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Technology gap ratio decomposition in smallholder solar saltworks in Indonesia using meta-frontier data envelopment analysis (MetaDEA)

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A B S T R A C T

The increasing population in Indonesia results in the rising demand for consumer goods, including salt. Meanwhile, salt production in Indonesia remains traditional, using direct methods by evaporating seawater in open ponds near the coast, producing a final product called “solar salt”. This process depends on sunlight, air, weather, and seasonal climate conditions. This research aims to analyze the technical, technological, and managerial disparities among traditional solar salt farming businesses operated by local communities across regions in Madura Island—the foremost solar salt-producing region in Indonesia. This study employs primary data collected through surveys conducted during the production season in 2023/2024 in three regencies in Madura: Pamekasan, Sampang, and Sumenep. The structured questionnaires captured the input and output data. Meta-frontier Data Envelopment Analysis (meta-DEA) was applied to assess the technical efficiency of conventional solar salt productions across the research regions. The efficiency analysis revealed that, with the current production methods, solar salt farmers achieved an efficiency rate of 46.98%, with an average technical efficiency of 80.83%. This result shows that the decision-making units (DMUs) can enhance their technical efficiency by 19.07%. Meanwhile, the technology gap ratio (TGR) analysis indicates that Sumenep Regency has the highest TGR value, nearing the threshold of 1, suggesting a relatively low technology gap in this regency. The meta-DEA decomposition indicates that the determinant of the average meta-technical inefficiency among solar salt farmers is the technological disparities, with average technological gap inefficiency (TGI) values surpassing managerial gap inefficiency (MGI) values. Conversely, Sumenep Regency has a larger MGI than TGI value, implying that solar salt farmers in Sumenep possess lower managerial decision-making skills than in other regions. The findings suggest the need to enhance the adoption of the latest production technology innovations to address technological gaps in the research locations.

1. Introduction

According to the US Geological Survey (2018), global salt production reached 288 million tons in 2017. Over one-third of this production is through seawater evaporation, which is commonly referred to as “solar salt,” another third is through mining salt deposits, both on the surface and underground, and the remainder is through brine solution mining (Sedivy, 2009; Crisman *et al*., 2009). Salt is a valuable commodity used as a raw material and as an auxiliary substance in industry, with the latter taking up about 60 percent of total global salt production (Sedivy, 2009). In Indonesia, the fast industrial expansion constitutes 82.28 percent of total salt consumption in the country (Indonesia’s Ministry of Industry, 2018). Indonesia is endowed with abundant natural resources, with 70 percent of its territory being ocean. The country’s coastline spans 95,181 kilometers, the second-longest in the world, but not all areas are suitable for solar salt production. In fact, only

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34,731 hectares of these areas are suitable for solar saltworks (Department of Maritime Affairs and Fisheries, 2018) because the land needs to meet specific conditions, i.e., suitable weather and climate, high evaporation rates, sufficient wind speed, and high air temperatures (Zeno, 2009; Sovinc, 2009; Dardir & Wali, 2009; Prihantini *et al*., 2017a,b; Sarker et al., 2016).

In terms of productivity, the data from the Department of Maritime Affairs and Fisheries (2018) indicates that the national production of solar salt in 2017 reached 1.02 million tons, fulfilling merely 40 percent of the national salt demand. Traditional solar salt production is highly dependent on weather and climate conditions, so when the dry season is brief, the production will be adversely impacted. Historically, solar salt production in Indonesia hit a peak in 2012, allowing the country to achieve self-sufficiency. This achievement serves as a testament to the success of the People's Salt Business Empowerment (*Pemberdayaan Usaha Garam Rakyat* - PUGAR) launched on 29 December 2010, aimed at enhancing national solar salt production and the welfare of solar salt farmers (Ariyani et al., 2020a; Prihantini et al., 2016). However, this success was short-lived, and imports were needed afterward to meet the industrial salt demands. In 2013 and 2016, Indonesia experienced La Niña, a weather condition wherein winds transport moisture to the Indonesian region, resulting in heavy rainfall during the dry season (Davis, 2009). Solar salt production declined in 2013 with a further downturn in 2016 as the conditions of low rainfall and a certain level of dryness were not met. Table 1 shows the data on solar salt production, land area, and traditional solar salt productivity in Indonesia from 2011 to 2017.

Table 1

Solar Salt Production, Land Area, and Productivity in Indonesia from 2012 to 2017

Indicators	Years					
	2012	2013	2014	2015	2016	2017
Production (in Tons)	2,473,716.00	1,163,608.00	2,502,891.00	2,915,461.00	118,055.00	1,020,925.00
Land Area (in Hectares)	22,632.00	25,098.00	23,422.00	25,830.00	12,560.00	20,821.00
Productivity (in Tons/ Hectare)	91.70	39.62	89.72	112.87	9.40	49,03
Duration of Dry Season (in Months)	5	2	5	6	< 2	5

Source: Department of Maritime Affairs and Fisheries (2018)

The production of solar salt involves the transfer of seawater between salt ponds, which are divided into three main parts: (1) *bozem*, which is a seawater-holding pond with low salt content, commonly referred to as young water, (2) *peminihan*, which is an evaporation pond, and (3) a crystallization pond or a salt table, where salt is formed (Ariyani et al., 2020b).

Madura Island is part of East Java Province and is known as the salt island due to the widespread presence of solar salt ponds across all regencies, namely Bangkalan, Sampang, Pamekasan, and Sumenep. Madura's solar salt production reached 280,971.65 tons in 2017, covering an area of 5,415.19 hectares. This production accounted for 75% of the total solar salt production in East Java Province and 25% nationally. For more detail, the centers of traditional solar salt production in East Java Province are depicted in Fig. 1. Such productivity indicates the level of technical efficiency in solar salt farming, i.e., the maximum output that can be harvested per unit of the available input. Research conducted by Balde *et al*. (2014) reveals that the average technical efficiency of solar salt farming in Guinea is 27 percent, with the highest efficiency level at 92% and the lowest at 0%. This value is low compared to the averages in Indonesia. For example, solar salt farmers in Indramayu achieve an average technical efficiency of 80% (Aligori, 2013), and those in Sampang Regency achieve an average of 77.5% (Amami & Ihsannudin, 2016).

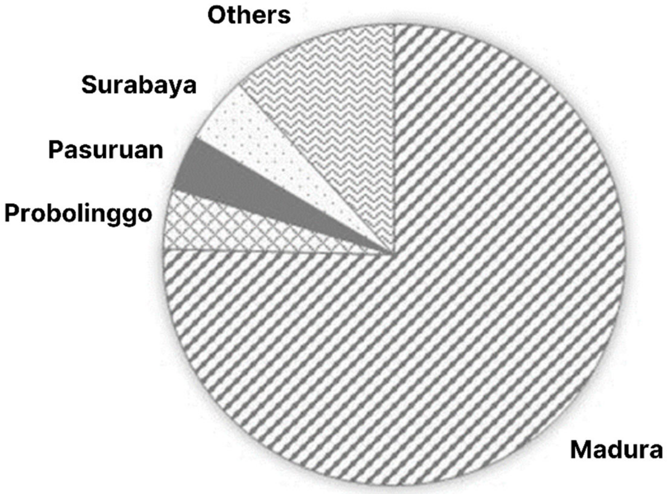

Fig. 1. The Centers of Traditional Solar Salt Production in East Java Province in 2017
Source: Department of Maritime Affairs and Fisheries (2018)

The aforementioned research and the government's data demonstrate that solar salt farming in Indonesia is relatively efficient. Research by Osborne and Trueblood (2006) suggests that a benchmark of efficiency is 70%. Coelli *et al.* (2005) agree that this value represents the minimum threshold of efficiency. This technical efficiency is positively correlated to the productivity of traditional solar saltworks—the higher the efficiency, the higher the productivity (Banker et al., 1984; O'Donnell et al., 2008; Hanani et al., 2023).

Aside from technical efficiency, technological and managerial capabilities are also determinants of productivity. However, to date, there is only limited research in the context of Indonesian solar salt farming that simultaneously encompasses technical efficiency levels, Technological Gap Inefficiency (TGI), and Managerial Gap Inefficiency (MGI). Thus, using meta-DEA, this research aims to fill the gap by examining variations in technical efficiency levels, technology, and management in traditional solar salt farming across three sites in Madura Island, East Java, Indonesia.

2. Methods

2.1 Research Data

The samples in this study were farmers in specific solar salt production centers in Madura Island, East Java Province, selected through multistage sampling. These centers contribute 25% of the national solar salt production. First, centers in Pamekasan, Sampang, and Sumenep Regencies were selected for their significant production, the harvested land area, and productivity level. Next, a district was chosen from each regency. Then, four central villages were selected from each district. Finally, farmers were selected from a total of 12 villages, resulting in a total of 215 farmers as samples for this study. The primary data were gathered through surveys conducted during the solar salt production in 2023, exactly on September until December 2023.

2.2 Data Analysis

This study focuses solely on analyzing technical efficiency. The meta-DEA assessment does not involve computing average (mean) values but instead evaluates the efficiency of input utilization. The inputs include land area, harvesting frequency in one season, land management, water, labor, and diesel fuel. The output variable is the quantity of solar salt production. The DEA efficiency approach can be considered parametric and non-parametric. Ramanathan (2003) and Hanani *et al.* (2023) asserted that the DEA model consists of several inputs and outputs, which are linearly aggregated using weighting. As a result, inputs used by farmers are represented as the linear sum of all inputs' weights. The formulation is detailed in Eqs. (1-3).

$$Aggregated\ input = \sum_{i=1}^{I} u_i x_i \tag{1}$$

$$Aggregated\ output = \sum_{j=1}^{J} v_j y_j \tag{2}$$

$$Efficiency = \frac{\sum_{i=1}^{I} u_i x_i}{\sum_{j=1}^{J} v_j y_j} \tag{3}$$

This model was calculated by utilizing Data Envelopment Analysis Program (DEAP) software version 2.1. Meta-frontier derived from the DEA method was computed using Equation 4.

$$\begin{aligned} & max_{\emptyset_{it}\lambda_{it}} \quad \emptyset_{it} \\ & -\emptyset_{it} b_{it} + B_{it}\lambda_{it} \geq 0 \\ & a_{it} - A_{it}\lambda_{it} \geq 0 \\ & \lambda_{it} \geq 0 \end{aligned} \tag{4}$$

where: b_{it} is an $M \times 1$ vector representing the output quantity of decision-making units (DMUs) i-th at period t; a_{it} is an $N \times 1$ vector representing the input quantity of economic activity units (EAUs) i-th at period t; B_{it} is an $M \times L$ vector representing the output quantity of all EAUs (where L is total EAUs); A_{it} is an $N \times L$ vector representing the input quantity of all EAUs; λ_{it} is considered the weighting vector; while Φ_{it} is a scalar. This research uses the DEA method and meta-frontier analysis to examine data from three research locations. Each location possesses distinct characteristics identified through meta-frontier analysis. Assuming the input is x and the output is y, the technologies utilized by producers are formulated in Eq. (5).

$$T = \{(X, y): X \geq 0, y \geq 0\} \tag{5}$$

Regarding the meta-technology set, with the use of input and output, Equation 6 formulates the representation of the output set in the meta-frontier.

$$P\ (X) = \{y: (X, y) \in T\} \tag{6}$$

The input production conversion into output within the technological framework establishes the maximum production limits or boundaries. If factors affecting production, such as distinctive characteristics of the locations, are present, the production efficiency from the meta-frontier analysis can differ across regions. A lower efficiency in one group compared to another corresponds to a lower efficiency value on the meta-frontier. Eq. (7)corresponds to the gap between the meta-frontier and the performance of the solar salt farmers in this research.

$$D\ (X, y) = inf_{\theta}\ \{\theta > 0; (X) \epsilon\ P\ (X)\} \tag{7}$$

The production range, as stated in Eq(7), *D*(*X*,*y*) shows the input set utilized by producers that will generate maximum output in the observation ((*X*,*y*)*i*), deemed technically efficient at the meta-frontier if *D*(*X*,*y*) = 1. This implies that in the absence of distance, the outcome ratio to the frontier remains constant (*D*(*X*, *y*) equals 1).
If *K* represents a region, technology established in a certain area is defined as in Eq. (8).

$$T^K = \{(X, y): X\ \geq 0, y \geq 0\} \tag{8}$$

Meanwhile, Eq. (9) and Eq. (10) delineate the relevant technology and its corresponding output, along with the production distance for each area.

$$P^K(X) = \{y: (X, y)\ \epsilon\ T^K \tag{9}$$

$$D^K\ (X, y) =\ inf_{\theta}\ \{\theta > 0; (X) \epsilon\ P^K\ (X)\} \tag{10}$$

We assume that Group Technical Efficiency (GTE) and Technical Meta-Efficiency (TME) signify technical efficiency as shown in the meta-frontier, whereas meta-TE indicates the technical efficiency in every region (group frontier) or region-TE (see Fig. 2). In this context, analysis of the group frontier and meta-frontier can result in the Technology Gap Ratio (TGR) or Meta-Technology Ratio (MTR), as outlined in Eq. (11).

$$0\ \leq MTR\ \leq \frac{MEE}{GEE} \leq 1 \tag{11}$$

Meta-Technology Ratio (MTR) approaching 1 indicates a reduction in technological diversity, resulting in the group frontier becoming nearer to the meta-frontier, and vice versa (Chiu et al., 2012; Hanani et al., 2023).

Meta-Technology Ratio (MTR) also offers insights into the technological distinctions among decision-making units (DMUs) in diverse groups within the meta-frontier. This shows that the inefficiency is affected by factors beyond the technical aspects of inputs and outputs, such as a specific location’s characteristics. Chiu et al. (2012) and Chen and Jia (2017) advocate for breaking down DMU inefficiency in the meta-frontier analysis. Decomposing inefficiency in the meta-frontier results in disparities in Managerial Gap Inefficiency (MGI) and Technological Gap Inefficiency (TGI), as formulated in Eq. (12) and Eq. (13).

$$TGI = GEE\ (1 - MTR) \tag{12}$$

$$GMI = (1 - GEE) \tag{13}$$

Technological Gap Inefficiency (TGI) reveals the degree of inefficiency within a decision-making unit (DMU) relative to its group and its efficiency at the meta-frontier. A smaller TGI value shows that a DMU is closer to the meta-frontier. If a DMU's efficiency within its group diverges further from group-frontier environmental efficiency (GEE) and surpasses meta-frontier environmental efficiency (MEE), a DMU is considered to be increasingly inefficient. Additionally, managerial gap inefficiency (MGI) decomposes managerial-related inefficiency, reflecting the DMU's capacity to achieve lower input productivity than expected within its group. This inefficiency is often attributed to managerial deficiencies or production shortcomings in a DMU.

Finally, the ultimate metric combines managerial and technological shortcomings and is termed environmental inefficiency, as expressed in Eq. (14).

$$MTI = TGI + MGI \tag{14}$$

MTI stands for environmental inefficiency, TGI for technological inefficiency, and MGI for managerial inefficiency.

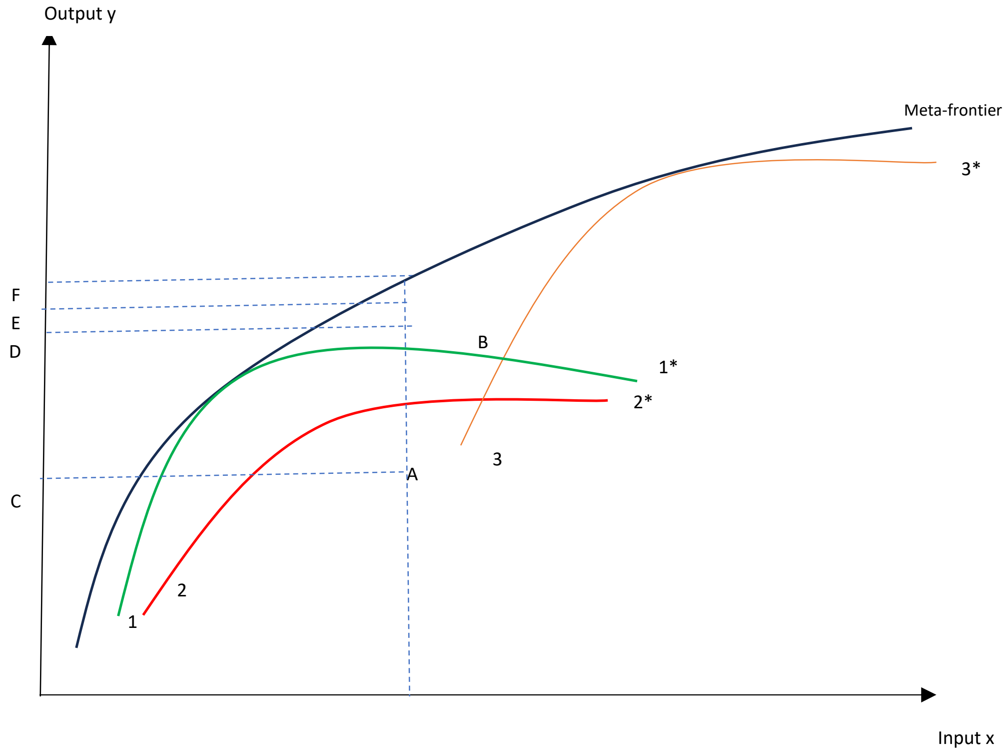

Fig. 2. Meta-frontier and group frontier

*Note: * = Last point of curve *i*
Source: O'Donnell *et al.* (2008)

3. Results and Discussion

3.1 Descriptive Statistics

This section presents the descriptive statistics of the variables applied in this research, encompassing the measurement, mean values, and standard deviations. As shown in Table 2, average solar salt production amounts to 94 tons per season, with an average land area of 10,179 m^2 or 1.0179 hectares. The inputs utilized comprise solar salt fields, harvest frequency per season, land management, water, labor, and diesel fuel. Concerning land management, the land area is categorized into three: water-storage ponds (referred to as *bozem*), saltwater evaporation ponds, and salt crystallization ponds or tables. The percentage of each pond is computed relative to the total land area. The average harvest frequency per season is 13.20 times. The average percentage of *bozem* ponds is 16.79%, saltwater evaporation ponds is 54.98%, and crystallization tables is 28.23%. On average, solar salt farmers use 4284.84 cm^3 of water per season. The average labor per season is 133.71 workdays, while the average diesel fuel consumption amounts to 306.48 liters per season.

Table 2
Descriptive Statistics

Variables	Measurement	Mean	Std. Dev.
Production	The amount of solar salt produced per season (in tons)	94.97	52.359
Area	Land area used for production (in m^2)	1,0179.30	4,947.908
Harvesting Frequency	Number of harvests per season	13.20	3.298
Percentage of Seawater-Holding Ponds (*Bozem*)	Percentage of seawater-holding pond area to total area	16.79	12.067
Percentage of Evaporation Ponds	Percentage of evaporation pond area to total area	54.98	14.7119
Percentage of Salt Crystallization Table	Percentage of salt crystallization table area to total area	28.23	8.791
Water Volume	The volume of water used (in m^3)	4,282.84	2,950.958
Labor	Labor in working days	133.71	89.376
Diesel Fuel	Amount of diesel fuel used during the production season (in liters)	306.48	214.4322

3.2 Analyses of Technical Efficiency and Technological, Managerial, and Environmental Gaps among Solar Salt Production Regions

Technical efficiency differs across regions (research locations) due to differences in input capacities, which result in varying output levels. Individual examinations of research locations often show that each employs different technologies depending on the environmental factors, particularly resources, and climatic conditions (Rahman *et al.*, 2019). Therefore, aggregating regional technical efficiency becomes challenging (Suhendra, 2016; Syafrial et al., 2021). Variations in production input environments (e.g., resources and technology) make the technical efficiency values fail to capture disparities among regions. In this case, meta-analysis can be an indispensable alternative for assessing technical efficiency across regions. Table 3 displays the comparisons in technical efficiency across the research locations based on the meta-analysis and the mean values of regional/group technical efficiency (GTE), technical meta-efficiency (TME), and technology gap ratios (TGR). Meanwhile, Meta-DEA was employed to scrutinize efficiency trends among solar salt production centers. The evaluation of 215 farmer respondents indicates that the average technical meta-efficiency across three research locations was 0.808. The result implies that average farmers could save inputs at 19.2% without jeopardizing their outputs. In line with the research by Susanto (2015), traditional salt farmers tend to overuse inputs. Based on the technical meta-efficiency values, the finding by Susanto (2015) shows that there were 37 fully efficient traditional salt farmers, constituting 17.21% of the total sample. Meanwhile, in this study, 35 farmers in Pamekasan Regency (46.67%), 41 in Sumenep Regency (51.25%), and 25 in Sampang Regency (41.67%) achieved full efficiency. These fully efficient farmers could serve as role models or mentors for other farmers striving to attain optimal efficiency. Notably, other farmers scored low in their technical efficiency, namely between 0.359 and 0.999, which shows considerable potency to minimize production inputs up to 82.79%.

Table 3
Comparisons of Technical Efficiency among the Research Locations

TE value	Pamekasan		Sumenep		Sampang	
	Number	%	Number	%	Number	%
1.00	35	46.67	41	51.25	25	41.67
0.836-0.999	6	8.00	4	5.00	4	6.67
0.677-0.835	5	6.67	13	16.25	16	26.67
0.518-0.676	13	17.33	11	13.75	5	8.33
0.359-0.517	16	21.33	11	13.75	10	16.67
Mean	0.799		0.828		0.798	
Std. Deviation	0.243		0,211		0,209	
Mean of All DMUs					0.808	
Std. Deviation					0.013	

3.2.1 *Explanation of GTE/GEE*

Table 4 presents the mean values in the meta-TE across three research locations. Sumenep Regency stands out as the most efficient, while Pamekasan and Sampang Regencies show almost identical levels of technical efficiency. The average technical efficiency of farmers across the research locations is lower than the regional or group levels. The difference arises because the analysis on meta-technical efficiency utilizes data from the entire sample in all locations. Farmers with the highest technical efficiency at the meta-level can be models for the others. Meanwhile, technical efficiency at a group level only indicates the best technical efficiency within that group.

Table 4
Mean and Standard Deviation of Meta Technical Efficiency, Region Technical Efficiency, and Technology Gap Ratio

Locations		TE Region/GEE	TEMeta/MEE	TGR=MTR
Mean	Pamekasan	0.915	0.799	0.872
	Sumenep	0.899	0.828	0.984
	Sampang	0.921	0.798	0.860
Std. Deviation	Pamekasan	0.170	0.243	0.199
	Sumenep	0.189	0.211	0.439
	Sampang	0.136	0.209	0.159

Group environmental efficiency (GEE) represents the group technical efficiency (GTE) value. Sampang Regency scores the highest in GEE, while Sumenep Regency scores the lowest. Pamekasan and Sampang have nearly identical GEE values, nearing the GTE/GEE threshold (approaching 1.00). These findings suggest that the majority of DMUs in Sampang and Pamekasan employ similar solar salt production practices, resulting in relatively uniform average efficiency scores approaching the GEE threshold. Sumenep Regency's GEE is the lowest among the two other regencies. This indicates greater heterogeneity in input consumption and/or output in this region. This variability can be attributed primarily to farmer decision-making. The potential minimization of inputs in this region is around 11%, which can be achieved with adjustments in managerial decisions and input combinations (Lin & Zhao, 2016; Ullah *et al*., 2019).

3.2.2 *Explanation of MEE/MTE*

Meta-frontier environmental efficiency (MEE) or meta-technology efficiency (MTE) indicates the technical efficiency value across all DMUs. Differences in MEE/MTE scores between regions reflect disparities in input consumption among regions (Medal-Bartual *et al*., 2014). A significantly lower MTE of a region may be due to severe biophysical constraints. To address these limitations, farmers in this region increase (1) fuel consumption during land preparation and crop cultivation, such as for mechanical weeding, irrigation, and mechanized chemical implementation, and (2) quantities of pesticides and urea of more than average (Ullah *et al*., 2019; Hanani *et al*., 2023). Sampang and Pamekasan have nearly identical MEE values (0.798 and 0.799), both of which are lower than the MEE value of Sumenep Regency (0.828). This suggests that the input consumption or utilization in these two regencies is lower or less efficient compared to Sumenep Regency, which means that Sumenep Regency manages input production more efficiently than the other two regencies.

3.2.3 Explanation of TGR/MTR

The technology gap ratio (TGR) represents the technology disparity value within a DMU. TGR can also reflect the meta-technology efficiency ratio (MTR). The TGR value is obtained by comparing MTE to GEE. Differences in the TGR system indicate the scale variability of different attributes across diverse production systems (Wang et al., 2013). Assessment and comparison of the efficiency across all productions under the meta-frontier can determine the strategies to optimize efficiency, for example, by using the most advanced production technology available in the country. The research findings suggest that while the average TGR values from the three research locations display relatively minor differences, they still indicate disparities. This suggests that the productions utilize different technologies and varying resource scales (Lin & Du, 2013; Ullah *et al*., 2019; Anam & Prihatini, 2022).

Upon examining the TGR values, these three regencies can be considered technically efficient, but the Sumenep Regency stands out as the most efficient. Sumenep scores the highest in TGR, exceeding 90, which also indicates that the technology gap in Sumenep Regency is the lowest (approaching 1).

TGR merely reflects performance heterogeneity among different production systems or methods, but it does not directly identify the sources of managerial and technological inefficiency (MTI). Hence, policymakers need to comprehend the origins or causes of inefficiency to formulate sound policies specific to areas requiring enhancement. Consequently, MTI needs to be decomposed into TGI and MGI. These indicators can pinpoint the factors contributing to inefficiency, thus informing the strategy to enhance MTI (Ullah et al., 2019).

Additional meta-DEA analysis was carried out to investigate environmental inefficiencies in each region (see Table 5). This involved decomposing the group technology gap relative to the meta (TGI) as well as the managerial gap among the regions relative to the meta (MGI). Therefore, inefficiency in the environment is known as managerial and technology inefficiency (MTI). TGI indicates technological gap inefficiency resulting from the technological resources used, whereas MGI signifies managerial gap inefficiency stemming from managerial skills.

Table 5
Levels of Technology Gap Inefficiency (TGI), Managerial Gap Inefficiency (MGI), and Managerial and Technological Inefficiency (MTI) Across Three Research Locations

Regencies	**TGI**			**MGI**			**MTI**		
	Mean	**Std. Dev.**	**%**	**Mean**	**Std. Dev.**	**%**	**Mean**	**Std. Dev.**	**%**
Pamekasan	0.119	0.197	58.62	0.085	0.170	41.38	0.203	0.242	100
Sumenep	0.071	0.253	41.28	0.1009	0.189	58.72	0.172	0.211	100
Sampang	0.123	0.149	60.89	0.079	0.136	39.11	0.202	0.209	100
Total	**0.104**	**0.023**	**53.89**	**0.088**	**0.009**	**46.11**	**0.193**	**0.015**	100

Sampang and Pamekasan Regencies exhibit higher TGI values compared to MGI values (TGI > MGI). This indicates that managerial and technological inefficiency (MTI) in Sampang and Pamekasan is primarily attributed to suboptimal resource utilization. These values may also suggest a scenario where production practices and methods employed by farmers do not support efficient resource management. According to Ullah *et al.* (2019), higher TGI and lower MGI scores imply that farmers within the region compete with each other in terms of resource utilization or production inputs. For instance, land and water are the main inputs for solar salt production, which farmers in different regions do not have to compete for (Ullah *et al*., 2019; Alvarez *et al.,* 2020; Hanani *et al.,* 2023).

In the interviews with three Heads of the Cultivation Section at the Maritime Affairs and Fisheries Department, all unanimously agreed that Sampang Regency has reached its land capacity limit. This implies that there are no more potential lands available for the development of traditional solar salt production areas—a situation similarly observed in Pamekasan Regency. The most promising area for expanding traditional solar salt production is Sumenep Regency, as it boasts larger potential solar salt lands, including the island areas. However, the main challenge lies in transportation to the solar salt production areas, particularly in the island area, which requires higher costs. Additionally, these areas have distinct characteristics, such as wind patterns, soil, and water, that are different from the mainland, which will affect solar salt production capability.

Furthermore, Sumenep Regency has MGI > TGI. This indicates that managerial and technological inefficiency (MTI) in Sumenep is primarily attributed to managerial factors. This means that farmers in this region have not capitalized on the resources and services offered by factories or governmental entities, which may be due to the small, medium, and large farming scales. Furthermore, socioeconomic factors could affect their access to machinery and other services in the factories, as shown by Ullah *et al.* (2019). Introducing a mechanism through which they can avail themselves of these services may help improve their performance.

Sumenep Regency has the highest MGI value, indicating lower managerial capabilities and decision-making compared to the other two regencies, such as managerial skills in allocating production inputs, decisions on salt sales, sources of business capital (loans or self-capital), participation decisions in profit-sharing schemes, and other decisions related to technical efficiency. According to Ullah *et al*. (2019) and Hanani *et al*. (2023), one of the reasons for this low capability is the level of education and experience among solar salt farmers. Sumenep Regency is known as one of the oldest solar salt producers in Indonesia and PT Garam (Indonesia's state-owned enterprise engaging in salt production) is located in this regency. On average, solar salt farmers in this regency have relatively low education levels, mostly only completing elementary school. However, they have a lot of experience as salt farming is often a generational occupation. Unfortunately, this also implies that they may use outdated production methods and practices, for example, traditional production methods. As such, their managerial capabilities and skills do not improve as much as their technical efficiencies.

In Sumenep, managerial inefficiency accounts for over 50% of the overall inefficiency. This suggests that while farmers have relatively favorable resources, they still need to improve their agriculture management practices. Nevertheless, addressing technological inefficiency is also essential, as it contributes to around 41% of MTI in Sumenep Regency. Overall, the average MGI values are lower than the average TGI values ($0.087 < 0.105$). This implies that managerial and technological inefficiency (MTI) in the three regencies under study is predominantly caused by MGI or managerial inefficiency. In addition, DMUs in all these regencies, on average, have not been able to utilize natural resources. One of the causes is the solar salt production methods or technologies that are not compatible with resource utilization or production inputs.

Interestingly, field data (gathered through interviews with the Maritime Affairs and Fisheries Department) indicates that nearly 80–85% of solar salt farmers have adopted the latest innovation, i.e., geo-isolator technology. However, the analysis results reveal that the TGI exceeds the MGI. This means that the adoption of cutting-edge technology remains a source of technical inefficiency in traditional solar salt production. PT Garam and related stakeholders may have conducted socialization regarding the latest production methods and technology. However, farmers have not fully implemented this technology according to the recommendations. They may even have reverted to the old production systems.

4. Conclusions

Based on the efficiency analysis, more than 50% of the decision-making units (DMUs) in Sumenep Regency have achieved perfect efficiency ($TE = 1$), while the other two regencies have not reached 50% of their DMUs. Furthermore, the average technical efficiency of DMUs across the three research locations is 80.83%. This suggests that these DMUs can still improve their technical efficiency by up to 19.17%.

The average TGR values exhibit low variability, but differences remain. This implies that the three research locations employ distinct production practices, methods, and resource availabilities. However, Sumenep Regency boasts the highest TGR value among them, approaching the threshold of 1. This indicates a relatively low technology gap in this region.

The TGR decomposition analysis indicates that, overall, the average TGI value exceeds the MGI ($TGI > MGI$). This suggests that the primary factor contributing to managerial and technological inefficiency (MTI) is technological inefficiency. The same applies to two research locations, namely Sampang and Pamekasan, where the current production technology has not yet fully utilized the available natural resources optimally. In contrast, in Sumenep Regency, the MGI value exceeds the TGI, which indicates that the cause of managerial and technological inefficiency (MTI) is managerial inefficiency. Some of these factors are related to the low capabilities and skills of solar salt farmers in making decisions regarding the allocation of production inputs, solar salt sales decisions, business capital sources, profit-sharing pattern decisions, land and water management, and other managerial factors.

It is expected that the government and related stakeholders can intervene to address this technological inefficiency, such as increasing the adoption of the latest technology. Based on the interviews with the Department of Maritime Affairs and Fisheries, solar salt farmers in Madura Island sometimes hesitate to adopt the latest production technology. As a result, they lag behind other solar salt farmers in Indonesia. Additionally, the government, through the Maritime Affairs and Fisheries Department and PT Garam, should continue offering support, guidance, and counseling on sustainable solar salt production to achieve optimal outcomes. Farmers may still prefer improvising techniques and revert to old practices. Consequently, their production results are suboptimal, including in the management of natural resources or production inputs.

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