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Article

# Technical and Allocative Efficiency of Garlic Production in Karanganyar Regency: A Data Envelopment Analysis (DEA) Approach

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**ABSTRACT**

Garlic is one of Indonesia's strategic horticultural commodities however, domestic production remains insufficient to meet national demand, resulting in continued dependence on imports. Improving the efficiency of garlic farming is therefore essential to enhance domestic production and reduce import dependency.This study attempts to analyze the technical and allocative efficiency of garlic farming production in Karanganyar Regency in response to the still suboptimal use of production inputs by farmers. The study employs a quantitative approach with a sample of 110 garlic farmers in Karanganyar Regency. Technical and allocative efficiency are analyzed using Data Envelopment Analysis (DEA), while the determinant of technical efficiency are examined using a Tobit regression model. The findings show that the average level of technical efficiency falls into the low category ($0.375 \leq x < 0.583$), whereas allocative efficiency is in the moderate category (0.585–0.792). The Tobit regression results show that education and farmer group participation have a positive effect on technical efficiency, while the frequency of extension participation and rainfall risk severity have a negative effect on technical efficiency. These findings suggest the need for strategies focused on strengthening farmer education, enhancing the role of farmer groups, improving the effectiveness of extension services, and developing adaptation measures to mitigate rainfall-related production risks in garlic farming.

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## INTRODUCTION

The agricultural sector plays a vital role in national development by contributing to food supply, employment generation, and economic growth. Agricultural activities also support household income and generate foreign exchange through international trade in agricultural commodities (Ferreira et al., 2022).

The potential of horticultural crops plays a pivotal role in agricultural development in maintaining food balance. Garlic is a horticultural commodity with high economic value due to its extensive utilization and strong market demand worldwide, with global production exceeding 28 million tons in 2020 (Martín et al., 2026). This commodity is widely utilized for culinary purposes and holds significant value due to its therapeutic and pharmacological properties, with a distinctive flavor resulting from complex biochemical reactions (Ezeorba et al., 2022) . Owing to its extensive utilization in both food and health-related applications, garlic remains an important agricultural commodity in many countries (Verma et al., 2023).

Indonesia still depends on garlic imports because domestic production is insufficient to meet demand (Kiloes et al., 2024). More than 95% of Indonesia's garlic demand has been fulfilled through imports in recent years, creating challenges for the development and competitiveness of local garlic farming (Puspitasari et al., 2024). Despite efforts to increase domestic production, the contribution of garlic-producing regions remains uneven, with several provinces serving as the main production centers in Indonesia (Maharani et al., 2024).

In general, garlic production outside Java has increased at a growth rate of approximately 10.31%, while production in Java has grown at a higher rate of 14.17%. During 2019–2023, Central Java consistently recorded the highest garlic production in Indonesia, followed by West Nusa Tenggara. Central Java is an important garlic-producing region in Indonesia, with cultivation concentrated in highland areas. Environmental conditions, particularly temperature, play an important role in garlic growth and development (Azmi et al., 2022). Areas such as Temanggung, Magelang, Karanganyar, and Wonosobo possess fertile land and ideal altitudes ranging from approximately 800 to 1,200 meters above sea level. As one of the major garlic-producing districts in Central Java, Karanganyar Regency plays an important role in supporting domestic garlic production. Therefore, improving production performance and resource-use efficiency is essential to strengthen domestic garlic production and help reduce Indonesia's dependence on imports (Yusuf et al., 2025). Data on garlic production and harvested area in Central Java for the period 2020–2024 are presented in Table 1.

Table 1 shows that garlic harvested area and production in Indonesia experienced a declining trend after reaching their peak in 2020. This pattern indicates that increasing domestic garlic production remains a challenge despite government efforts to reduce import dependence and achieve self-sufficiency. Previous studies have reported that low market prices and limited marketing opportunities have discouraged farmers from continuing garlic cultivation (Azis et al., 2024). These conditions highlight the importance of improving farm-level production performance. In this context, evaluating the efficiency of resource utilization in garlic farming is essential to identify opportunities for increasing output without necessarily expanding cultivated land or production inputs (Feryanto et al., 2025).

Karanganyar Regency is one of the major garlic-producing regions in Indonesia and plays an important role in supporting domestic garlic supply. Although garlic production in the regency increased during 2020–2023, reaching 5,688.3 tons at its peak, higher production does not necessarily indicate efficient resource utilization. Garlic farming in Karanganyar Regency remains technically and economically inefficient, suggesting that opportunities still exist to improve production performance through better resource management (Ruzhani & Mushunje, 2025).

**Table 1**
**Harvested Area and Garlic Production in Central Java Province, 2020–2024**

| No. | Description | Year | | | | |
|---|---|---|---|---|---|---|
| | | 2020 | 2021 | 2022 | 2023 | 2024 |
| 1. | Harvested area (ha) | 5.137 | 3.875,4 | 3.026,6 | 3.920,4 | 4.127,8 |
| 2. | Production (ton) | 31.651,4 | 25.544,5 | 21.620 | 29.812 | 27.784 |

Source: Ministry of Agriculture Data, 2025

However, recent data indicate that production challenges persist. Based on data from BPS Karanganyar Regency (2024), garlic production declined substantially from 5,688.3 tons in 2023 to 2,446.8 tons in 2024. One possible explanation is the variation in farmers' input management practices. According to the Department of Agriculture of Karanganyar Regency (2024), the recommended basal fertilizer application consists of 10 tons/ha of organic manure and 375 kg/ha of chemical fertilizers. Nevertheless, field observations revealed that some farmers apply chemical fertilizers beyond recommended levels, whereas others rely primarily on organic manure due to limited financial resources. In the context of these fertilization practices, the use of organic fertilizers is considered a more environmentally friendly alternative and may potentially have a positive impact on farmers' subjective well-being (Dakhi et al., 2026). In addition to input management, climatic conditions such as the occurrence of a wet dry season may increase pest and disease pressure, thereby reducing garlic productivity (Anum et al., 2024) . These conditions highlight the importance of assessing technical and allocative efficiency to identify opportunities for improving the use of production inputs in garlic farming (Chekol et al., 2023).

Given the persistence of production constraints and the potential inefficiencies in input utilization, assessing the efficiency of garlic farming has become increasingly important. While previous studies have evaluated the efficiency of garlic farming in Karanganyar Regency, limited attention has been given to the broader set of factors that may influence technical efficiency, particularly institutional and climate-related factors. Therefore, this study evaluates the technical and allocative efficiency of garlic farming in Karanganyar Regency using Data Envelopment Analysis (DEA) and examines the determinants of technical efficiency through a Tobit regression model. By incorporating variables such as farmer group participation and rainfall risk severity, this study aims to provide a more comprehensive understanding of the factors affecting efficiency performance. The findings are expected to support policies aimed at improving farmer capacity, strengthening farmer group participation, optimizing input use, and mitigating production risks associated with climate variability.

## RESEARCH METHOD

This study employed a quantitative descriptive method. The research was conducted in Tawangmangu District and Jatiyoso District, Karanganyar Regency, Central Java, which are among the main garlic-producing areas in the regency. The research location was selected using a multi-stage sampling method. At the village level, purposive sampling was applied based on the criterion that the villages are major garlic-producing areas in Karanganyar Regency. According to information from the Agricultural Extension Center (BPP), Kalisoro and Blumbang Villages in Tawangmangu District and Wonorejo and Beruk Villages in Jatiyoso District were selected because they are the main garlic-producing villages in their respective districts. These villages were considered representative of garlic farming in Karanganyar Regency because garlic cultivation is widely practiced and contributes substantially to local garlic production.The total sample size in this study was 110 respondents, distributed proportionally. The sources used in primary and secondary data.The presentation of formulas and their explanations can be seen below:

The data analysis methods used in this study include the analysis of technical and allocative efficiency in garlic production, as well as the analysis of factors affecting technical efficiency of production. The technical and allocative efficiency of garlic farming production in Karanganyar Regency were analyzed using the Data Envelopment Analysis (DEA) approach with DEAP 2.1 software. This study applies the Variable Returns to Scale (VRS) assumption.

$$\text{Min } \theta,\lambda\ \theta$$

Subjek to:

$$St - yi + Y\lambda \geq 0;$$

$$\theta\, xi - X\lambda \geq 0;$$

$$N1'\ \lambda = 1$$

$$\lambda \geq 0 \qquad (1)$$

Where θ is the technical efficiency score, yi is the vector of garlic output, xi is the vector of garlic production inputs, Y is the total garlic production, $X_1$ is land area, $X_2$ is seed, $X_3$ is labor, $X_4$ is organic fertilizer, $X_5$ is chemical fertilizer, $X_6$ is pesticides, and $\lambda$ is a weight vector of size N×1.

$$min\lambda,xi \;\; Pixi$$

$$Subject\ to: -yi + Y\lambda \geq 0$$

$$\theta\ xi - X\lambda \geq 0,$$

$$N1\lambda = 1,$$

$$\lambda \geq 0 \qquad (2)$$

Furthermore, allocative efficiency is analyzed by incorporating input price variables, where Pi is the vector of input prices at time i, Y is the total garlic production, $Xi_1$ is the price per unit of land area (land rent/land tax), $Xi_2$ is the price of seed per kg, $Xi_3$ is the wage rate per labor day (HOK), $Xi_4$ is the price of organic fertilizer per kg, $Xi_5$ is the price of chemical fertilizer per kg, $Xi_6$ is the price of pesticides per liter, and $\lambda$ represents the weight of each DMU.

To identify determinant technical efficiency of garlic farming in Karanganyar Regency, a Tobit regression analysis was conducted using STATA version 17 software. The data to be analyzed contain a limited dependent variable (censored), Ordinary Least Squares (OLS) cannot be applied to estimate the regression coefficients. If OLS is used, it will result in biased and inconsistent parameter estimates. The Tobit regression model is specified as follows:

$$\text{TE} = \beta_0 + \beta_1 Z_1 + \beta_2 Z_2 + \beta_3 Z_3 + \beta_4 Z_4 + \beta_5 Z_5 + \beta_6 Z_6 + \varepsilon \qquad (3)$$

Where TE is the technical efficiency score obtained from the DEA analysis, Z1 is age (years), Z2 is education (years), Z3 is the frequency of participation in extension activities (dummy), where 1 = participated and 0 = never participated, Z4 is rainfall risk severity (dummy), where 1 = high and 0 = low, Z5 is participation in farmer groups (dummy), where 1 = yes and 0 = no, Z6 is land ownership status (dummy), where 1 = owned land and 0 = non-owned (rented), ε is the error term, and β represents the estimated parameters.

## RESULTS AND DISCUSSION

### Technical Efficiency

Technical efficiency in production is related to the ability of farmers, as Decision Making Units (DMUs), to generate output using a given set of inputs. Technically efficient farmers are able to achieve higher yields using the same amounts of seed, labor, fertilizers, and pesticides compared to less efficient farmers. Therefore, measuring technical efficiency can help determine whether inputs are being used optimally or whether there is still room for improvement to enhance productivity. The distribution of production scale in garlic farming in Karanganyar Regency can be seen in Table 2.

Based on Table 2, the distribution of production scale in garlic farming in Karanganyar Regency shows that the majority of farmers operate under Increasing Returns to Scale (IRS), accounting for 83 farmers or 75.5%. In this condition, most DMUs operate under Increasing Returns to Scale (IRS), it indicates that there is still potential to increase output at a greater proportion through additional input use, suggesting that the current scale of operation is not yet optimal (Permadhi et al., 2026). Meanwhile, 14 farmers or 12.7% are operating under Constant Returns to Scale (CRS), meaning that an increase in inputs leads to a proportional increase in output (Salam et al., 2022).

On the other hand, 13 farmers or 11.8% are under Decreasing Returns to Scale (DRS), indicating that additional inputs result in a less than proportional increase in output, suggesting excessive or inefficient use of production factors. This is consistent with Sui et al. (2022), about studies on garlic farming in China, which indicate that scale efficiency has not yet reached optimal levels, suggesting that output can still be improved through scale adjustments. Therefore, policies that promote the adoption of efficient production technologies, mechanization, and better input management are crucial to improving the productivity and overall performance of garlic farming (Jiang et al., 2025). Previous studies have shown that improvements in cultivation practices and resource management can increase garlic yield, reduce environmental burdens, and

generate higher economic benefits, thereby supporting the sustainable development of the garlic industry (Chen et al., 2024). Based on the analyzed production scale conditions, the distribution of technical efficiency among garlic farmers is presented in Table 3.

Table 3 about the distribution of technical efficiency levels in garlic farming in Karanganyar Regency shows that most farmers are still in the low efficiency category. Farmers in the low category ($0.375 \leq x < 0.583$) represent the largest group, totaling 28 farmers or 25.5%. Meanwhile, 25 farmers or 22.7% fall into the fully efficient category. This indicates that the majority of farmers have not yet achieved optimal technical efficiency. The low level of technical efficiency may be associated with substantial variation in input-use practices among farmers. Field observations revealed that some farmers applied chemical fertilizers beyond recommended levels, whereas others used less than the recommended amount due to financial constraints. In addition, climate-related challenges, particularly persistent rainfall during the dry season, may increase pest and disease pressure and reduce the effectiveness of production inputs. Garlic growth, biomass accumulation, and yield formation are strongly affected by environmental and climatic conditions, indicating that adverse weather conditions may limit production performance (Yun et al., 2022). These findings suggest that both behavioral factors (input management decisions) and structural factors (resource constraints and climate risks) contribute to the observed inefficiency.

This finding corroborates with Rahmawati & Jamhari (2019), who reported that mean score of technical efficiency is 0.6061 among respondent farmers, with the highest value of 0.9998 and the lowest of 0.1968. These values suggest that most farmers are still technically inefficient in garlic farming in Karanganyar Regency. Overall, the majority of farmers operate at a low level of technical efficiency, indicating substantial room for improvement through better use of production factors. According to Nurkomariyah et al. (2025), about efforts such as improving farmers' skills, adopting more appropriate technologies, and managing inputs more efficiently can enhance technical efficiency, which in turn can increase production and farmers' income.

**Allocative Efficiency**

Allocative efficiency aims to assess farmers' ability to combine input use based on the prices of each input in order to achieve minimum production costs. The analysis of allocative efficiency in this study employs the VRS model, using input price data for each production factor. Table 4 presents the frequency distribution of allocative efficiency in garlic farming in Karanganyar Regency

**Table 2**
**Distribution of Production Scale in Garlic Farming**

| Scale Distribution | Number of Farmer | Percentage (%) |
|---|---|---|
| Increasing Return to Scale | 83 | 75,5 |
| Constant Return to Scale | 14 | 12,7 |
| Decreasing Return to Scale | 13 | 11,8 |
| Total | 110 | 100 |

Source: Primary Data Processed, 2026

**Table 3**
**Distribution of Technical Efficiency in Garlic Farming Production**

| Efficiency Level | Technical Efficiency Score | Number of Farmer | Percentage (%) |
|---|---|---|---|
| Very Low | 0,167 – 0,375 | 27 | 24,5 |
| Low | 0,376 – 0,583 | 28 | 25,5 |
| Moderate | 0,584 – 0,791 | 19 | 17,3 |
| High | 0,792 – 1,00 | 11 | 10,0 |
| Fully Efficient | 1,00 | 25 | 22,7 |
| Jumlah | | 110 | 100 |
| Rata-rata TE | 0.617 | | |
| Minimum TE | 0,167 | | |
| Maksimum TE | 1,00 | | |

Source: Primary Data Processed, 2026

**Table 4**
**Distribution of Allocative Efficiency in Garlic Farming Production**

| Efficiency Level | Technical Efficiency Score | Nuber of Farmer | Percentage (%) |
|---|---|---|---|
| Very Low | 0,169 – 0,376 | 14 | 12,7 |
| Low | 0,377 – 0,584 | 33 | 30,0 |
| Moderate | 0,585 – 0,792 | 50 | 45,5 |
| High | 0,793 – 0,999 | 8 | 7,3 |
| Fully Efficient | 1,00 | 5 | 4,5 |
| Jumlah | | 110 | 100 |
| Rata-rata TE | 0.617 | | |
| Minimum TE | 0,167 | | |
| Maksimum TE | 1,00 | | |

Source: Primary Data Processed, 2026

Based on Table 4, the distribution of allocative efficiency levels in garlic farming in Karanganyar Regency shows that most farmers fall into the moderate efficiency category. Farmers in the moderate category (0.585–0.792) represent the largest group, totaling 50 farmers or 45.5%. Meanwhile, the smallest proportion of farmers is in the fully efficient category, consisting of 5 farmers or 4.5%. Moderate allocative efficiency may indicate that production inputs have not been allocated optimally, with some inputs being overutilized while others remain underutilized, leading to higher production costs and suboptimal farm performance (Mivumbi & Yuan, 2023). Field observations conducted during the study support this finding, as some farmers applied fertilizers and pesticides beyond recommended levels, whereas others used lower amounts due to financial constraints. In addition, climate-related challenges, particularly persistent rainfall during the dry season, may increase pest and disease pressure, thereby reducing crop performance. These conditions may prevent farmers from achieving the cost-minimizing combination of production inputs and contribute to the observed allocative inefficiency.This finding is consistent with Kadakoğlu et al. (2023), on allocative efficiency in garlic farming in Türkiye, where the average allocative efficiency was 0.490, indicating that inefficiency arises from input use that does not align with optimal price ratios. Danasari et al. (2023), highlight that the uniformity of prices received by farmers restricts variation in allocative behavior. This condition is reflected in the relatively homogeneous market environment faced by farmers, where output prices are generally similar across producers. As a result, differences in input allocation are driven more by variations in production performance than by differences in input prices.

**Factors Affecting Technical Efficiency in Garlic Production**

The technical efficiency results show differences among the respondent farmers. Therefore, further analysis is needed to determine the factors influencing technical efficiency in production. Table 5 presents the variables used in the Tobit regression analysis.

After identifying the distribution of factors affecting technical efficiency, Table 6 presents the results of the Tobit regression analysis. Based on the Tobit regression results in Table 6, the Prob > chi² value is 0.0053. This value is lower than the 5% significance level (0.05), indicating that the regression model is statistically significant overall. This result demonstrates the simultaneous influence of the explanatory variables on the dependent variable. The Pseudo $R^2$ value of 0.1581 or 15.81% of the variation dependent variable can be explained by the independent variables. Meanwhile, the remaining 84.19% is driven by other factors were not included in this study.

The education level of respondent farmers has a positive and statistically significant effect on the technical efficiency of garlic production in Karanganyar Regency, with a probability value of 0.041, indicating significance at the 10% level. The coefficient of farmer education is 0.205281, which implies that an additional year of education increases technical efficiency by 0.205281. This finding is consistent with Hestina et al. (2017), who found that education positively influences technical efficiency. Higher educational attainment enhances farmers' capacity to acquire and utilize agricultural information, adopt improved production practices, and make informed decisions regarding input use and farm management. Consequently, more educated farmers are better positioned to achieve higher levels of technical efficiency (Ahmad et al., 2024).

**Table 5**
**Distribution of Variables Affecting Technical Efficiency of Garlic Production in Karanganyar Regency**

| Variable | Mean | Min | Max | Category | Number of Farmer |
|---|---|---|---|---|---|
| Age | 57,2 | 35 | 79 | - | 110 |
| Education | 7,7 | 0 | 16 | - | 110 |
| Frequency of Participation in Extension Activities (Dummy) | - | - | - | Participated(1) | 73 |
| | | | | Not participated (0) | 82 |
| Rainfall Risk Severity (Dummy) | - | - | - | High (1) | 104 |
| | | | | Low (0) | 6 |
| Farmer Group Membership (Dummy) | - | - | - | Yes (1) | 72 |
| | | | | No (0) | 38 |
| Land Ownership (Dummy) | - | - | - | Owned (1) | 91 |
| | | | | Rented (0) | 19 |

Source: Primary Data Processed, 2026

**Table 6**
**Tobit Regression Results of Garlic Farming in Karanganyar Regency**

| Variabel | Koefisien | Probabilitas (Pr>\|t\|) |
|---|---|---|
| Age (Z1) | 0.0037964 | 0.936 |
| Education (Z2) | 0.205281 | 0.041** |
| Frequency of Participation in Extension Activities (Z3) | -0.3056607 | 0.014** |
| Rainfall Risk Severity (Z4) | -0.4501972 | 0.005*** |
| Farmer Group Membership (Z5) | 0.1926337 | 0.095** |
| Land Ownership (Z6) | 0.134604 | 0.113 |
| Constanta | 0.8896579 | |
| Prob > chi2 | 0.0053 | |
| Pseudo R2 | 15,81% | |
| *** Signifikasi pada taraf 5% | | |
| ** Signifikasi pada taraf 10% | | |

Source: Primary Data Processed, 2026

The frequency of farmers participation in agricultural extension activities is categorized into those who have participated and those who have never participated. The analysis results indicate that participation in extension activities significant negative effect on the technical efficiency with a probability value of 0.014, which is significant at the 10% level. The coefficient of extension participation is -0.3056607, implying that an increase in farmers' attendance in agricultural extension activities leads to a decrease in technical efficiency by -0.3056607. The negative relationship between extension participation and technical efficiency may indicate that extension activities have not fully addressed the specific needs of garlic farmers. Field observations revealed that extension programs were conducted infrequently and often covered agricultural topics other than garlic cultivation. In some cases, farmers attended extension activities mainly because they were invited through farmer groups rather than due to the direct relevance of the material. As a result, participation in extension activities may not necessarily translate into improvements in technical efficiency. In line with study by Dewi et al. (2026), who found that farmers who had access to extension services exhibited lower levels of technical efficiency compared to those who did not receive such services, although the effect was not statistically significant.

Rainfall risk severity negatively significantly effect on the technical efficiency of garlic production in Karanganyar Regency, with a probability value of 0.005, indicating significance at the 5% level. The coefficient of rainfall risk severity is -0.4501972, meaning that an increase rainfall risk severity reduces technical efficiency by -0.4501972. This finding is consistent withJ. Ahmad et al. (2026), who reported that climate risk significantly affects technical efficiency. Uncertain climate conditions, such as extreme rainfall and increased pest and disease incidence due to climate change, can reduce farm productivity. According to Santoso et al. (2022),

fluctuations in production can be influenced by unstable climatic conditions, particularly rainfall, as well as the harvested and cultivated land area, which ultimately affects production output.

Farmer group participation significant positive effect on the technical efficiency of garlic production in Karanganyar Regency, with a probability value of 0.095, indicating significance at the 10% level. The coefficient of farmer group participation is 0.1926337, meaning that increased participation in farmer groups leads to an increase in technical efficiency by 0.1926337. This finding is consistent with Chaniago et al. (2025), who report that greater farmer participation in farmer groups tends to improve efficiency in farm management. Active involvement in farmer groups enables farmers to acquire knowledge and information through extension activities, which in turn enhances their farming practices. Similarly, Abdul-Rahaman et al. (2023), found that participation in agrifood systems significantly improves technical efficiency among smallholder farmers in Ghana by facilitating better access to inputs, information, and extension services. Addai et al. (2024), also reported that farmer organization membership contributes to improved farm performance through enhanced knowledge sharing and more efficient resource utilization. Overall, these studies suggest that collective action through farmer groups plays a crucial role in reducing inefficiency and improving production outcomes. among smallholder farmers.

The average age of farmers in the study area is 57.2 years, with the oldest being 79 years old and the youngest 35 years old. The Tobit results show that age has no significant effect with a probability value of 0.936. This finding is consistent with Lutfi & Baladina (2018), who stated that farmers' age is closely related to labor productivity in farming activities, as most cultivation processes heavily depend on physical ability. As shown in the study by Kerorsa (2025), variables such as education, access to extension services, and input utilization play a more dominant role in determining technical efficiency.

Land ownership status does not have a significant effect with a probability value of 0.113. Land ownership status does not significantly affect technical efficiency. This is supported by Rondhi et al. (2024), that land tenure is not always a significant determinant of technical efficiency, as efficiency is more strongly influenced other factors such as access to inputs and farm management play a more dominant role.

## CONCLUSION

In terms of technical efficiency, farmers in the low category ($0.375 \leq x < 0.583$) constitute the largest group, totaling 28 farmers or 25.5%, indicating that the majority of farmers operate at a low level of technical efficiency. For allocative efficiency, most farmers fall into the moderate category (0.585–0.792), accounting for 50 farmers or 45.5%.The Tobit regression results show that education (Z2) and farmer group participation (Z5) have a positive effect on technical efficiency, while the frequency of extension participation (Z3) and rainfall risk severity (Z4) have a negative effect on technical efficiency. Based on these findings, efforts to improve garlic farming efficiency should focus on enhancing farmer capacity through targeted training programs, strengthening the role of farmer groups in facilitating knowledge exchange, and improving the relevance of extension services to the specific needs of garlic farmers. Furthermore, climate adaptation strategies, including improved pest and disease management and the provision of weather-based farming information, should be promoted to reduce production risks associated with rainfall variability.

## AI DISCLOSURE STATEMENT

During the preparation of this manuscript, the authors used Grammarly to assist with grammar checking, language editing, translation, and improving academic English writing. All outputs generated by these tools were carefully reviewed, verified, and revised by the authors to ensure the accuracy, clarity, and appropriateness of the content. The authors take full responsibility for the integrity, originality, and final content of this manuscript.

## DATA AVAILABILITY

The datasets generated and/or analyzed during the current study are available from the corresponding author upon reasonable request.

## CONFLICT OF INTEREST

The authors declare no conflict of interest.

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