Performance Assessment of Insulator Media Crystallization Technology for Cleaner and More Resource-Efficient Industrial Salt Production

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Abstract

Indonesia continues to rely on large-scale industrial salt imports despite its extensive coastal resources, primarily because community-based solar salt production remains constrained by low productivity and inconsistent product quality. This study evaluates the performance of Insulator Media Technology (IMT), a patented polyethylene-based crystallization system, from Cleaner Production and Resource Efficiency perspectives to support sustainable industrial salt production. A quasi-experimental field study was conducted in Sumenep, Madura, Indonesia, using twelve conventional soil-based salt plots as reference controls. Operational performance, NaCl purity, resource efficiency, and economic benefits were compared between conventional soil-based crystallization systems and IMT. Laboratory analysis of NaCl purity was performed using three paired harvest-age samples (3, 4, and 5 days), while long-term technology performance was validated using multi-season implementation data from Madura (2011–2014) and Central Java (2013–2019). The results demonstrate that IMT eliminated brine seepage losses (Material Loss Ratio = 0; Brine Utilization Efficiency = 100%), increased harvest frequency from 7–8 to 14–15 cycles per season, and improved land productivity from 70 to 88–125.72 t ha^{-1}. Mean NaCl purity increased significantly from 87.32 ± 1.75% to 94.75 ± 0.37% (p = 0.014), enabling compliance with the Indonesian industrial salt standard. Resource Productivity improved by 26–42%, generating an estimated additional revenue of IDR 27.46 million ha^{-1} per production season with a payback period of less than one season. Beyond evaluating technological performance, this study proposes an integrated Cleaner Production–Resource Efficiency–Industrial Competitiveness assessment framework together with five operational Resource Efficiency indicators specifically developed for community-based solar saltworks, providing a practical approach for technology benchmarking and performance evaluation. The study was limited to operational and production performance; direct measurements of soil salinity, groundwater quality, greenhouse gas emissions, and *other environmental impacts were beyond its scope and should be addressed in future research.*

Keywords: *Cleaner Production; Resource Efficiency; Industrial Salt Upgrading; Insulator Media Technology; Solar Saltworks; Sustainable Salt Production*

INTRODUCTION

Indonesia continues to rely on large-scale industrial salt imports despite possessing extensive coastal resources and favorable climatic conditions for solar salt production. The primary challenge is not resource availability but the limited capacity of community-based saltworks to consistently produce industrial-grade salt meeting national quality requirements. Industrial salt applications require high NaCl purity and controlled impurity levels, whereas conventional salt production systems frequently generate products with variable quality and low productivity. Recent studies have identified crystallization conditions, impurity management, and process efficiency as critical determinants of industrial salt quality (Agrawal, Kumar, & Malviya, 2025; B. T. I. Ali et al., 2024; Amir, Febriyanti, Aminullah, & Prasetyo, 2024). National standardization initiatives have similarly emphasized the need for technological upgrading and improved production practices to strengthen domestic industrial salt supply and reduce import dependence (SNI 4435:2017; SNI 9425:2025).

Conventional soil-based crystallization tables face three major limitations. First, porous soil substrates allow significant brine seepage, reducing material utilization efficiency and salt recovery. Second, relatively slow evaporation and crystallization rates limit harvest frequency and annual productivity. Third, direct contact between brine and soil introduces impurities that reduce NaCl purity and product consistency. Similar constraints have been reported in solar saltworks across tropical regions, where seepage losses, contamination, and uncontrolled crystallization remain major barriers to industrial-grade salt production (B. T. I. Ali et al., 2024; Bagastyo et al., 2021; Sedivy, 2009). To address these limitations, Sudarto (2011) developed Insulator Media Technology (IMT), a patented crystallization system designed to eliminate brine seepage, accelerate salt formation, and improve product quality.

Cleaner Production (CP) and Resource Efficiency (RE) provide complementary frameworks for evaluating technological interventions in resource-based industries. CP emphasizes preventive strategies that minimize waste generation and environmental impacts, whereas RE focuses on maximizing value creation from available resources. Recent studies have demonstrated that resource conservation, circular-economy practices, and process-efficiency improvements can simultaneously enhance environmental and economic performance (Alrabiah & Hicks, 2025; Batlles-delaFuente, Franco-García, Belmonte-Ureña, & Plaza-Úbeda, 2023; Cisternas, Ordóñez, Jeldres, & Serna-Guerrero, 2022; Sartika, Aqla, Firman, & Megasukma, 2025). In solar salt production, concentrated brine represents the principal production resource; therefore, reducing brine loss can improve both operational efficiency and sustainability performance. Table 1. summarizes research gaps addressed by the present study

Table 1. Research gaps addressed by the present study

Previous studies	Remaining gap	Contribution of this study
Studies on solar salt production primarily evaluate productivity improvement or NaCl purity.	Operational Resource Efficiency has rarely been quantified using integrated indicators.	Proposes five operational Resource Efficiency indicators (BUE, MLR, LUE, TEI, RP).
Geomembrane and crystallization technologies mainly focus on technical performance.	Cleaner Production and Resource Efficiency have rarely been integrated into a unified assessment framework.	Develops an integrated Cleaner Production–Resource Efficiency–Industrial Competitiveness framework.
Previous studies generally assess technical or economic performance separately.	Simultaneous evaluation of technical, environmental, and economic dimensions remains limited.	Provides an integrated multidimensional technology assessment.
Most studies report short-term experimental results.	Long-term validation under actual production conditions is limited.	Provides multi-season field validation in Madura and Demak.

Although previous studies have reported significant advances in solar salt production, most investigations have focused on improving productivity, salt quality, or individual process technologies. Studies evaluating geomembrane systems and crystallization technologies generally emphasize technical performance, whereas integrated assessment of Cleaner Production, Resource Efficiency, and industrial competitiveness remains limited. Furthermore, operational Resource Efficiency indicators specifically designed for community-based solar saltworks have not been systematically developed or validated. These gaps restrict comprehensive evaluation of technology performance and limit the development of standardized benchmarking approaches for sustainable industrial salt production.

This study contributes both theoretically and methodologically to the Cleaner Production and Resource Efficiency literature. Theoretically, it extends the application of Cleaner Production and Resource Efficiency concepts to community-based solar salt production through an integrated assessment framework that incorporates industrial competitiveness. Methodologically, the study introduces five operational Resource Efficiency indicators specifically designed for evaluating crystallization performance under actual production conditions. These contributions provide a practical framework for technology benchmarking and future resource-efficiency assessment in tropical solar salt production systems.

Research Questions

Based on the identified research gaps, this study addresses the following research questions:

1. RQ1. Does Insulator Media Technology improve operational performance and industrial salt quality compared with conventional soil-based crystallization systems?
2. RQ2. To what extent does Insulator Media Technology improve Resource Efficiency and Cleaner Production performance in community-based solar salt production?
3. RQ3. Can the proposed operational Resource Efficiency indicators provide a practical framework for evaluating technology performance in community-based solar saltworks?

Despite recent advances in solar salt production technologies, important scientific gaps remain regarding the integration of Cleaner Production, Resource

Efficiency, and industrial competitiveness within community-based salt production systems. Existing studies generally focus on individual technical improvements without providing comprehensive operational indicators capable of evaluating material conservation, process performance, and resource utilization simultaneously.

Accordingly, this study makes four principal contributions. First, it proposes five operational Resource Efficiency indicators (Brine Utilization Efficiency, Material Loss Ratio, Land Use Efficiency, Throughput Efficiency Index, and Resource Productivity) specifically designed for community-scale solar saltworks. Second, it develops an integrated Cleaner Production–Resource Efficiency–Industrial Competitiveness assessment framework. Third, it provides long-term empirical validation of Insulator Media Technology under actual production conditions in two major salt-producing regions of Indonesia. Finally, it demonstrates how engineering-based process innovation can simultaneously improve productivity, industrial salt quality, resource efficiency, and economic performance while supporting sustainable industrial salt development.

METHODS

Study Area and Technology Description

This study evaluated the performance of Insulator Media Technology (IMT) in community-based solar salt production systems in Indonesia. Primary field observations were conducted at Kebundadap Timur Village, Sumenep Regency, Madura, East Java, during the 2011 production season, with subsequent productivity validation in Madura (2011–2014) and Demak, Central Java (2013–2019). IMT is a patented crystallization technology consisting of a multilayer structure comprising: (1) a non-stick upper surface facilitating salt harvesting; (2) a black intermediate layer enhancing solar-energy absorption; and (3) an impermeable bottom layer preventing brine seepage into the underlying soil. The technology was developed to improve brine retention, accelerate crystallization, and enhance salt quality.

Research Design

This study employed a quasi-experimental field design using a non-equivalent control group approach to evaluate the operational performance of

Insulator Media Technology (IMT) under actual community-based salt production conditions. Random allocation of treatment and control plots was not feasible because salt farmers had already established their production systems prior to the study. Consequently, the evaluation compared IMT-treated crystallization tables with adjacent conventional soil-based crystallization tables operating under comparable environmental and production conditions.

The treatment group consisted of salt production units implementing IMT, whereas the control group comprised twelve conventional soil-based crystallization plots located within the same production area. The control plots were selected because they represented the dominant production practice in the study area and were operated using similar brine sources, climatic conditions, production schedules, and management practices. This approach minimized potential confounding factors while allowing technology performance to be evaluated under realistic field conditions.

As illustrated in Figure 1, following the primary field experiment conducted during the 2011 production season, long-term validation was performed using historical implementation records from Madura (2011–2014) and Demak, Central Java (2013–2019) to evaluate the consistency and practical applicability of IMT across different production seasons and environmental conditions.

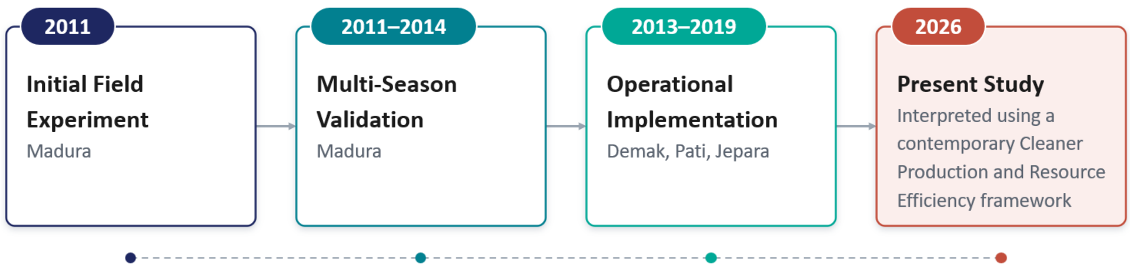

Figure 1. Timeline of the long-term field validation and implementation of Insulator Media Technology (IMT). From the initial field experiment in Madura (2011) to the interpretation of the present study within a contemporary Cleaner Production–Resource Efficiency framework (2026).

Data Collection

Operational and production data were obtained through field measurements, production records, and laboratory analyses. Performance parameters included evaporation period, crystallization period, brine loss, harvest frequency, productivity, product homogeneity, and NaCl purity. Productivity data from twelve conventional soil-based salt plots at the same location were used as control values. Long-term productivity validation was conducted using historical implementation records from Madura and Demak.

To improve comparability between treatment and control groups, operational observations were conducted under similar environmental conditions within the same production season, using identical field observation procedures and analytical protocols for all salt samples. This design minimized potential bias, allowing the observed performance differences to be primarily attributed to the application of IMT.

NaCl content was analyzed at the THP Laboratory, Diponegoro University, using the Mohr argentometric titration method. Three harvest-age samples (3, 4, and 5 days) were analyzed for both IMT and conventional soil-based production systems.

Resource Efficiency Assessment

Resource Efficiency (RE) performance was evaluated using five operational indicators developed for community-scale solar saltworks:

1. Brine Utilization Efficiency (BUE)
2. Material Loss Ratio (MLR)
3. Land Use Efficiency (LUE)
4. Throughput Efficiency Index (TEI)
5. Resource Productivity (RP)

The indicators were calculated as follows:

MLR = Brine Loss / Total Brine Input

BUE = (1 − MLR) × 100

LUE = Actual Productivity / Baseline Productivity

TEI = Harvest Frequency (IMT) / Harvest Frequency (Control)

RP = Productivity / (Land Area × Production Duration)

These indicators were selected to quantify material conservation, land-use performance, process efficiency, and resource productivity.

Development and Validation of Resource Efficiency Indicators

The five Resource Efficiency (RE) indicators proposed in this study were developed to provide an operational framework for evaluating community-based solar salt production systems from the perspectives of material conservation, land productivity, process efficiency, and resource utilization. Indicator development was guided by Cleaner Production principles, resource-efficiency concepts, and the physical characteristics of solar salt production, where concentrated brine represents the principal production resource.

Unlike manufacturing industries, community-scale solar saltworks currently lack standardized operational indicators for quantifying resource efficiency during crystallization. Existing studies generally evaluate productivity, NaCl purity, or production costs separately, without integrating material utilization, process throughput, and land-use performance into a unified assessment framework. Therefore, this study introduces five complementary indicators that collectively represent the major dimensions of operational resource efficiency.

Brine Utilization Efficiency (BUE) and Material Loss Ratio (MLR) quantify conservation of the primary production resource by measuring the proportion of concentrated brine effectively retained during crystallization. Land Use Efficiency (LUE) evaluates the productivity achieved from a fixed production area relative to baseline conditions. Throughput Efficiency Index (TEI) measures improvements in production-cycle frequency, while Resource Productivity (RP) integrates production output with land area and production duration to quantify overall resource utilization efficiency.

The validity of the proposed indicators was evaluated through their conceptual consistency with Cleaner Production objectives and their practical applicability under actual field conditions. Operational measurements demonstrated that each indicator responded consistently to technological improvements introduced by IMT, indicating their suitability for comparative performance assessment in community-based solar saltworks. Although further validation across broader production environments is recommended, the proposed indicator framework provides a practical basis for future benchmarking and technology evaluation in tropical solar salt production systems.

Cleaner Production Assessment

Cleaner Production (CP) performance was assessed using the five UNEP Cleaner Production principles: input efficiency, process efficiency, product quality improvement, waste minimization, and environmental risk reduction (UNEP, 2000; UNIDO & UNEP, 2010). Operational results from IMT were mapped against these principles using quantitative performance indicators derived from field measurements and laboratory analyses.

Statistical Analysis

Differences in NaCl purity between IMT and conventional soil-based production were evaluated using a paired t-test with a significance level of $\alpha = 0.05$. Prior to hypothesis testing, paired observations were examined to verify their suitability for paired comparison. Because NaCl purity measurements were obtained from matched harvest-age samples collected under identical production conditions, paired comparisons were considered appropriate for minimizing between-sample variability. Owing to the limited number of paired observations ($n = 3$), statistical inference was interpreted together with descriptive statistics and long-term field validation rather than relying solely on p-values. Because laboratory analysis was limited to three paired harvest-age observations, confidence intervals and effect-size estimates would provide limited statistical reliability. Therefore, statistical interpretation was supported by descriptive statistics and long-term operational validation rather than relying solely on inferential statistics.

Descriptive statistical analysis was applied to operational performance, productivity, and resource-efficiency indicators. Results are presented as mean values, standard deviations, percentage improvements, and efficiency ratios where appropriate. Figure 2 summarizes the conceptual relationships among Insulator Media Technology, operational improvements, Resource Efficiency indicators, Cleaner Production principles, and Industrial Competitiveness evaluated in the present study.

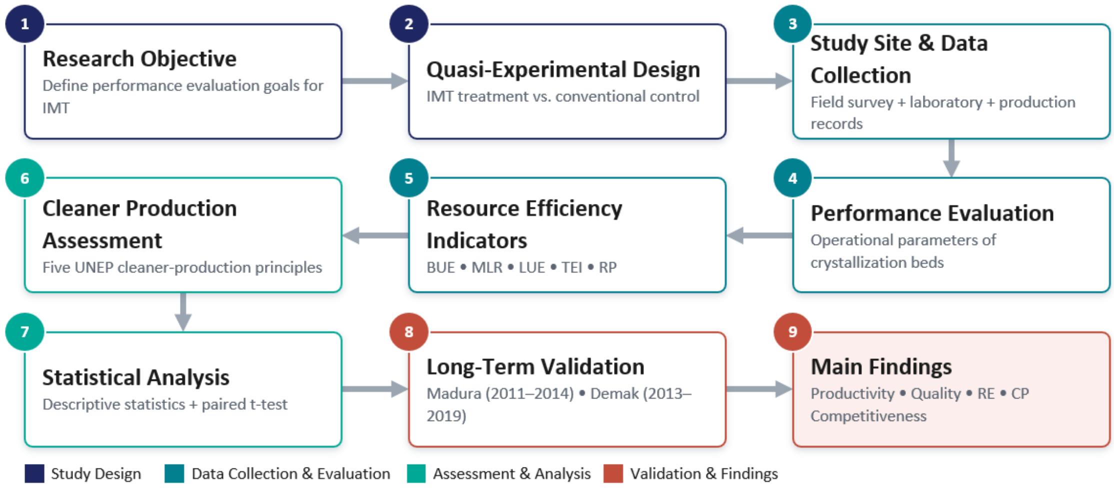

Figure 2. Research workflow adopted for evaluating the performance of Insulator Media Technology (IMT) using an integrated Cleaner Production–Resource Efficiency framework.

RESULT AND DISCUSSION

The primary experimental observations reported in this study were conducted during the 2011 production season, representing the first field implementation of Insulator Media Technology (IMT). Although the experimental dataset is historical, the engineering principles underlying the technology—including brine conservation, crystallization enhancement, and resource efficiency—remain unchanged. To improve the contemporary relevance of the findings, the original field results are interpreted using current Cleaner Production and Resource Efficiency concepts and supported by recent international literature published between 2023 and 2026. Furthermore, long-term implementation records from Madura and Demak are incorporated to demonstrate the sustained operational performance of the technology under actual production conditions.

Brine Conservation and Resource Utilization Efficiency

Brine conservation represents the most fundamental resource-efficiency challenge in conventional solar salt production because concentrated brine serves as the principal material input for salt crystallization. Figure 3 illustrates the contrasting brine-retention mechanisms of conventional soil-based crystallization tables and Insulator Media Technology (IMT).

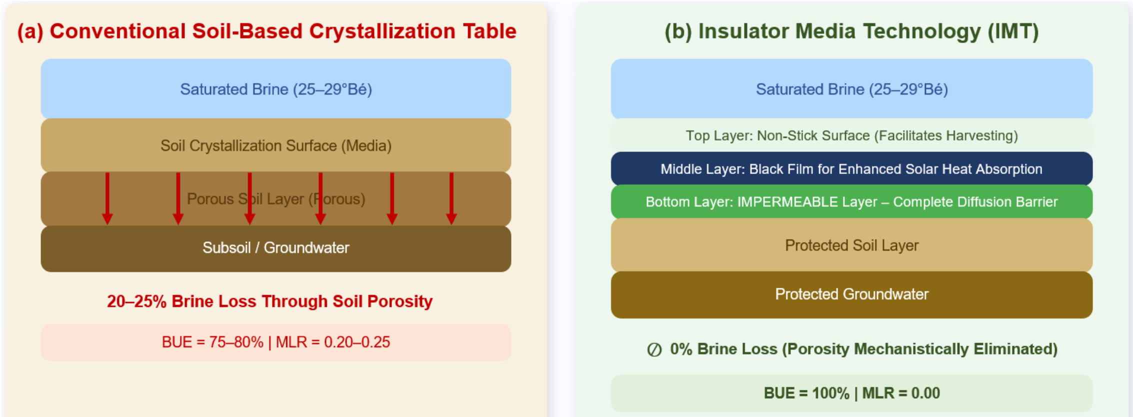

Figure 3. Conceptual comparison between conventional soil-based crystallization tables and Insulator Media Technology (IMT). Sources: (Allwood & Cullen, 2012; Sudarto, 2011).

As shown in Figure 3, conventional soil-based crystallization tables experience brine losses through porous soil layers, resulting in an estimated 20–25% loss of concentrated brine during each production cycle (Sudarto, 2011). In contrast, IMT employs an impermeable multilayer barrier that physically prevents brine seepage into the underlying soil. Consequently, Material Loss Ratio (MLR) was reduced to zero, resulting in a Brine Utilization Efficiency (BUE) of 100%.

The observed performance is consistent with studies reporting the long-term impermeability and durability of HDPE-based barrier systems under saline conditions (M. Ali & Rowe, 2024). Similar improvements in brine retention have also been reported in geomembrane-based salt production systems, where impermeable surfaces improved process stability and resource utilization efficiency (Agrawal et al., 2025).

Similar findings have been reported in recent studies investigating geomembrane-based salt production, solar evaporation enhancement, crystallization engineering, and sustainable saline-resource management (Agrawal et al., 2025; B. T. I. Ali et al., 2025; Chen et al., 2023; Alrabiah & Hicks, 2025; Amadghous et al., 2025).

From a Cleaner Production perspective, elimination of material loss at the source represents the highest level of preventive intervention within the UNEP hierarchy (UNEP, 2000). Recent circular-economy studies similarly recognize resource retention as a critical strategy for improving material efficiency and environmental performance (Alrabiah & Hicks, 2025; Amadghous et al., 2025).

By preventing brine losses before waste generation occurs, IMT simultaneously improves resource conservation and production efficiency.

The improvement in brine utilization can also be interpreted from a mass-balance perspective. Under conventional soil-based crystallization, a considerable proportion of concentrated brine is lost through seepage before crystallization is completed, thereby reducing the quantity of dissolved NaCl available for crystal formation. By physically isolating the brine from the porous soil substrate, IMT conserves the initial salt mass within the crystallization system, resulting in higher process efficiency and greater material recovery. This mechanism illustrates how relatively simple engineering modifications can substantially improve resource utilization without increasing raw-material consumption or production area.

Although direct measurements of soil salinity and groundwater quality were beyond the scope of this study, elimination of seepage pathways provides a plausible mechanism for reducing environmental risks associated with saline infiltration. Similar containment principles are widely applied in geomembrane-based environmental protection systems (M. Ali & Rowe, 2024; Wiwoho & Prasada, 2024; Zidan, Kemnitz, & Ritter, 2024). Future studies should evaluate long-term effects on soil and groundwater quality through dedicated environmental monitoring programs.

Operational Efficiency Improvement

Operational performance determines the efficiency with which brine is converted into harvestable salt. Table 2 summarizes the comparative operational performance of conventional soil-based production and IMT during the 2011 production season.

Table 2. Comparative Operational Performance of Conventional Soil-Based Crystallization Tables and Insulator Media Technology (IMT) in Kebundadap Timur, Madura, Indonesia (Season I, 2011)

No.	Performance Parameter	Conventional Soil-Based System	IMT	Improvement Achieved	Gain (%)
1	Evaporation period (2–25°Bé)	15–17 days	11–12 days	4–5 days shorter	26–29

2	Crystallization period per cycle	10–11 days	6–7 days	4 days shorter	30–36
3	Brine loss through seepage (%)	20–25	0	Loss eliminated	100 (MLR → 0)
4	Harvest frequency (102-day production season)	7–8 cycles	14–15 cycles	+7 harvest cycles	88–100
5	Kesap-guluk maintenance requirement	2–3 days month^{-1}	Not required	2–3 days saved month^{-1}	—
6	Productivity (t ha^{-1} season^{-1})	70.08 ± 13.77 (n = 12)[a]	88.00	+17.92 t ha^{-1}	25.71
7	Salt quality classification	Mixed K1–K3 grades	Uniform K1 grade	Quality upgraded	—
8	Product homogeneity	Heterogeneous	Homogeneous	Consistency improved	—

[a] Mean productivity of 12 control plots located within the same study area (Sudarto, 2011). The national average productivity of approximately 70 t ha^{-1} season^{-1} was used as a policy benchmark.

Source: Field data adapted from Sudarto (2011); crystallization and evaporation kinetics reported in Sudarto (2026).

The results indicate substantial improvements across all operational parameters. Evaporation time decreased from 15–17 days to 11–12 days, while crystallization time decreased from 10–11 days to 6–7 days per cycle. These improvements shortened the overall production cycle and nearly doubled harvest frequency from 7–8 to 14–15 cycles within a 102-day production season.

The improved performance can be attributed to enhanced thermal and mass-transfer conditions created by the multilayer structure of IMT. The black intermediate layer promotes solar-energy absorption, while the impermeable bottom layer stabilizes brine conditions throughout evaporation and crystallization. Similar performance improvements have been reported in solar evaporation and thermal-management studies involving saline-water systems

(Abdel-Aziz, Kabeel, Attia, & Elnasr, 2024; Abdullah et al., 2025; Chaichan et al., 2023).

From a thermodynamic perspective, the improved performance of IMT is associated with enhanced solar-energy absorption and reduced conductive losses through the impermeable multilayer structure. Increased heat retention accelerates water evaporation, while more stable brine concentration gradients promote uniform crystal nucleation and growth. These coupled heat- and mass-transfer processes explain the observed reductions in evaporation time and crystallization duration, ultimately contributing to higher production throughput.

An additional operational advantage was the elimination of kesap-guluk maintenance activities, which conventionally require 2–3 working days per month to restore soil-surface conditions. Removal of this requirement reduced labor inputs and increased the effective production period.

The improved homogeneity of IMT-produced salt further indicates a more stable crystallization environment. Stable thermal and concentration gradients promote uniform crystal growth and reduce variability in product quality (B. T. I. Ali et al., 2024; Chen et al., 2023; Manik et al., 2025). Overall, the results demonstrate that IMT improves both process efficiency and operational reliability in community-scale solar salt production.

From a process-engineering perspective, the observed reduction in production-cycle duration indicates improved heat-transfer efficiency during evaporation and more stable crystallization conditions. Shorter production cycles not only increase annual throughput but also reduce farmers' exposure to unpredictable weather interruptions during the dry season. Consequently, operational efficiency improvements contribute simultaneously to production resilience and economic sustainability, reinforcing the role of process optimization as a key element of Cleaner Production.

Productivity Enhancement and Land Use Efficiency

Productivity improvement represents one of the most important outcomes of IMT because it directly determines resource utilization and economic performance. Figure 4 presents long-term productivity data from Madura and Demak compared with the Indonesian national average productivity benchmark.

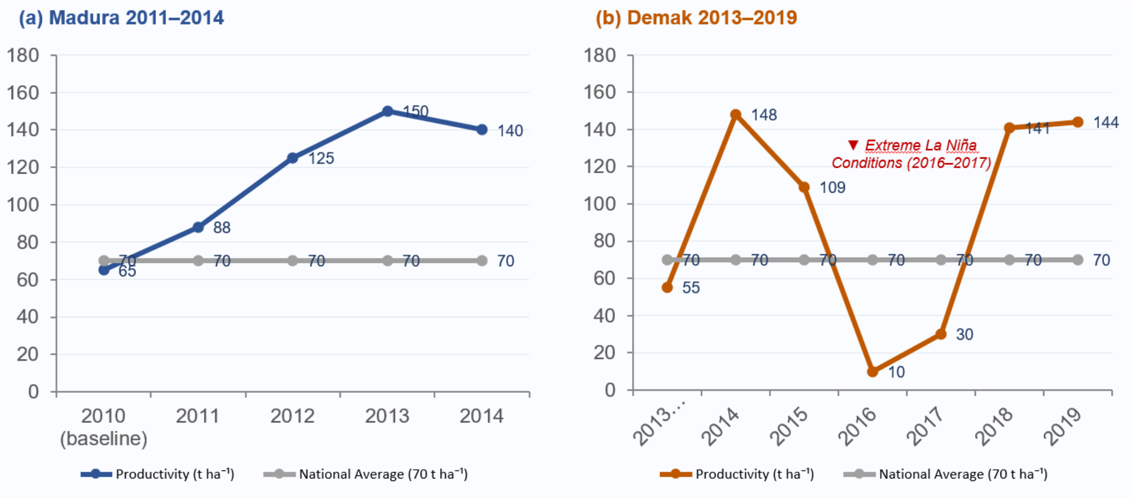

Figure 4. Long-term productivity performance of Insulator Media Technology (IMT) in (a) Madura (2011–2014) and (b) Demak (2013–2019). Sources: Sudarto (2011). The figure illustrates operational implementation records collected across multiple production seasons rather than repeated experimental observations; therefore, variability indicators such as confidence intervals or error bars are not presented.

As shown in Figure 4, IMT consistently achieved productivity levels exceeding the national average of approximately 70 t ha^{-1} $season^{-1}$. In Madura, productivity increased from 70.08 t ha^{-1} under conventional conditions to 88 t ha^{-1} during Season I and 125.72 t ha^{-1} during Season II. Similar performance was observed in Demak, where productivity remained above the national benchmark despite climatic variability, including extreme La Niña conditions during 2016–2017.

These results correspond to Land Use Efficiency (LUE) values of 1.26 and 1.80, indicating that 26–80% more salt was produced from the same land area without additional land expansion. Such performance reflects productive decoupling, where production output increases while resource requirements remain relatively constant (André, Buendía, & Santos-Arteaga, 2024).

The findings suggest that Indonesia's productivity gap is primarily technological rather than climatic. Similar studies have identified production-surface design, brine management, and process control as key determinants of salt productivity in tropical environments (Agrawal et al., 2025; Amril et al., 2026).

Consequently, IMT can be viewed as a land-use intensification strategy that increases production while improving resource efficiency.

The productivity improvement achieved by IMT also demonstrates that increasing industrial output does not necessarily require expansion of production land. Instead, technological intensification enables greater production from existing saltworks, thereby supporting sustainable land management. This finding is particularly relevant for coastal regions where land availability is increasingly constrained by urbanization, aquaculture development, and climate-related environmental pressures.

Industrial Salt Quality Improvement

Product quality is a critical requirement for expanding the use of community-produced salt in industrial applications. Table 3 compares NaCl purity levels achieved by conventional soil-based production and IMT.

Table 3. Comparison of NaCl Purity Between Conventional Soil-Based Salt Production and Insulator Media Technology (IMT) (THP UNDIP Laboratory Analysis, 2011)

Harvest Age (days)	NaCl Purity – IMT (%)	NaCl Purity – Conventional Soil-Based System (%)	Difference (percentage points)
3	94.33	86.16	8.17
4	94.93	86.47	8.46
5	95.00	89.33	5.67
Mean	94.75	87.32	7.43
SD	0.37	1.75	—
n	3	3	—

Statistical comparison (paired t-test): $t = 8.39$; $df = 2$; $p = 0.014$ (significant at $\alpha = 0.05$).

Industrial salt requirement (SNI 4435:2017): NaCl ≥ 94.7%

System	Compliance Status
IMT	✓ Meets industrial salt specification
Conventional Soil-Based System	✗ Does not meet industrial salt specification

Source: THP Laboratory, Diponegoro University (Sudarto, 2011). NaCl content determined using the Mohr argentometric titration method.

Statistical comparison summary

Statistical comparison	Value
Mean difference	7.43 percentage points
Paired t-test	t = 8.39
Degrees of freedom	2
p-value	0.014

Because NaCl purity measurements were obtained from only three matched harvest-age observations, the statistical comparison should be interpreted as supportive evidence rather than as the sole basis for evaluating technology performance. The laboratory findings are complemented by long-term operational validation and consistent improvements observed across multiple field implementation sites.

The results show that IMT consistently produced higher NaCl purity than conventional soil-based systems across all harvest ages. Mean NaCl content increased from 87.32 ± 1.75% to 94.75 ± 0.37%, representing an average improvement of 7.43 percentage points. Statistical analysis confirmed that the difference was significant ($p = 0.014$).

Although the laboratory comparison involved a limited number of matched harvest-age observations, the magnitude and consistency of the observed differences across all harvest ages, together with long-term field performance validation, provide converging evidence supporting the reliability of the technology's quality improvement.

Three factors contributed to this improvement: elimination of soil-contact contamination, more stable crystallization conditions, and removal of kesap-guluk maintenance activities that can reintroduce impurities into the crystallization surface. Similar studies have reported that impurity control during crystallization is a major determinant of industrial-grade salt quality (B. T. I. Ali et al., 2025; M. Ali & Rowe, 2024).

Importantly, the average NaCl content achieved by IMT exceeded the minimum requirement for industrial salt specified in Indonesian standards (SNI 4435:2017). This result demonstrates that upstream process innovation can substantially improve product quality without requiring complex downstream refining processes. The findings are consistent with previous field observations reported during the development and implementation of IMT in Indonesian salt-producing regions (Sudarto, 2011).

The improvement in NaCl purity further illustrates the close relationship between process control and product quality. By minimizing physical contamination from soil particles throughout crystallization, IMT promotes more selective crystal formation and reduces impurity incorporation into the final product. These findings emphasize that improvements in upstream production technology may substantially reduce the need for additional downstream purification processes, thereby contributing to both resource efficiency and industrial cost reduction.

From a process-engineering perspective, IMT improves process stability by maintaining more consistent operating conditions throughout crystallization. Reduced interaction between concentrated brine and the underlying soil minimizes process disturbances and impurity incorporation, thereby enhancing both product consistency and overall process reliability.

Resource Efficiency Assessment

To quantify the overall performance of IMT, operational results were evaluated using five Resource Efficiency (RE) indicators. Table 4 summarizes the calculated indicator values for conventional soil-based production and IMT.

Table 4. Resource Efficiency Performance Indicators for Conventional Soil-Based Salt Production and Insulator Media Technology (IMT)

Indicator	**Definition**	**Conventional Soil-Based System**	**IMT**	**Improvement Achieved**	**Calculation Basis**
BUE (%)	Brine Utilization Efficiency	75–80	100	+20–25 percentage points	BUE = (1 − MLR) × 100
LUE (ratio)	Land Use Efficiency	1.00 (70.08 t ha^{-1})	1.26 (Season I); 1.80 (Season II)	+26%; +80%	Actual productivity ÷ baseline productivity
TEI (ratio)	Throughput Efficiency Index	1.00 (7–8 harvest cycles)	1.93 (14.5 ÷ 7.5	+93%	Harvest frequency ratio

			harvest cycles)		
MLR (decimal)	Material Loss Ratio	0.20–0.25	0.00[a]	−100%	Brine loss ÷ total brine input
RP (kg m⁻² day⁻¹)	Resource Productivity	0.0686 (Season I)	0.0863 (Season I); 0.0975 (Season II)	+26%; +42%	Productivity ÷ land area ÷ production duration

[a] *Brine seepage was completely eliminated by the impermeable multilayer structure of IMT, resulting in zero measurable material loss during crystallization.*

Season I = 2011 production season; Season II = 2012 production season. Resource Productivity (RP) was calculated using total saltwork area as the denominator. BUE = Brine Utilization Efficiency; LUE = Land Use Efficiency; TEI = Throughput Efficiency Index; MLR = Material Loss Ratio; RP = Resource Productivity.

The assessment demonstrates substantial improvements across all RE dimensions. Complete elimination of brine losses resulted in a Brine Utilization Efficiency (BUE) of 100% and a Material Loss Ratio (MLR) of zero. Resource Productivity (RP) increased by 26–42%, while Throughput Efficiency Index (TEI) nearly doubled due to increased harvest frequency.

From a resource-conservation perspective, complete retention of concentrated brine represents an optimal outcome because the principal production resource remains fully available for crystallization. Recent studies similarly identify resource retention as a key strategy for improving environmental and economic performance in saline-resource systems (Abdesharif E, Ebrahimi, Ebrahimi Sarindizaj, & Arab, 2026; Amadghous et al., 2025).

The proposed indicators provide a practical framework for evaluating material conservation, land productivity, process performance, and resource utilization in community-scale solar saltworks. While resource-efficiency frameworks are widely applied in manufacturing and industrial systems, their application in solar salt production remains limited. Therefore, the indicator set proposed in this study offers a useful contribution for future technology assessment and performance benchmarking.

Beyond evaluating individual operational parameters, the integrated indicator framework facilitates a systems-level understanding of resource performance in community-based salt production. The combination of material conservation, land productivity, process throughput, and overall resource productivity provides a multidimensional perspective that cannot be obtained from conventional productivity indicators alone. Such integrated assessment may also support technology benchmarking and policy evaluation in future industrial salt development programs.

The proposed indicator framework is not intended to replace existing productivity or quality indicators but rather to complement them by integrating material conservation, process performance, land utilization, and production efficiency within a single operational assessment framework. This integrated approach provides a more comprehensive evaluation of technology performance and may facilitate standardized benchmarking for future resource-efficiency studies in community-scale solar salt production.

The consistency of improvements observed across multiple Resource Efficiency indicators further strengthens the practical significance of the findings. Although statistical inference was limited by the number of laboratory observations, the convergence of operational evidence—including elimination of brine loss, increased harvest frequency, improved land productivity, and enhanced NaCl purity—provides coherent support for the overall effectiveness of IMT under field conditions.

Cleaner Production Assessment

The Cleaner Production implications of IMT were evaluated using the five UNEP Cleaner Production principles. Table 5 summarizes the assessment results.

Table 5. Cleaner Production Assessment of Insulator Media Technology (IMT) Based on the Five UNEP Cleaner Production Principles

UNEP Cleaner Production Principle	Performance Indicator	Conventional Soil-Based System	IMT Performance	Assessment Outcome
1. Input Efficiency	Brine Utilization Efficiency (BUE); Material Loss Ratio (MLR)	BUE = 75–80%; MLR = 0.20–0.25	BUE = 100%; MLR = 0.00	Achieved – complete elimination of brine loss
2. Process Efficiency	Throughput Efficiency Index (TEI); Resource Productivity (RP)	TEI = 1.00; RP = 0.0686 kg m^{-2} day^{-1}	TEI = 1.93; RP = 0.0863–0.0975 kg m^{-2} day^{-1}	Achieved – significant improvement in process throughput and resource productivity
3. Product Quality Improvement	NaCl purity; Industrial salt compliance	87.32 ± 1.75%; mixed K1–K3 grades	94.75 ± 0.37%; uniform K1 grade (p = 0.014)	Achieved – statistically significant quality improvement
4. Waste Minimization	Material Loss Ratio (MLR); product-grade consistency	MLR = 0.20–0.25; mixed-grade production	MLR = 0.00; 100% K1-grade production	Achieved – elimination of material loss and quality downgrading
5. Environmental Risk Reduction	Potential saline seepage to soil and groundwater	Diffuse infiltration estimated at 20–25% of concentrated brine	Seepage pathway physically interrupted by impermeable multilayer barrier	Achieved – environmental risk reduction through source prevention mechanism

BUE = Brine Utilization Efficiency; MLR = Material Loss Ratio; TEI = Throughput Efficiency Index; RP = Resource Productivity.

Environmental-risk assessment is based on the physical elimination of brine seepage pathways. Direct measurements of soil salinity and groundwater quality were beyond the scope of the present study and are recommended for future investigation.

The results indicate that IMT satisfies all five Cleaner Production principles. Input efficiency improved through complete brine retention, while process efficiency increased through shorter production cycles and higher harvest frequency. Product quality improved significantly through increased NaCl purity and consistent K1-grade production. Simultaneously, waste generation was reduced through elimination of material losses and quality downgrading.

Cleaner Production literature emphasizes preventive interventions that address inefficiencies at their source rather than relying on corrective measures after losses occur (UNEP, 2000). In this respect, IMT functions as a source-prevention technology because brine losses are eliminated before waste generation takes place. Similar approaches are increasingly recognized as effective strategies for improving industrial sustainability and resource productivity (André et al., 2024; Bandh, Malla, Wani, & Hoang, 2024).

The findings suggest that IMT has the potential to reduce environmental risks by eliminating brine seepage pathways, although direct environmental measurements were beyond the scope of the present study.

The findings further demonstrate that Cleaner Production in community-based salt production should not be interpreted solely as pollution prevention. Instead, preventive engineering interventions that improve resource retention, operational stability, and product quality can simultaneously generate environmental, technical, and economic benefits. This broader interpretation aligns with the evolving concept of Cleaner Production, which increasingly emphasizes integrated resource optimization across the production system.

Environmental-risk reduction was achieved through physical interruption of saline seepage pathways. Although direct environmental measurements were not conducted, the impermeable barrier provides a scientifically plausible mechanism for reducing contamination risks associated with concentrated brine infiltration.

Industrial Competitiveness and Economic Feasibility

Technological improvements are sustainable only if they generate measurable economic benefits. The results demonstrate that IMT provides both cost and quality advantages that enhance the competitiveness of community-based salt production systems.

Higher productivity increased total output without requiring additional land, while elimination of brine losses improved material utilization efficiency. Simultaneously, improved NaCl purity enabled production of uniform K1-grade salt, creating opportunities to access higher-value industrial markets. Similar studies have shown that resource-efficiency improvements frequently generate economic benefits through increased productivity and product quality (Alrabiah & Hicks, 2025; André et al., 2024).

Based on field data, the additional productivity achieved by IMT generated substantial increases in revenue, with estimated gains exceeding IDR 27 million ha^{-1} per production season. The dual effect of higher production volume and improved quality suggests a relatively short payback period, making the technology attractive for adoption by salt farmers.

The findings are consistent with innovation-diffusion theory, which identifies economic advantage as a primary driver of technology adoption. Therefore, IMT offers a practical pathway for improving the competitiveness of Indonesia's community-based salt industry.

The relatively short investment payback period also increases the practical feasibility of technology adoption among small-scale salt farmers, who frequently face financial constraints when introducing production innovations. Therefore, economic feasibility should be considered alongside technical performance when evaluating pathways toward industrial salt upgrading.

Industrial Sustainability and Policy Implications

The benefits of IMT extend beyond farm-level productivity improvement and have broader implications for industrial sustainability and national salt development. By simultaneously improving resource efficiency, product quality, and production performance, the technology contributes to more sustainable utilization of coastal production resources.

Improving the quality of domestically produced salt is strategically important because dependence on imported industrial salt remains a persistent challenge in Indonesia. The ability of IMT to consistently achieve industrial-grade quality suggests that technological upgrading can help narrow the gap between community-produced salt and industrial raw-material requirements (B. T. I. Ali et al., 2025; Amir et al., 2024).

From a circular-economy perspective, elimination of brine losses represents a resource-retention strategy that maximizes utilization of existing material flows. This approach aligns closely with contemporary sustainability frameworks emphasizing resource conservation, productivity improvement, and waste prevention (Alrabiah & Hicks, 2025; Amadghous et al., 2025).

Overall, the results indicate that IMT supports Cleaner Production, Resource Efficiency, and sustainable industrial development objectives. The technology therefore provides a practical model for transforming community-based salt production into a more productive, competitive, and sustainable industrial supply system in tropical coastal regions.

From a policy perspective, the findings indicate that technological upgrading at the primary production stage may represent one of the most cost-effective strategies for reducing Indonesia's dependence on imported industrial salt. Integrating IMT within national salt-development programs, technical extension services, and industrial standardization initiatives could accelerate the transition toward a more productive, competitive, and sustainable domestic salt industry.

It should also be noted that the present study combines historical field observations with contemporary scientific interpretation. While the experimental implementation was initiated in 2011, the engineering mechanisms of IMT remain directly applicable to current industrial salt production because the underlying crystallization processes and resource-conservation principles are independent of the observation period. Consequently, recent literature is employed to interpret the findings within the current scientific context rather than to update the original experimental data.

Study Limitations and Future Research

This study has several limitations that should be considered when interpreting the findings. First, the primary field experiment was conducted during the 2011 production season, although the operational performance of Insulator Media Technology (IMT) was subsequently validated through multi-season implementation in Madura (2011–2014) and Demak (2013–2019). The engineering mechanisms underlying the technology remain unchanged;

however, future studies involving contemporary experimental datasets would further strengthen external validity.

Second, laboratory evaluation of NaCl purity was based on three paired harvest-age observations, resulting in limited statistical power for inferential analysis. Accordingly, statistical results should be interpreted together with the operational consistency observed across multiple performance indicators and long-term field implementation.

Third, the present study focused primarily on operational, production, and resource-efficiency performance. Direct measurements of environmental parameters, including soil salinity, groundwater quality, greenhouse gas emissions, and broader ecological impacts, were beyond the scope of this investigation. Consequently, the environmental benefits discussed in this study should be interpreted as plausible mechanisms resulting from the elimination of brine seepage rather than directly verified environmental outcomes.

Future research should expand the evaluation through multi-site experimental validation, life cycle assessment, carbon footprint analysis, long-term environmental monitoring, economic sensitivity analysis, and broader assessment of technology adoption under different climatic and socio-economic conditions.

CONCLUSION

This study demonstrates that Insulator Media Technology (IMT) substantially improves the operational performance of community-based solar salt production through the application of Cleaner Production and Resource Efficiency principles. The technology enhanced productivity, increased industrial salt quality, eliminated brine seepage losses, and improved resource utilization efficiency, thereby enabling more sustainable production of industrial-grade salt under actual field conditions.

Beyond demonstrating the technical performance of IMT, this study contributes to the Cleaner Production and Resource Efficiency literature by proposing an integrated assessment framework together with five operational Resource Efficiency indicators specifically designed for community-based solar saltworks. The proposed framework provides a practical basis for technology benchmarking, performance evaluation, and future development of sustainable industrial salt production systems.

From a policy perspective, the findings support technological upgrading as a strategic pathway for strengthening Indonesia's industrial salt self-sufficiency. The integrated assessment framework may also assist policymakers in evaluating future salt-production technologies using operational, environmental, and resource-efficiency perspectives within a unified evaluation approach.

Future research should extend the present study through multi-site validation across different salt-producing regions, life cycle assessment (LCA), carbon footprint analysis, long-term monitoring of soil and groundwater quality, economic sensitivity analysis under different market conditions, and broader investigation of technology adoption by community salt farmers. Such studies would further strengthen understanding of the environmental, economic, and industrial implications of sustainable salt-production technologies.

Overall, the findings demonstrate that relatively simple engineering innovations can generate substantial improvements in productivity, resource efficiency, product quality, and industrial competitiveness, thereby providing a practical contribution toward more sustainable industrial salt production in tropical coastal regions.

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