & Malcolm, 2017; Amin et al., 2021).

East Java Province emerges as a key player in the Indonesian salt production landscape, contributing a substantial 36.5% to the national output (Gozan et al., 2018; Kurniawan et al., 2019a, Aris et al., 2022). Predominantly located on the North Coast of East Java

How to Cite:
Amin, A. A., Yanuar, A. T., Pramudia, Z., Susanti, Y. A. D., Zamzami, I. M. A., Salamah, L. N., … Kurniawan, A. (2025). Analysis of Environmental Dynamic Factors During Salt Crystallization Process in Greenhouse Salt Tunnel (A Case Study in South Coastal and North Coastal East Java, Indonesia). *Jurnal Penelitian Pendidikan IPA*, *11*(4), 567–574. https://doi.org/10.29303/jppipa.v11i4.7131

and Madura Island, salt production has ventured into developmental phases on the South Coast, specifically in Malang Regency.

Divergent geographical features between the North and South Coasts of East Java yield a spectrum of environmental conditions (Sui et al., 2020; Nurwadjedi et al., 2019; Mahasin et al., 2020). The North Coast, predominantly characterized by dense sandy or sandy clay soil (Sumarmi et al., 2020; Chun et al., 2008), serves as the epicenter for salt production in East Java (Sudaryana & Pramesti, 2018; Bagastyo et al., 2021). Conversely, the South Coast boasts an extensive sandy beach terrain, characterized by pristine saltwater sources.

However, salt production faces challenges, with sustainability, quality, and quantity at the forefront. Unpredictable weather emerges as a prominent obstacle, significantly impacting production volumes and leading to a nationwide scarcity of salt supplies (Rusdi, 2018). This shortage ripples across diverse industries heavily reliant on salt as a raw material or process enhancer (Punanto et al., 2020), compelling Indonesia to resort to salt imports, particularly for industrial use (Ministry of Marine Affairs and Fisheries, 2021). Consequently, technological innovation becomes paramount for optimizing salt production in Indonesia, necessitating a method adaptable to both dry and rainy seasons (Umam et al., 2019).

Despite limited research on salt production during the rainy season in Indonesia, this study aims to scrutinize salt production technology, specifically focusing on Greenhouse technology for rainy-season production. Environmental parameters such as water temperature, air temperature, wind speed, and humidity significantly influence salt quantity and quality (Kurniawan et al., 2019b). Employing the Continuously Dynamic Mixing (CDM) method and Greenhouse Salt Tunnel (GST) technology, this research seeks to analyze the environmental dynamics during the crystallization process within the Greenhouse Salt Tunnel, unraveling their impact on salt production quality and quantity along the South and North Coasts of East Java, Indonesia.

The experiment conducted in East Java, Indonesia, aimed to investigate how environmental factors influence the salt crystallization process within the Greenhouse Salt Tunnel (GST) system, which has the potential to improve both the quality and quantity of salt production compared to traditional methods. By measuring key environmental variables—such as air and water temperatures, humidity, wind speed, and evaporation rates—across two distinct coastal regions, Tuban Regency (North Coast) and Malang Regency (South Coast), the study provides insights into the effects of these factors on salt production.

Method

The research process conducted to investigate the environmental factors affecting salt crystallization within the Greenhouse Salt Tunnel (GST) system in East Java, Indonesia. The research flow was shown at Figure 1.

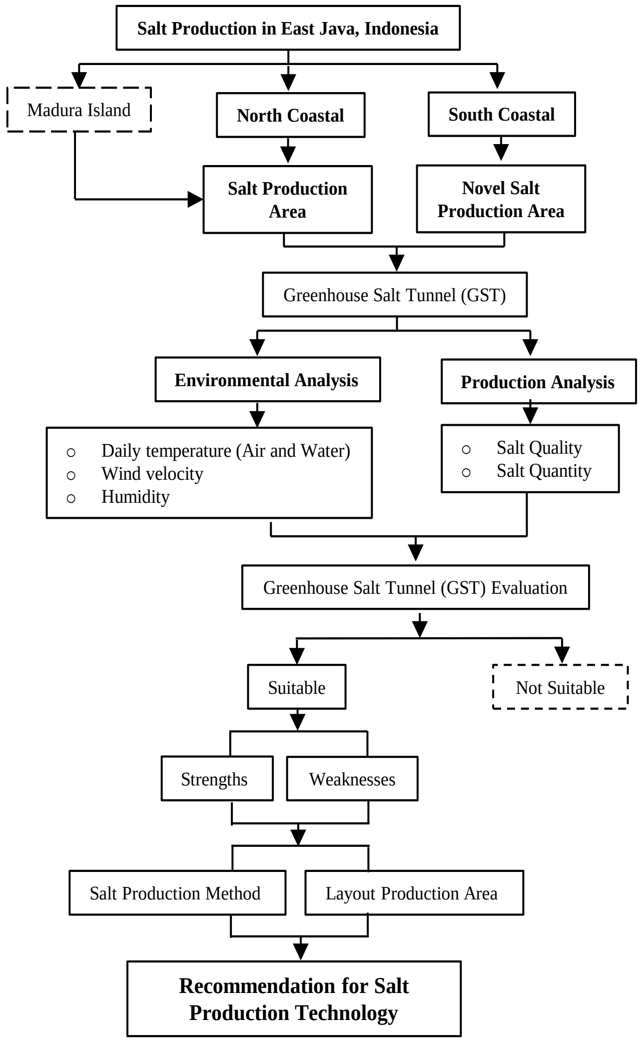

Figure 1. Flow schematic of the study

Research Location

This study was conducted at two representative salt production sites, chosen to mirror the environmental conditions of the North and South Coasts of East Java—Leran Wetan Village in Tuban Regency and Gajahrejo Village in Malang Regency. Both villages host community groups actively engaged in salt production using the Greenhouse Salt Tunnel (GST) innovation.

Environmental Parameter Measurement

To comprehend micro-environmental conditions, we conducted environmental parameter measurements, with a primary focus on daily temperature, wind speed, evaporation rate, and humidity. Data collection transpired three times a day at 07:00, 12:00, and 17:00. Air temperature readings were obtained using a Digital Thermometer (HTC-2), while wind speed measurements employed a Digital Anemometer (GM8902, Benetech). Evaporation rates were estimated by monitoring the reduction in water levels within each square meter of the GST. Humidity readings utilized a Digital Hygrometer (HTC-2), and water saturation levels were gauged through a Boumehydrometer (Alla France, 0-30).

Salt Quality Measurement

The quality of salt produced was assessed using Saltdeck (Saltdec, M102). Parameters under scrutiny encompassed water and NaCl content within the produced salt. These measurements were executed post-harvest, following the draining and drying processes.

Greenhouse Salt Tunnel Specifications

The GST construction design uses a light steel frame (galvalum) measuring 0.75 and 1.5" PVC pipe. In this design, the tunnel construction is made open at the front and back to adapt to variations in the duration of sunlight on the South Beach and North Beach. This open state facilitates more optimal wind flow into the tunnel, speeding up the evaporation process even though the air temperature is not high. A distance of 1 meter at the front and back of the tunnel is designed to prevent water from entering it. The GST model used in this study is shown in Figure 2.

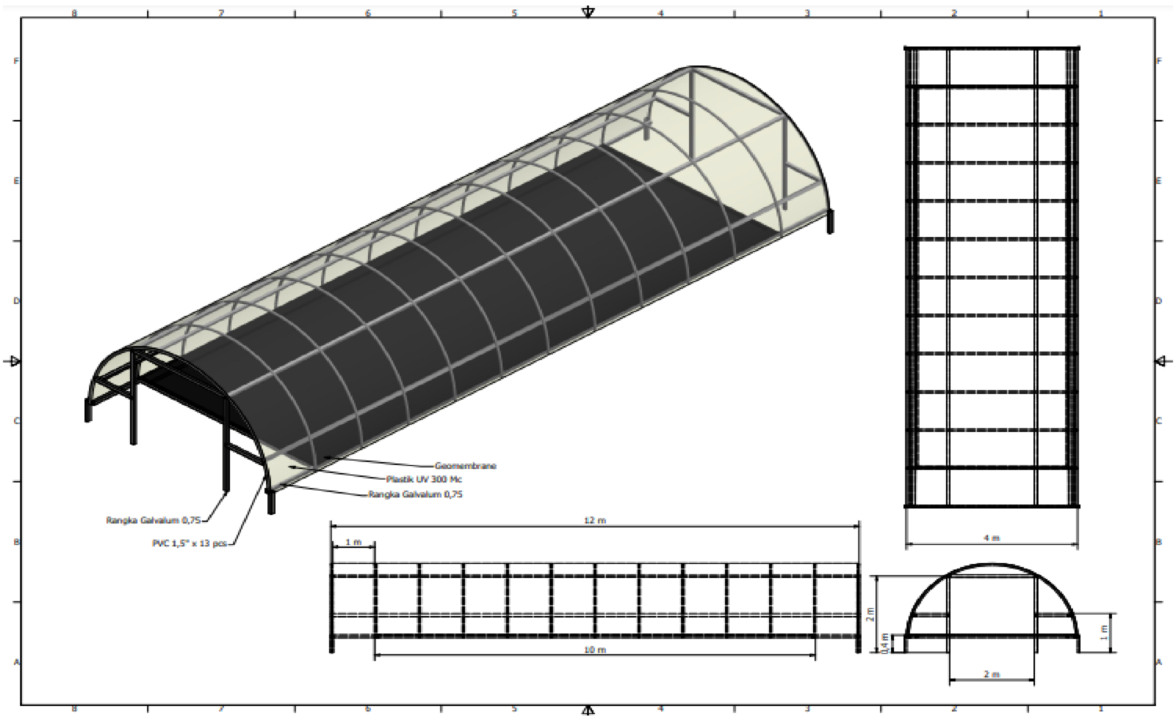

Figure 2. Salt tunnel greenhouse design

Result and Discussion

Daily Temperature (Air and Water)

The recorded daily temperature encompasses both water and air temperature within the GST structure (Figure 3 and Figure 4). On the North Coast, the average morning water temperature hovers around 31°C, reaching approximately 38°C in the afternoon and returning to 31°C in the evening. Conversely, in the South Coast region, the average morning water temperature is approximately 26°C, climbing to around 38°C in the afternoon and stabilizing at 31°C later in the day. These findings underscore the GST construction's ability to sustain a more stable and elevated water and air temperature compared to the surrounding ambient conditions. It highlights the successful trapping of heat within the Greenhouse Salt Tunnel, establishing a conducive environment for the evaporation process. The retained heat serves as the driving force behind water aging and salt crystallization, aligning with studies emphasizing the pivotal role of controlled temperature in enhancing these processes (Tambunan et al., 2012).

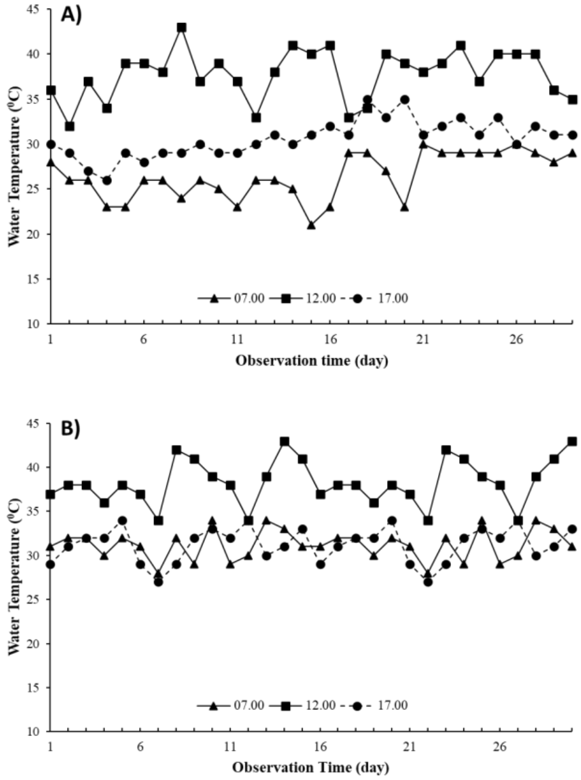

Figure 3. Water temperature dynamics in the greenhouse salt tunnel (A: North coast; B: South coast)

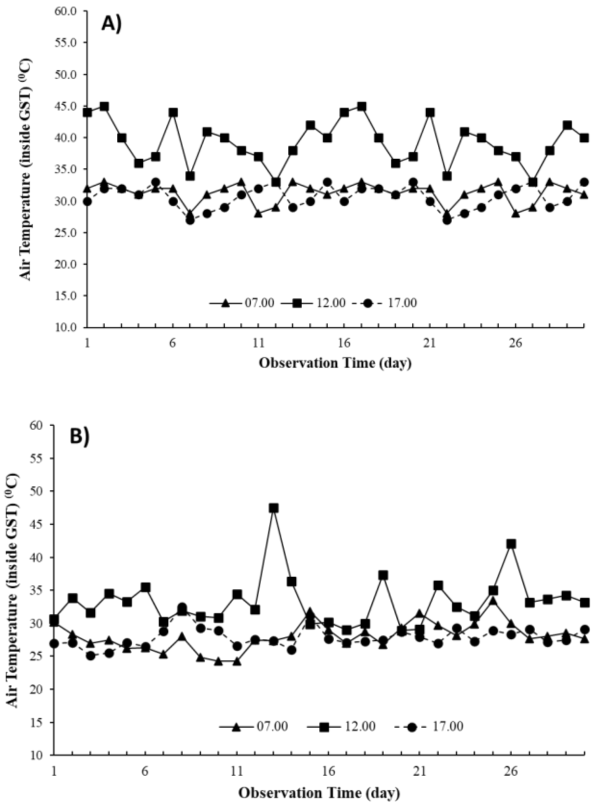

Figure 4. Air temperature dynamics in the greenhouse salt tunnel (A: North coast; B: South coast)

Previous study by Kurniawan et al. (2024) and Amin et al. (2023) state that water and air temperature dramatically affects the evaporation rate of water, where the more significant the evaporation, the greater the number of salt crystals that settle. The observed temperature dynamics not only affirm the efficiency of the GST design in heat retention but also signify its potential to provide a controlled environment conducive to optimal salt production. This insight sheds light on the practical application of the Greenhouse Salt Tunnel technology, showcasing its capacity to influence and elevate crucial environmental factors for enhanced salt crystallization and production).

Wind Velocity

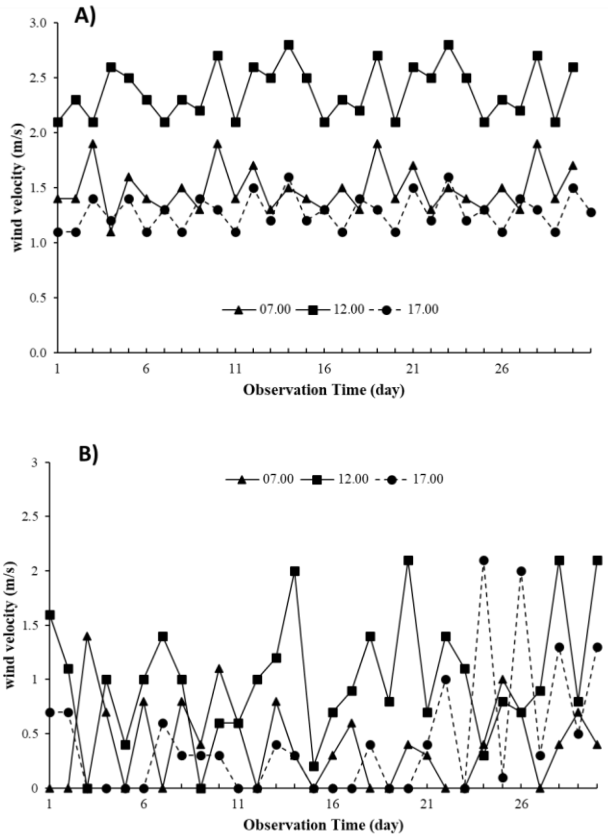

Figure 5. Wind velocity dynamics in the greenhouse salt tunnel (A: North coast; B: South coast)

The result of wind velocity showed at Figure 5. On the North Coast of East Java, where the salt production site faces no significant obstacles, wind speed within the GST remains relatively stable. The study's findings reveal an average wind speed of 1.5 m/s in the morning, approximately 2.4 m/s in the afternoon, and around 1.3 m/s in the evening. Conversely, in the South Coast region, wind speed exhibits more unpredictable variations due to the salt production site being enveloped by rocky hills, subjecting it to multidirectional wind influences. Morning wind speeds average at 0.4 m/s, increase to 1.0 m/s in the afternoon, and subsequently decrease to 0.4 m/s later in the day (Umam et al., 2019).

Wind speed emerged as a crucial parameter in this study due to its potential impact on salt production, wherein the presence of wind facilitates the transportation of water vapor within the Greenhouse Salt Tunnel (GST), directly influencing salt production levels (Kurniawan et al., 2019b; Amin et al., 2023; Yusuf et al., 2018).

This variability in wind speed on the South Coast poses potential challenges for the GST operation, necessitating adaptable design considerations to mitigate its impact. The observed disparities in wind dynamics between the North and South Coasts further emphasize the need for tailored strategies in constructing and managing Greenhouse Salt Tunnels based on the distinct geographical features of the production locations (Kurniawan et al., 2024; Purbani, 2003).

Humidity

The results of humidity value in GST shown at Figure 6. The measured humidity levels on the North Coast of East Java exhibit variations throughout the day. In the morning, the humidity stands at 71%, decreasing to 54% in the afternoon, and rising again to 76% in the evening. Conversely, on the South Coast, the morning humidity measures 78%, drops to 54% in the afternoon, and climbs to 80% in the evening.

Humidity, defined as the amount of water vapor present in the air, serves as a pivotal environmental factor influencing salt production within the Greenhouse Salt Tunnel (GST) (Kurniawan et al., 2019b; Jaziri et al., 2017, 2018; Amin et al., 2023). Elevated humidity levels within the GST are indicative of favorable conditions for water evaporation, thereby facilitating the formation of salt crystals, even during the rainy season (Kartika et al., 2021; Akinaga et al., 2018; Purbani, 2006).

These observations underscore the GST's capability to maintain conducive humidity levels, affirming its potential to sustain salt production activities even in regions susceptible to rain. The fluctuations in humidity emphasize the dynamic nature of environmental conditions within the GST, presenting a promising avenue for adaptable salt production strategies. This insight holds significant implications for optimizing salt production during diverse climatic conditions (Herho et al., 2017), further emphasizing the versatility of the Greenhouse Salt Tunnel technology.

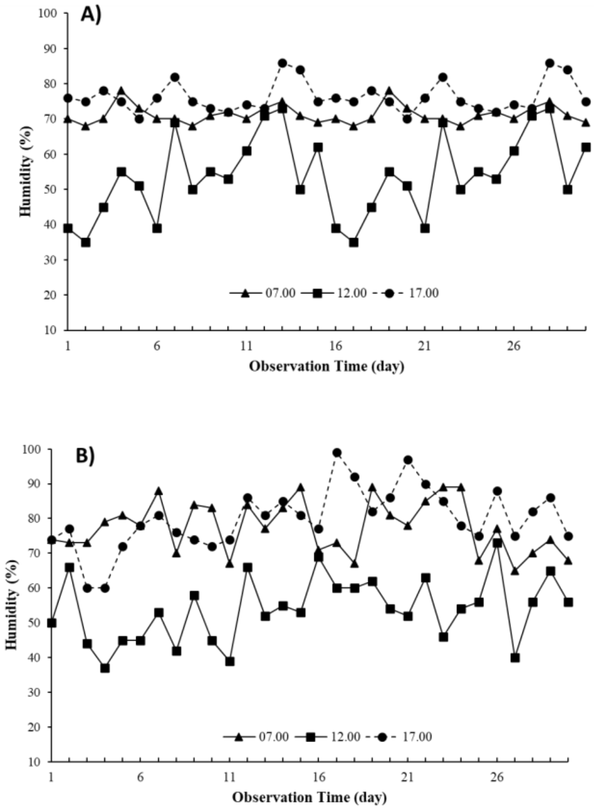

Figure 6. Humidity dynamics in the greenhouse salt tunnel (A: North coast; B: South coast)

Salt Quality and Quantity Analysis

The paramount factors in the salt production industry are the characteristics of production and the quality of salt, both of which significantly influence the success of the business (Sasongko & Satrianto, 2021). A comparative analysis between traditional production methods, excluding Greenhouse Salt Tunnel (GST) and geomembranes, and those incorporating GST applications reveals notable distinctions. This substantiates the transformative impact of home salt crystallization technology on enhancing both production quality and salt content (Amin et al., 2023).

In traditional salt production methods, as per Onie et al. (2021), the production quality typically hovers around 29.18 tonnes/ha. In terms of salt quality, NaCl content falls below 70% (Rusdi, 2018; Santosa, 2014), while magnesium (Mg) content is approximately 0.183 (mg/l). The resulting salt tends to exhibit a brownish-white color (Ariyani et al., 2020). These traditional salt products fetch relatively lower market prices, ranging from approximately Rp. 550-750 (East Java Prices) (Kurniawan & Azizi, 2012).

In contrast, the implementation of GST technology in design trials on the North Coast of East Java yields a significant improvement in salt production. The quantity of salt produced per square meter in these trials reaches 6.5 kg/m², with NaCl content averaging around 95%, resulting in a pristine white salt color. Additional trials on the North Coast further affirm this positive trend, showcasing a quantity of salt production of 6.3 kg/m², with NaCl content at approximately 94%, and the salt maintaining a white color. These outcomes underscore the efficacy of GST technology in enhancing both the quantity and quality of salt production, positioning it as a transformative solution within the salt industry (Kurniawan et al., 2024).

Tabel 1. Comparative data on greenhouse salt tunnel trial results

Characteristic	Traditional	Greenhouse Salt Tunnel	
		South Coast	North Coast
Production Quantity (kg/m²)	3.00	6.00	6.40
Production Quality			
NaCl %	< 70	94	95
Color	Brown	White	White
Water Content %	> 7	6	6

Conclusion

The study concludes that the Greenhouse Salt Tunnel (GST) technology significantly enhances both the quality and quantity of salt production compared to traditional evaporation methods. The results show that the GST system effectively maintains optimal conditions for salt crystallization, with higher NaCl content (over 94%) and increased salt production rates (6.4 kg/m²). Environmental factors such as water temperature, wind speed, and humidity were found to vary between the North and South Coasts, influencing the salt production process. Despite these variations, the GST system proved to be more efficient, although design modifications are necessary to adapt to the dynamic and seasonal changes of coastal environments. These findings support the potential of GST as a sustainable and effective alternative for salt production in not only North Coastal area but also South Coastal area East Java Province.

Acknowledgments
The author extends gratitude to the Malang Regency Fisheries Service, the Tuban Regency Fisheries and Livestock Service, the Bojogan salt business group, and the Bajul Mati Sejahtera salt business group for their invaluable contributions to this research endeavor. This study received crucial support from a Non-Lecturer Doctoral Grant (Hibah Doktor non Lektor Kepala), provided by the Faculty of Fisheries and Marine Sciences at Brawijaya University, under contract number 005/UN 10.F06/KS/2020.

Author Contributions
All authors have contributed to the final manuscript. The contribution of each author is: A.A.A.: writing, investigation, data curation, formal analysis, methodology; A.T.Y., Z.P., Y.A.D.S., and R.A.L.: investigation, data curation, formal analysis, methodology; I.M.A.Z.: formal analysis, methodology; L.N.S.: data curation, formal analysis, methodology; G.A., L.H., and M.H.: investigation, methodology; A.K.: conceptualization, investigation, data curation, formal analysis, methodology, writing – review & editing, funding acquisition, project administration, resources.

Funding
This research was supported by a non-Lector Doctoral Grant (Hibah Doktor non Lektor Kepala), Faculty of Fisheries and Marine Sciences, Brawijaya University with contract number 005/UN 10.F06/KS/2020.

Conflicts of Interest
The author declares that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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