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Impact of climate variability at local, regional, and global scales on chili productivity in Sleman Regency, Indonesia

Aristya Ardhitama[1,2], Bayu Dwi Apri Nugroho[3*], Junun Sartohadi[4], Supari[5], Indah Retno Wulan[2,3]

[1] Doctor Programme of Agricultural Engineering Science, Faculty of Agricultural Technology, Universitas Gadjah Mada, Yogyakarta, 55281 Indonesia
[2] Indonesia Agency for Meteorology Climatology and Geophysics (BMKG), Climatology Station of Yogyakarta, Yogyakarta, 55284, Indonesia
[3] Department of Agricultural and Biosystems Engineering, Faculty of Agricultural Technology, Universitas Gadjah Mada, Yogyakarta, 55281, Indonesia
[4] Center of Land Resources Management, Universitas Gadjah Mada, Yogyakarta, 55281, Indonesia
[5] Center for Climate Change, Indonesia Agency for Meteorology Climatology and Geophysics (BMKG), Jakarta, 10610, Indonesia

Abstract. As a strategic commodity for inflation stabilization, red chili relies heavily on Sleman Regency, a vital agricultural area. Nevertheless, climate variability poses significant threats, with irregular rainfall and temperature fluctuations driving water scarcity, flooding, and pest and disease outbreaks. This study analyzes climate variability impacts on chili productivity using 2014–2023 yield and rainfall data from 17 districts in Sleman across local to global scales. Key climatic drivers rainfall, Sea Surface Temperature (SST), El Niño–Southern Oscillation (ENSO), and Indian Ocean Dipole (IOD) were assessed using multiple linear regression and Spearman correlation. To detect anomalies, a Monte Carlo Bootstrap with 1000 resamplings was applied during ENSO years across four climatological seasons (DJF, MAM, JJA, SON). Rainfall was the dominant factor in most districts, while SST showed regional influence. Although ENSO and IOD were not statistically significant in regressions, ENSO events triggered marked spatial and seasonal anomalies. El Niño reduced yields by about 40% during JJA and MAM, while La Niña caused greater declines, exceeding 40%, especially in MAM and JJA. These findings highlight the urgency of climate-informed planning through adjusted planting calendars, irrigation development, and resilient varieties to sustain chili production under rising climate pressure. **Keyword**. Red Chili Cultivation, Productivity, Climate Indices, Relationship, Monte Carlo Bootsraap

1 Introduction

Red chili (Capsicum annuum L.) is a strategic horticultural commodity in Indonesia, particularly in Sleman Regency, which serves as one of the main agrarian centers. The region benefits from fertile volcanic soils originating from Mount Merapi and a tropical monsoonal climate that supports high agricultural productivity. Despite this natural advantage, chili production remains highly vulnerable to climate variability, with fluctuating rainfall and temperature patterns leading to reduced water availability, greater pest and disease pressures, and unstable farmer income. This condition has also been reported in other regions of Indonesia, where chili farmers are forced to adapt their practices to cope with increasing climate risks [1].

At a global scale, numerous studies have demonstrated that large-scale climate drivers such as the El Niño–Southern Oscillation (ENSO) strongly influence agricultural yields by altering rainfall distribution and seasonal weather patterns [2]. These global phenomena interact with regional conditions in Southeast Asia, where the Indonesian monsoon system is highly sensitive to ENSO and the Indian Ocean Dipole (IOD). In this context, previous research has shown that rainfall variability in Indonesia is significantly modulated by ENSO events, thereby affecting local agricultural production and food security [3].

Nevertheless, while such relationships are well established at global and regional levels, their combined impact on chili productivity in Sleman Regency remains insufficiently understood. Consequently, given the economic importance of chili for both household income and inflation control, a better understanding of how climate variability at local, regional, and global scales affects production is urgently needed. To address this gap, the present study investigates the interactions between rainfall, sea surface temperature (SST), ENSO, and IOD, and their influence on chili productivity in Sleman over the last decade. Specifically, the objectives are to (i) identify which climate variables significantly affect chili productivity using statistical approaches, and (ii) examine the extent of ENSO-driven anomalies and their impact on yields, employing the Monte Carlo Bootstrap method to strengthen the robustness of the analysis.

2 Material and Methods

2.1 Data

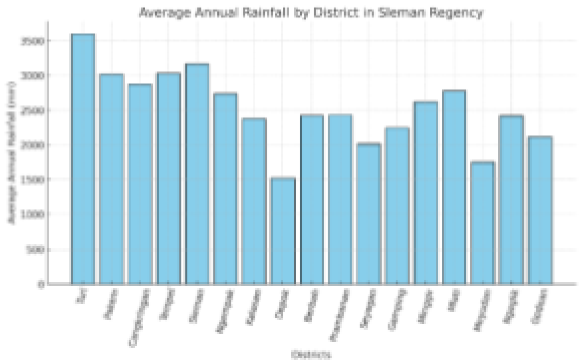
The location of this study is Sleman Regency, which is located in the Special Region of Yogyakarta Province, precisely in the central and southern part of Java Island. Geographically, it is located between 7°34‘ - 7°47’ S and 110°21‘ - 110°37’ E (Figure 1). Sleman has a strategic position as it borders Yogyakarta City to the south, Magelang and Temanggung Regencies to the north, Boyolali Regency to the northeast, and Kulon Progo Regency to the west. Its location on the slopes of Mount Merapi in the north makes it have a varied topography, ranging from lowlands to mountainous areas.

Sleman Regency consists of 17 districts with a total area of approximately 574.82 Km². The districts include Ngemplak, Depok, Gamping, Kalasan, Pakem, Sleman, Turi, Tempel, Cangkringan, Ngaglik, Mlati, Seyegan, Prambanan, Godean, Berbah, Moyudan and Minggir. Most of Sleman Regency's population is involved in agriculture, working as farmers. This study utilizes various data sources to support a comprehensive analysis of factors influencing chili production in Sleman Regency.

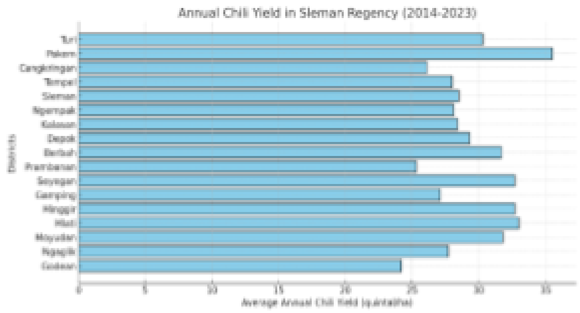
Rainfall data for each district in Sleman Regency from 2014 to 2023 were obtained from the Meteorology, Climatology, and Geophysics Agency (BMKG), while annual chili production data including planted area, harvested area, and productivity (quintals/ha) were collected from the Department of Agriculture and Food Security of Sleman Regency (DP3). The analysis focused on understanding how climate variability particularly rainfall and global climate indices such as SST, ENSO, IOD correlates with chili productivity across 17 districts in Sleman Regency. Prior to analysis, data normality was assessed using the Shapiro–Wilk test, which indicated that the majority of climate and productivity variables were not normally distributed ($p < 0.05$). Based on this, we employed Spearman rank correlation, a non-parametric statistical method suitable for identifying monotonic relationships without requiring the assumption of normal distribution [4].

This approach allowed us to measure the strength and direction of associations between each climate variable and chili productivity. All statistical analyses were performed using Microsoft Excel and R software. The average chili productivity in each district of Sleman over the past 10 years can be seen in Figure 2b.

The study also incorporates SST data to analyze its regional-scale influence on chili productivity. SST data can be accessed from the NOAA Physical Sciences Laboratory through the following link: https://psl.noaa.gov/data/gridded/data.noaa.oisst.v2.html, using coordinates 8°22'30.0"S, 110°22'30.0"E.



(a)



(b)

Fig. 1. (a) Average rainfall data in Sleman Regency 2014 – 2023 (b) Annual chili yield

Moreover, the ENSO phenomenon is represented by the Oceanic Niño Index (ONI) using the Niño 3.4 three-month seasonal index, which can be downloaded at the following link: https://origin.cpc.ncep.noaa.gov/products/analysis_monitoring/ensostuff/ONI_v5.php. The Dipole Mode Index (DMI) data were retrieved from this link: https://psl.noaa.gov/data/timeseries/month/data/dmi.had.long.data.

2.2 Statistical Methods

This study employs multiple linear regression analysis to examine how climate variables namely rainfall, SST, ENSO, and IOD influence chili productivity across 17 districts in Sleman Regency. The dependent variable was annual chili productivity (quintals/ha), while the independent variables consisted of rainfall and climate indices. Prior to analysis, all variables were standardized to z-scores to ensure comparability. Regression analysis was conducted individually for each district, and significance was determined at a 95% confidence level ($p < 0.05$). This method enabled the identification of spatial differences in how climate variables impact productivity across local areas. This method allows for assessing the contribution of each independent variable to changes in the dependent variable. The regression model is represented by Equation 1 as follows:

$$Y=\beta_0+\beta_1X_1+\beta_2X_2+\beta_3X_3+\beta_4X_4+\epsilon \quad (1)$$

Where Y represents chili production, X_1 is Sea Surface Temperature (SST), X_2 is the Dipole Mode Index (DMI), X_3 is the El Niño–Southern Oscillation (ENSO), and X_4 is rainfall. β_0 is the intercept, β_1, β_2, β_3, and β_4 are the regression coefficients, while ϵ represents the error or residual term.

The Spearman correlation test is used to evaluate the relationship between independent variables (SST, DMI, ENSO, and rainfall) and chili production. This non-parametric method was chosen because all the data were found to not follow a normal distribution [5]. The Spearman correlation coefficient (**r**□) ranges from -1 to +1, indicating the strength and direction of the relationship. A positive **r**□ (> 0) means that an increase in the independent variable corresponds to higher chili production, while a negative **r**□ (< 0) suggests the opposite. The closer **r**□ is to ±1, the stronger the relationship, whereas values near zero indicate a weak or insignificant correlation.

2.3 Monte Carlo Technique

This study uses three-monthly indicators as a reference to assess the strength of El Niño and La Niña's influence on extreme climate events. To assess the impact, the data are categorized by seasons, namely summer (June-July-August, JJA), autumn (September-October-November, SON), winter (December-January-February, DJF), and spring (March-April-May, MAM). A seasonal overview of El Niño and La Niña years is presented in Table 1.

Table 1. El Niño and La Niña year events based on ONI data.

Phase	Season	Years
El Niño	JJA	2015, 2023
	SON	2015, 2018, 2023
	DJF	2015/2016, 2018/2019, 2023/2024
	MAM	2015, 2016, 2019
La Niña	JJA	
	SON	2016, 2017, 2020, 2021, 2022
	DJF	2017/2018, 2020/2021, 2021/2022
	MAM	2018, 2021, 2022

Monte Carlo Bootstrap simulations were performed to detect significant productivity anomalies during ENSO years. Chili productivity data from neutral years (non-ENSO periods based on Oceanic Niño Index thresholds) were grouped seasonally into DJF, MAM, JJA, and SON. From each group, synthetic productivity values were resampled 1000 times with replacement to create a null distribution of expected yields. The 5th and 95th percentile thresholds were used to identify statistically significant deviations in ENSO years. An anomaly exceeding these bounds was classified as significant. This method accounts for the inherent variability in agricultural data and improves robustness over conventional parametric approaches. Then, the chili productivity anomaly was calculated (quintal/ha) of the ENSO year by comparing with the neutral year, using Equation 2.

$$Productivity\ Anomaly\ (\%) = \left(\frac{P_{ENSO} - P_{NEUTRAL}}{P_{NEUTRAL}}\right) \times 100\% \quad (2)$$

Where: P_{ENSO} = Productivity during ENSO years (El Niño or La Niña); Pneutral = Productivity during neutral years, productivity data in units of quintals/ha.

The interpretation of the productivity anomaly formula is straightforward. A positive anomaly value indicates that productivity during ENSO years (El Niño or La Niña) is higher compared to neutral years, suggesting a beneficial impact on agricultural yield. Conversely, a negative anomaly value means that productivity has decreased during ENSO years, implying adverse effects on crop production. If the anomaly value is zero, it signifies that there is no significant difference in productivity between ENSO and neutral years, indicating a stable agricultural performance regardless of ENSO conditions. The anomaly in chili productivity is presented using a geographic information system. The statistical calculations were performed using RStudio software.

3 Result and Discussion

3.3 Influence of Climate Variables on Chili Productivity across Sleman Districts

The results of the multiple linear regression analysis presented in Table 2 show that the relationship between chili productivity and climatic variables namely rainfall, SST, IOD, and ENSO varies significantly across districts in Sleman. Rainfall, as a local-scale variable, exhibited statistically significant influence ($p < 0.05$) on productivity in several northern and central districts such as Tempel, Cangkringan, Pakem, Ngemplak, and Mlati, indicating that precipitation patterns are a dominant factor in yield determination. Meanwhile, sea surface temperature (SST) demonstrated a significant effect in Tempel, suggesting that regional sea temperature variability may influence microclimatic conditions in certain lowland areas. In contrast, global climate indices such as ENSO and IOD did not show widespread statistical significance, implying that their effects are likely indirect or modulated by site-specific environmental conditions. Interestingly, Minggir also displayed a significant relationship with rainfall, pointing to the spatially variable nature of local climate sensitivity.

This spatial heterogeneity in the statistical significance of climate variables reflects the role of local environmental factors in mediating the impacts of broader regional and global climate systems. In Tempel, for example, SST variability appears to interact with local elevation, which statistically favors convective cloud development through orographic lifting. Although not located directly along the coast, the area's topography can amplify atmospheric responses to SST anomalies through thermal and dynamical feedback mechanisms, underscoring the role of terrain in modulating ocean–atmosphere interactions. In contrast, higher-elevation regions such as Pakem and Cangkringan are more strongly influenced by orographic effects, cooler ambient temperatures, and rapid hydrological drainage due to their volcanic soils, which together may buffer or dilute the influence of SST and even rainfall variability. Moreover, the volcanic landscape in these areas often induces localized convection and rainfall, potentially decoupling local precipitation patterns from regional SST-driven anomalies.

In Minggir, the strong influence of rainfall is likely due to its fully rainfed farming system, with no technical irrigation and relatively small cultivated areas, making it highly sensitive to rainfall anomalies. In contrast, areas like Mlati and Ngaglik benefit from better irrigation and more intensive farming, which buffer against climatic fluctuations [6]. These differences in water access and land use help explain spatial variations in climate sensitivity.

Table 2. Relationship Between Climate Indices and Productivity Based on Multiple Linear Regression Analysis.

District	Climate Indices			
	Rainfall	SST	IOD	ENSO
Turi	*			
Tempel	*	*		
Cangkringan	*	*		
Pakem	*	*		
Ngemplak	*	*		
Ngaglik	*			
Kalasan		*		
Prambanan				
Sleman				
Mlati	*			
Seyegan		*		
Moyudan				
Minggir	*			
Gamping				
Godean		*		
Berbah		*		
Depok		*		

*) Significance P value <0.05

According to the results of the correlation analysis presented in Table 3, the relationship between chilli productivity and climatic variables shows a diverse pattern in each district. A fairly consistent negative correlation between productivity and local scale climatic variables such as rainfall has an inverse relationship in almost all districts (with values ranging from -0.267 to -0.567). This suggests that an increase in rainfall tends to be associated with a decrease in chilli productivity. Climate influences at the regional scale of SST also show a negative correlation in most districts, with the highest value in Depok (-0.568), indicating that rising sea surface temperatures may adversely affect chilli production. The IOD and ENSO indices show more variable correlations, with some districts such as Tempel showing a high positive correlation to IOD (0.477), while in other districts the correlation is weaker or negative. Compared to Table 2 which shows the regression results, the pattern of relationships shown in Table 3 is largely in line, especially in terms of the dominance of rainfall and SST as the main factors associated with productivity. However, since Table 3 only shows correlations without considering the simultaneous influence between variables as in the regression, the results may not fully reflect the causal relationship. Nevertheless, the findings still provide insight that climatic variables at the local and regional scale have a significant role in determining chilli productivity.

Table 3. Correlation Between Chili Productivity and Climate Variables.

District	Climate Indices			
	Rainfall	SST	IOD	ENSO
Turi	-0.501*	-0.288	0.306	0.160
Tempel	-0.538*	-0.454	0.477	0.239
Cangkringan	-0.489	-0.445	0.281	0.091
Pakem	-0.536*	-0.458	0.138	0.017
Ngemplak	-0.433	-0.423	0.097	-0.001
Ngaglik	-0.461	-0.201	0.181	0.029
Kalasan	-0.162	-0.480	0.106	0.041
Prambanan	-0.215	-0.287	-0.025	-0.021
Sleman	-0.238	-0.239	0.114	0.178
Mlati	-0.482	-0.196	-0.183	-0.156
Seyegan	-0.215	-0.566*	0.232	0.202
Moyudan	-0.378	-0.333	0.102	0.119
Minggir	-0.567*	-0.317	0.097	0.175
Gamping	-0.267	-0.126	-0.042	-0.114
Godean	-0.237	-0.484	0.026	0.068
Berbah	-0.431	-0.647*	-0.064	-0.158
Depok	-0.181	-0.568*	-0.020	-0.113

*) Significance

3.4 Impact of ENSO Events on Seasonal Chili Yield Variability

3.4.1 El Niño Event

Conventional statistical approaches do not specifically capture the impact of the global ENSO phenomenon in their calculations, a Monte Carlo Bootstrap technique approach is used to obtain more accurate results on the effect of ENSO on chilli productivity. Through this method, data variability can be analysed more deeply with a simulation-based approach. From the analysis, it was found that in Figure 2 the impact of El Niño on red chilli productivity in Sleman Regency is heterogeneous, with significant variations between seasons and locations.

In the DJF season (Figure 2a), which coincides with the peak of the rainy season in Java, especially Sleman Regency, the pattern of productivity anomalies shows that in general there is a decrease in chili productivity of 20–40% with a significant level of 95% in some parts of Sleman, particularly in the central and southern regions. This decrease is likely associated with excessive rainfall during the peak monsoon period, leading to soil saturation, waterlogging, and high relative humidity. Such conditions often create a favorable environment for plant diseases, including stem and root rot and anthracnose, which are commonly observed in chili fields under prolonged wet conditions [7].

In contrast, several northern districts displayed mixed responses, with some areas showing non-significant changes, and others such as Moyudan and Mlati even experiencing productivity increases of 20–40%. These localized differences can be explained by better water management practices and the use of more resilient chili varieties, which help mitigate the adverse effects of excessive rainfall and unstable climatic conditions [6].

Meanwhile, the MAM season (Figure 2b), which is the transition period from rainy to dry season, shows a relatively more visible impact of El Niño on chilli productivity. The map visualisation shows that all districts in Sleman experienced a significant decrease in productivity with a decrease of <20 - 40%. Areas that experienced a decrease in production of 40% during MAM were Berbah, Kalasan and Sleman Districts. The El Niño phenomenon significantly affects the productivity of horticultural crops in Indonesia, including chilli. This directly affects the growth and production of chilli plants, which are sensitive to water availability. This research is supported by the effect of El Niño on agricultural production which is significant [8].

The JJA period (Figure 2c) is the season most affected by El Niño, as shown by the dominance of the widespread red downward-pointing triangles across Sleman. The decline in chilli production was entirely between <20 - 40%, with the highest production decline areas occurring in Seyegan, Mlati, Depok, and Prambanan. In North Sleman, the decrease in chilli production was not statistically significant, indicated by the orange downward triangle (production reduced <20%), due to the existence of a good irrigation technique system [9].

In addition, northern Sleman is characterized by fertile volcanic soils, allowing year-round chili cultivation. This region is further supported by adequate irrigation infrastructure, including water reservoirs (*embung*), and favorable climatic conditions that contribute to stable production across seasons. As a result, the impact of El Niño particularly during the peak dry season was found to be statistically insignificant in this area, most likely due to the buffering effects of fertile volcanic soils and the relatively stable availability of water resources. Nevertheless, during years with strong El Niño episodes, the peak dry season was characterized by extreme rainfall deficits, reduced groundwater recharge, and elevated evaporation rates. Under these conditions, chili plants experienced severe water stress, which in this study resulted in yield losses reaching up to 43.68%.

Furthermore, during the SON season (Figure 2d), which is the transition period from the dry to the rainy season, a more heterogeneous pattern emerges. Some areas show significant decreases (red), while others show insignificant changes in production (orange). This spatial variability indicates heterogeneity in crop response to the

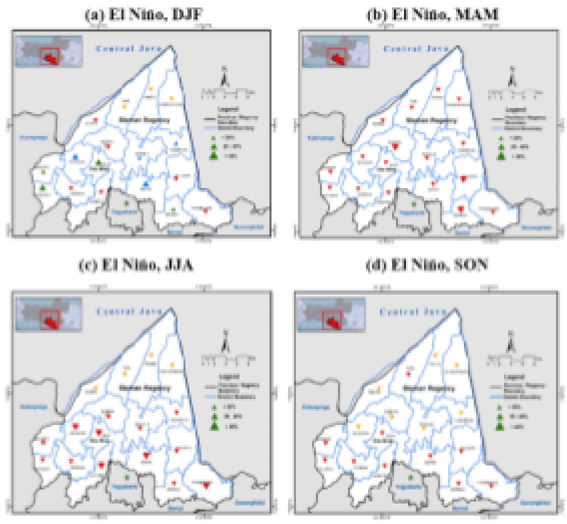


Fig. 2. Anomalies impact of El Niño on chili productivity in Sleman Regency using the Monte Carlo Bootstrap method (a) DJF, (b) MAM, (c) JJA, and (d) SON. Green upward triangles indicate a significant increase in productivity (significant at the 95% confidence level), red downward triangles represent a significant decline (95%), blue upward triangles show a non-significant increase (<5%), and orange downward triangles indicate a non-significant decrease (<5%).

delayed rainy season, which is one of the characteristics of El Niño. This is because differences in cultivation practices, such as planting timing, mulching and fertilisation, contribute to the sensitivity of chilli plants to the impact of the delayed onset of the rainy season due to El Niño [10].

3.4.2 La Niño Event

Figure 3 shows the impact of La Niña on chili productivity anomalies when compared to a normal year in Sleman Regency. In general, La Niña is the cool phase of ENSO that tends to increase rainfall in most parts of Indonesia, including Java (Widodo & Astuti, 2022). In the DJF (Figure 3a), which is the peak of the rainy season supported by the La Niña phenomenon, spatial analysis shows the dominance of inverted red triangle symbols that indicate a decrease in productivity between <20–40%. This can be explained by the high intensity of rainfall during La Niña, which resulted in soil water saturation and high humidity that reduced chili production [7]. However, some areas in Sleman such as Moyudan, Minggir, Mlati, and Berbah showed an increase in productivity between <20–40% of normal (marked with green symbols), indicating heterogeneity of impacts and the role of local mitigation measures such as mulching and improved drainage [11].

Entering the MAM and JJA seasons (Figures 3b and 3c), the data shows that La Niña continued to significantly impact chili productivity across the region with production declines ranging from 20 - >40%, especially in the JJA period where most districts in Sleman experienced a decline of >40%. This decline can be attributed to the wet drought that occurred due to La

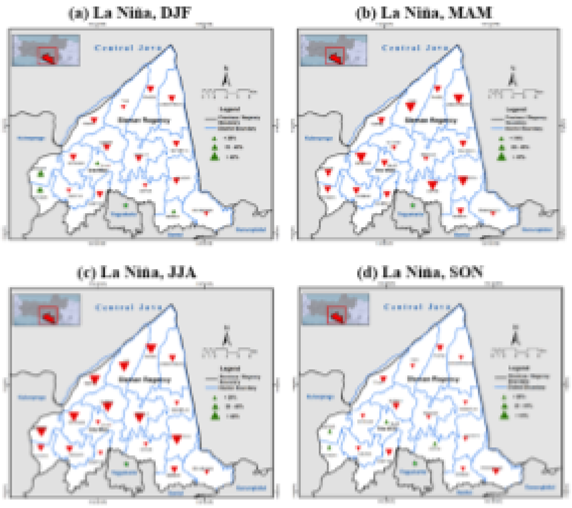


Fig. 3. Anomalies impact of La Niña on chili productivity in Sleman Regency using the Monte Carlo Bootstrap method (a) DJF, (b) MAM, (c) JJA, and (d) SON. (green: significant increase, red: significant decrease, blue: non-significant increase, orange: non-significant decrease)

Niña, which caused chilli plants to remain in high humidity conditions even in the generative phase. In the JJA period, which is usually the dry season, the presence of La Niña actually caused an increase in rainfall and the soil remained saturated throughout the year. This condition is incompatible with the physiological needs of chilli plants [12].

Meanwhile, in the SON period (Figure 3d), which is the transition from dry to wet season, the pattern of La Niña's impact becomes more complex and heterogeneous. Some areas showed an increase in productivity, especially in Moyudan, Minggir, Mlati and Berbah <20%. However, other areas still experienced a decrease in chilli production in the range of 20 - >40%. Global La Niña phenomenon in Sleman Yogyakarta generally decreased chilli production due to increased rainfall. This aligns with the physiological characteristics of chili plants, which are highly susceptible to excessive rainfall. Beyond chilli, the La Niña phenomenon tends to reduce global average yields for several major crops, including rice, maize and soybean, by 2.1%, 1.5% and 1.3%, respectively, while increasing wheat yields by 1.0% [13].

Therefore, these results emphasise the importance of cropping calendar management based on seasonal climate predictions, as well as the need to diversify agricultural varieties and technologies that are resilient to extreme climate variability such as La Niña. The spatial visualisation of the four seasons provides strong evidence that location- and season-based interventions are necessary in developing climate change adaptation strategies in the horticulture sector, especially for strategic commodities such as chilli.

Figure 4 reveals a seasonally nuanced yet consistently negative response of red-chili productivity to both ENSO phases. Monte Carlo-derived anomalies

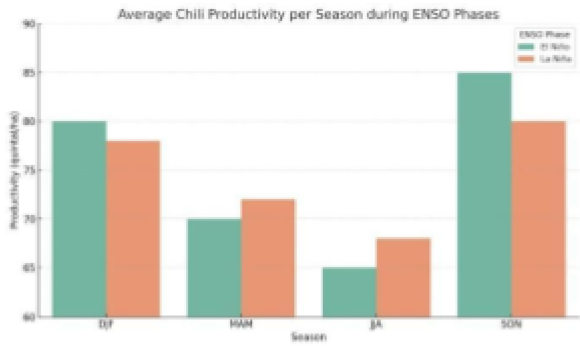


Fig. 4. Average Seasonal Chili Productivity (quintal/ha) during El Niño and La Niña Years in Sleman Regency. This figure compares average red chili productivity across four climatological seasons (DJF, MAM, JJA, SON) under different ENSO phases. The data were generated using Monte Carlo Bootstrap simulations from 2014 to 2023.

summarised in Table 4 show that El Niño depresses yields most sharply in the early-dry (MAM, −45 %) and peak-dry (JJA, −43 %) seasons, whereas La Niña exerts its strongest penalty in the same windows, albeit slightly less in magnitude (−35 % and −42 %). The wet-season (DJF) losses are comparable between phases (−25 % to −30 %), but Figure 4 indicates a modest absolute yield advantage for El Niño (80 q ha^{-1}) over La Niña (78 q ha^{-1}), likely because moderate drying alleviates waterlogging typical of Sleman's mid-monsoon. Conversely, during SON the spatially heterogeneous signature statistically partially significant suggests that only selected districts cross the 5th/95th bootstrap percentiles, reflecting local differences in irrigation access and cultivar tolerance. Importantly, all anomalies are negative relative to neutral years, underscoring that anomalous moisture stress whether excess or deficit undermines chili output across the agro-ecological calendar.

The contrasting mechanisms behind these losses align with regional climatological theory and previous empirical work. During El Niño, suppressed convective rainfall and higher vapour pressure deficit accelerate soil water depletion, driving stomatal closure and fruit set failure exactly when generative growth peaks [3]. La Niña, by contrast, prolongs humid conditions into the dry season: saturated root zones, reduced solar radiation, and heightened fungal pressure collectively trim yields despite ample water [6], [13]. The fact that JJA losses are severe in both phases highlights Sleman's dual vulnerability drought in El Niño years and "wet drought" in La Niña years echoing farmer-level impact studies from Bali and Central Java [1], [14].

Spatial heterogeneity in SON further points to the mediating role of micro-topography and infrastructure; districts with drip irrigation or lighter volcanic sand soils (e.g., Moyudan, Minggir) escape significant yield suppression. Collectively, Figure 4 and Table 4 stress that adaptation strategies cannot be season-agnostic: early dry and peak dry plantings demand drought-resilient cultivars and supplemental irrigation, while wet season production hinges on drainage management and disease suppression. Incorporating probabilistic ENSO forecasts into planting calendars therefore offers a tangible pathway to stabilise Sleman's chili supply and, by extension, its role in regional food price control [15].

Table 4. Summary of Seasonal Chili Productivity Anomalies and Statistical Significance during ENSO Events Based on Monte Carlo Bootstrap Analysis

Season	ENSO Phase	Yield Anomaly (%)	Significance ($p < 0.05$)	Mean Productivity
DJF	El Niño	-25	Yes	80
MAM	El Niño	-45	Yes	70
JJA	El Niño	-43	Yes	65
SON	El Niño	-20	Partially	85
DJF	La Niña	-30	Yes	78
MAM	La Niña	-35	Yes	72
JJA	La Niña	-42	Yes	68
SON	La Niña	-25	Partially	80

4 Conclusion

This study confirms that multi-scalar climate variability significantly influences chili productivity significantly influences chili productivity in Sleman Regency, with rainfall emerging as the most dominant local variable statistically significant ($p < 0.05$) in districts such as Tempel, Cangkringan, Pakem, Ngemplak, and Mlati. At the regional scale, Sea Surface Temperature (SST) showed spatially limited but significant effects, while global indices such as ENSO and the Indian Ocean Dipole (IOD) did not exhibit strong direct influence in regression models, suggesting more indirect or location-specific pathways of impact. Monte Carlo Bootstrap analysis revealed clear seasonal and spatial anomalies, with El Niño causing substantial productivity reductions of over 40% during JJA and MAM, while La Niña events also depressed yields across all seasons, particularly during JJA and MAM, due to high rainfall-induced waterlogging and disease pressure. These findings highlight the heterogeneous nature of climate impacts depending on seasonality, crop phenology, and local management practices. Therefore, integrating seasonal climate forecasts into agricultural planning such as adjusting planting schedules, adopting climate-resilient irrigation strategies, and promoting stress-tolerant chili varieties are crucial to maintaining stable production. This research reinforces the urgency of adaptive agricultural strategies to enhance resilience against increasing climate variability in horticultural systems.

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