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Projected Impacts of Climate Variables on Oil Palm Productivity at PT Kumala Jambi Prakasa

[1]Nurul Hidayah Yuliani, [2]Asmadi Saad, [3]Ermadani*
[1]Environmental Science, Universitas Jambi, Indonesia; email: nurulhday21@gmail.com
[2] Universitas Jambi, Indonesia
[3] Universitas Jambi, Indonesia*
*Correspondence

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Abstract
Introduction: *Oil palm productivity is influenced by climate variability through biological time lag effects due to its long reproductive cycle.* ***Objective:*** *This study aimed to analyze historical climate characteristics, evaluate the effects of macroclimatic variables on oil palm productivity using a time lag approach, develop the best regression model, and estimate the impacts of climate change under RCP 4.5 and RCP 8.5 scenarios at PT Kumala Jambi Prakasa.* ***Method:*** *Monthly data on rainfall, temperature, humidity, and Fresh Fruit Bunch (FFB) productivity during 2016–2025, along with bias-corrected Global Climate Model (GCM) projections, were analyzed using Pearson correlation with time lag (0–24 months) and multiple linear regression.* ***Results and Discussion:*** *The results showed that rainfall and humidity significantly affected productivity at an 8-month lag, while temperature had a significant effect at a 4-month lag. The developed multiple linear regression model explained 29.23% of the variation in oil palm productivity. Climate projections under RCP 4.5 and RCP 8.5 indicated declining productivity through 2035, with maximum reductions of 48.97% and 45.92%, respectively. These findings highlight the importance of adaptive strategies, including improved water management, climate-resilient varieties, and climate-based production planning.* ***Conclusion:*** *Oil palm productivity responds to climate variability through delayed physiological processes, and understanding these time lag effects is essential for developing long-term adaptation strategies under future climate change conditions.*

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Introduction

Oil palm (*Elaeis guineensis* Jacq.) is one of the most important plantation commodities worldwide, playing a strategic role in economic development, employment generation, and global vegetable oil supply (Harahap & Munir, 2022). Indonesia is the largest producer of crude palm oil (CPO), with national production reaching approximately 46 million tons from a plantation area of 14.3 million hectares (BPS, 2023); (Mustafa, 2022). The oil palm industry contributes substantially to Indonesia's non-oil export earnings, generates employment opportunities, and remains an important driver of national economic development (Septiani & Setiawan, 2023); (Saragih & Rahayu, 2022). Despite its economic importance, the sustainability of oil palm production is increasingly threatened by climate change. According to the Intergovernmental Panel on Climate Change (IPCC, 2023), the global average surface temperature has increased by approximately 1.1–1.2 °C above the pre-industrial level, resulting in changes in rainfall patterns and increasing climate variability, particularly in tropical regions. These climatic changes alter the environmental conditions required for optimal oil palm growth and may reduce productivity through prolonged drought, irregular rainfall distribution, increasing temperature variability, and more frequent extreme weather events (Wulandari et al., 2025).

Several studies have demonstrated that climate variability significantly affects oil palm productivity. Hasibuan et al. (2023) reported that the El Niño event caused substantial water deficits, resulting in reduced oil palm productivity at PT Sari Lembah Subur. Similarly, Alfajaraldi et al. (2022) found that the effects of rainfall deficits on oil palm production do not occur immediately but follow a biological *time lag*, reflecting the delayed physiological response of perennial crops to climatic conditions. In contrast, Wandana et al. (2024) reported that air temperature had no significant effect on productivity because the observed temperature remained within the optimum range for oil palm growth. However, these studies primarily focused on historical climate observations and did not incorporate future climate projections to assess long-term productivity under changing climate conditions. These challenges are also relevant to PT Kumala Jambi Prakasa, located in West Tanjung Jabung Regency, Jambi Province, where oil palm plantations established in 2009–2011 have experienced changing climatic conditions over the past decade. Variations in rainfall, temperature, and relative humidity are presumed to influence oil palm productivity through delayed physiological responses, making conventional simultaneous correlation analysis insufficient to explain the actual relationship between climate variability and crop productivity. Therefore, integrating a biological *time lag* approach with future climate projections is essential to improve the prediction of oil palm productivity under changing climate conditions.

Therefore, this study aims to evaluate the effects of climate variability on oil palm productivity using a biological *time lag* approach, develop a multiple linear regression model, and project future productivity under Representative Concentration Pathway (RCP) 4.5 and RCP 8.5 scenarios as a scientific basis for developing climate adaptation strategies for oil palm plantation management at PT Kumala Jambi Prakasa

Method

This study employed a quantitative approach with descriptive analysis and predictive modeling to analyze the effects of macroclimatic parameters on oil palm productivity at PT Kumala Jambi Prakasa, Jambi Province. Climate data were obtained from the Jambi Climatological Station, located on Jambi–Muara Bulian Road Kilometer

18, Simpang Sungai Duren, Jambi Luar Kota District, while oil palm productivity data were obtained from PT Kumala Jambi Prakasa. The data used consisted of secondary monthly time series data for the period 2016–2025, including rainfall (mm), air temperature (°C), humidity (%), and oil palm productivity (tons/ha). In addition, climate projection data from the Global Climate Model (GCM) under Representative Concentration Pathway (RCP) 4.5 and RCP 8.5 scenarios for the period 2026–2035 were used.

The analysis began with bias correction of climate projection data using the linear scaling method to minimize deviations between global climate model outputs and observed climate data. Bias correction was performed by adjusting projected climate variables using the ratio between the long-term mean observed data and the corresponding historical model data. The corrected values were then used for subsequent climate projection analyses using the following equations:

a. Rainfall (CH) Bias Correction

$$CH_{\text{mod\_kor}} = CH_{\text{mod}} \times \frac{\overline{CH}_{\text{obs}}}{\overline{CH}_{\text{mod}}}$$

b. Air Temperature (T) Bias Correction

$$T_{\text{mod\_kor}} = T_{\text{mod}} \times \frac{\bar{T}_{\text{obs}}}{\bar{T}_{\text{mod}}}$$

c. Relative Humidity (RH) Bias Correction

$$RH_{\text{mod\_kor}} = RH_{\text{mod}} \times \frac{\overline{RH}_{\text{obs}}}{\overline{RH}_{\text{mod}}}$$

where:

$CH_{\text{mod\_kor}}, T_{\text{mod\_kor}}, RH_{\text{mod\_kor}}$ = Monthly bias-corrected values of rainfall, temperature, and humidity.

$CH_{\text{mod}}, T_{\text{mod}}, RH_{\text{mod}}$ = Raw values of climate variables derived from the GCM for the corresponding month.

$\overline{CH}_{\text{obs}}, \bar{T}_{\text{obs}}, \overline{RH}_{\text{obs}}$ = Long-term mean values of climate variables obtained from actual observational data.

$\overline{CH}_{\text{mod}}, \bar{T}_{\text{mod}}, \overline{RH}_{\text{mod}}$ = Long-term mean values of climate variables derived from historical GCM data.

Subsequently, outlier identification and descriptive statistical analyses were performed to determine the basic characteristics of the historical data. The relationship between climate variables and oil palm productivity was analyzed using Pearson correlation with a time lag approach ranging from lag 0 to lag 24 months using Minitab software. The Pearson correlation coefficient was calculated using the following equation:

$$r = \frac{n \sum XY - (\sum X)(\sum Y)}{\sqrt{[n \sum X^2 - (\sum X)^2][n \sum Y^2 - (\sum Y)^2]}}$$

The time lag combination that produced the strongest and most significant correlation coefficient (p-value < 0.05) was selected as the predictor variable for the model. Oil palm productivity modeling was performed using multiple linear regression by integrating rainfall, relative humidity, and air temperature variables at the selected time lag, together with plant age. The regression model was expressed as:

$$Y = a + b_1X_1 + b_2X_2 + b_3X_3 + b_4X_4 + e$$

The reliability of the model was evaluated through classical assumption tests, including residual normality, multicollinearity using the Variance Inflation Factor (VIF), and homoscedasticity tests. Model accuracy was validated using the Root Mean Square Error (RMSE), calculated using the following equation:

$$\text{RMSE} = \sqrt{\frac{\sum_{i=1}^{n}\left(Y_{\text{aktual}} - Y_{\text{prediksi}}\right)^2}{n}}$$

The validated regression equation was subsequently used to project oil palm productivity for the period 2026–2035 by integrating bias-corrected climate projection data under the RCP 4.5 and RCP 8.5 scenarios. Gap analysis was conducted to evaluate the potential differences and declines in productivity between the two climate scenarios.

Result and Discussion

Characteristics of Actual Climate and Oil Palm Productivity

The characteristics of actual macroclimatic conditions were analyzed to obtain an overview of the agroclimatological conditions affecting oil palm productivity at PT Kumala Jambi Prakasa during the observation period of 2016–2025. The climate variables analyzed included rainfall, air temperature, and relative humidity. The results of the descriptive statistical analysis showed that rainfall exhibited a higher degree of variation compared to air temperature and relative humidity. A summary of the descriptive statistics of the actual climate variables is presented in Table 1.

Table 1

Quantification of Actual Climate Variables (2016–2025)

Research Variables	Number of Observations	Minimum Value	Maximum Value	Mean
Rainfall (X1) (mm/month)	120	15	632	177.7
Air Temperature (X2) (°C)	120	25.33	28.33	26.52
Relative Humidity (X3) (%)	120	71.85	93.18	85.96

Source: Processed secondary data (2026).

Based on Table 1, rainfall (X1) exhibited substantial variation, with a minimum value of 15 mm/month and a maximum value of 632 mm/month, resulting in a mean value of 177.7 mm/month. These conditions indicate that rainfall distribution in the study area was uneven throughout the year. In contrast, air temperature (X2) showed relatively small fluctuations, ranging from 25.33 °C to 28.33 °C, with an average value of 26.52 °C, whereas relative humidity (X3) ranged from 71.85% to 93.18%, with a mean value of 85.96%, indicating the humid tropical climate characteristics of the study area.

The monthly rainfall distribution pattern indicated that the PT Kumala Jambi Prakasa area exhibited a bimodal (equatorial) rainfall pattern, with two peak rainy seasons occurring during March–April and November. The lowest rainfall occurred in July, amounting to 96.10 mm, while the highest rainfall was recorded in November at 258.70 mm. According to the Schmidt–Ferguson climate classification, months with rainfall below 100 mm indicate periods of water deficit that may adversely affect the physiological performance of oil palm. Water deficit has been reported to reduce stomatal conductance, water use efficiency, flower differentiation, and reproductive development, thereby contributing to delayed reductions in oil palm productivity through biological time-lag responses (Teh et al., 2024). The monthly rainfall distribution pattern during the observation period is presented in Figure 1.

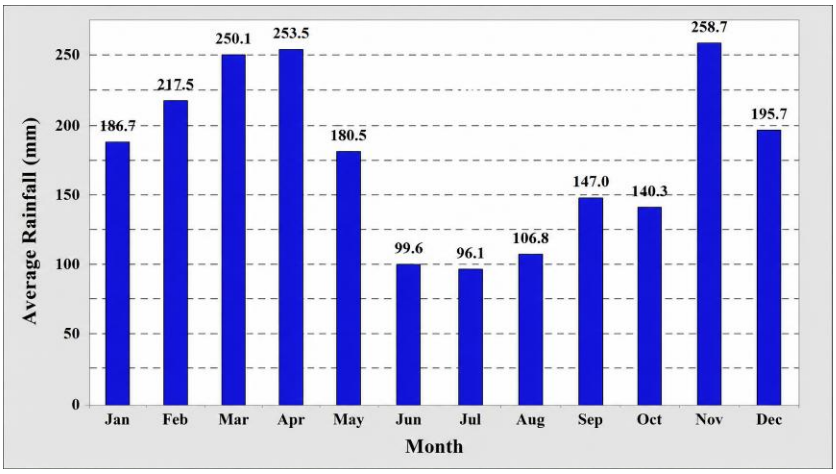

Figure 1. Average Monthly Rainfall (2016–2025)

In addition to climate characteristics, an analysis of actual productivity was conducted to identify production patterns in each Planting Year Block (PYB). The results showed that the 2011 PYB had the highest average productivity, reaching 2.198395 tons/ha/month, followed by the 2010 PYB at 2.175513 tons/ha/month and the 2009 PYB at 2.000254 tons/ha/month. These differences in productivity were associated with differences in plant age, where the 2011 PYB represented the optimum productive stage, whereas the 2009 PYB had entered a more mature growth stage. A summary of oil palm productivity statistics is presented in Table 2.

Table 2

Quantification of Oil Palm Productivity (2016–2025)

Planting Year	Number of Observations	Minimum Value	Maximum Value	Mean
2009	120	0.000000	3.290308	2.000254
2010	120	0.859049	3.692266	2.175513
2011	120	0.969416	4.159456	2.198395
Combined (2009, 2010, 2011)	360	0.000000	4.159456	2.124721

Source: Processed secondary data (2026).

Based on Table 2, oil palm productivity in the three planting year blocks showed differences in production capacity influenced by the plant growth phase. The 2011 PYB recorded the highest average productivity and the largest maximum value compared to the other blocks, indicating that this block was in its optimum productive phase. In contrast, the 2009 PYB exhibited lower average productivity because it had begun to enter the mature plant phase. The pattern of actual productivity fluctuations in the three planting year blocks during the observation period is presented in Figure 2.

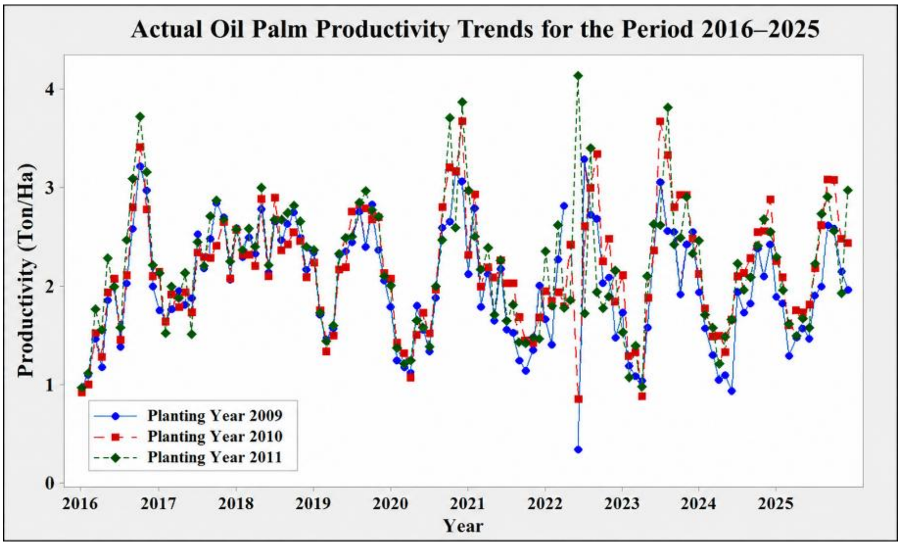

Figure 2. Trends in Actual Oil Palm Productivity (2016–2025)

Based on Figure 2, oil palm productivity in the three planting year blocks exhibited relatively similar seasonal fluctuation patterns throughout the observation period. Peak crop phases generally occurred during the third and fourth quarters, whereas low crop phases occurred during the first and second quarters. A decline in productivity was observed during 2016–2017, which was likely associated with the prolonged impacts of the 2015 El Niño event that caused drought stress and soil water deficits. Recent studies have shown that climate anomalies associated with the El Niño–Southern Oscillation (ENSO) can reduce oil palm productivity through delayed physiological responses, with impacts becoming evident several months after climatic disturbances (Wulandari et al., 2025). The productivity decline observed in 2022 was also likely influenced by excessive rainfall, which disrupted harvesting operations, reduced field accessibility, and delayed fresh fruit bunch transportation. Similar impacts of excessive rainfall and climate variability on plantation operations have been reported in recent studies (Abubakar et al., 2021).

Correlation and Time Lag Analysis

Correlation analysis was conducted to measure the strength and direction of the linear relationships between macroclimatic parameters, namely rainfall (X1), air temperature (X2), and relative humidity (X3), and oil palm productivity (Y). Considering that oil palm exhibits delayed physiological responses to environmental changes, the analysis was performed using both simultaneous correlation (current month) and Cross-Correlation Function (CCF) approaches to identify the most representative time lag. The results of the simultaneous correlation analysis (Lag = 0) indicated that the relationships between macroclimatic variables and oil palm productivity were weak and not significant, thereby necessitating cross-correlation analysis to identify the delayed physiological responses of oil palm to climate variability.

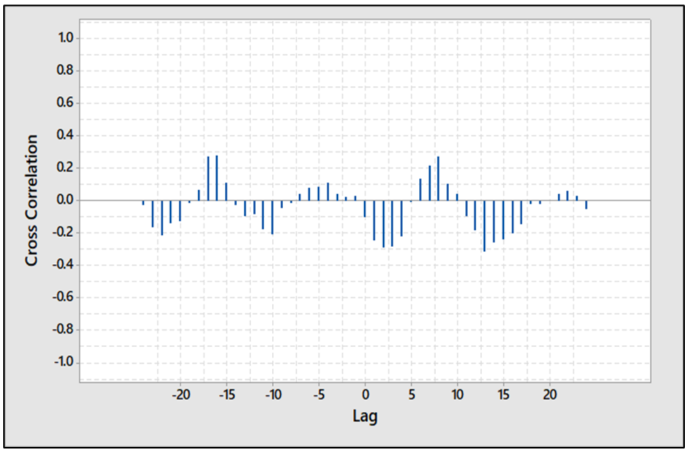

Figure 3. Time Lag Correlation Relationship Between Rainfall and Oil Palm Productivity

Based on the Cross-Correlation Function (CCF) graph presented in Figure 3, rainfall exhibited the strongest and most significant positive correlation with oil palm productivity at an 8-month lag (t-8). The occurrence of the correlation peak at Lag 8 indicates that fluctuations in rainfall have a positive relationship with oil palm productivity after an eight-month delay period. This relationship suggests that increased rainfall occurring eight months before harvest is potentially followed by increased productivity at the time of harvest. From an agroclimatological perspective, this condition indicates that rainfall plays an important role in supporting plant physiological processes during the formation and development of reproductive organs. Therefore, its effect on productivity does not occur directly but rather through biological processes occurring over a certain period of time.

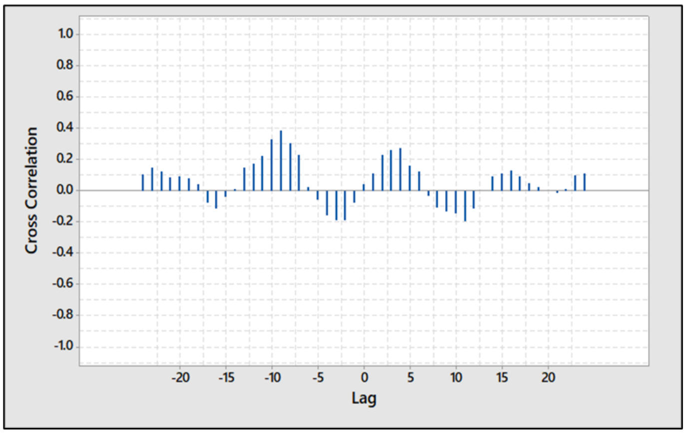

Figure 4. Time Lag Correlation Relationship Between Air Temperature and Oil Palm Productivity

The Cross-Correlation Function (CCF) visualization in Figure 4 showed that air temperature had the strongest positive relationship with oil palm productivity at a 4-month lag (t-4). Compared with rainfall, air temperature exhibited a faster response to productivity changes. From an ecophysiological perspective, the response at Lag 4 indicates that air temperature influences the final stages of fruit development, particularly during oil accumulation and bunch maturation. Favorable temperature conditions during this period enhance fruit development, assimilate accumulation, and biomass production, thereby supporting higher oil palm productivity under suitable climatic conditions (Teh et al., 2024; Abubakar et al., 2021).

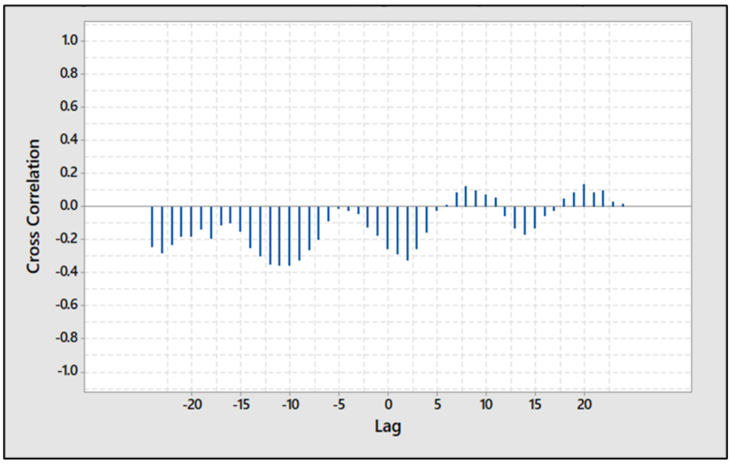

Figure 5. Time Lag Correlation Relationship Between Relative Humidity and Oil Palm Productivity

The results of the cross-correlation analysis presented in Figure 5 showed that relative humidity exhibited the most representative positive correlation with oil palm productivity at an 8-month lag (t-8). Although correlation fluctuations were observed at several other time periods, Lag 8 was selected as the optimal delay period because it demonstrated the most rational positive relationship based on agroclimatological considerations and data utilization efficiency. The selection of Lag 8 was also intended to maintain the simplicity of the statistical model and optimize the use of available historical data, thereby supporting the accuracy of oil palm productivity modeling for subsequent projection periods.

Based on the results of the cross-correlation function analysis, the selected delay periods for each climate parameter were identified as an 8-month lag for rainfall, a 4-month lag for air temperature, and an 8-month lag for relative humidity. The selection of these delay periods was based on the strength of the correlation relationships, agroclimatological considerations, and the efficiency of historical data utilization. The identified time lag values were subsequently used as the basis for developing the multiple linear regression model to project oil palm productivity in future periods.

Development of a Time Lag-Based Linear Regression Model

After determining the optimum time lag combinations, multiple linear regression analysis was performed to develop a predictive model of oil palm productivity based on climate variables and plant age. The inclusion of the plant age variable was intended to improve the model's ability to explain variations in oil palm productivity. A summary of the final regression model is presented in Table 6.

Table 3
Summary of the Final Multiple Linear Regression Model

Variables	Coefficient	P-Value	Description
Constant	-6.31	0.000	-
Rainfall (Lag8)	0.001586	0.000	Significant
Air Temperature (Lag4)	0.2046	0.000	Significant
Relative Humidity (Lag8)	0.04314	0.000	Significant
Plant Age	-0.0859	0.000	Significant
R-Square (R^2)	29.23%		
RMSE (S)	0.507499		

Source: Secondary data processed using Minitab (2026).

Based on Table 3, the following multiple linear regression equation was obtained:

$$\textbf{Productivity} = -6.31 + 0.001586\,(CH_{L8}) + 0.2046\,(Temperature_{L4}) + 0.04314\,(RH_{L8}) - 0.0859\,(Plant\ Age)$$

All variables in the model showed significant effects (p-value = 0.000). The inclusion of the plant age variable increased the coefficient of determination (R^2) to 29.23% and reduced the Root Mean Square Error (RMSE) value to 0.507499. These results indicate that the developed regression model was able to describe the effects of time lag climate variables and plant age on oil palm productivity. Therefore, this model was used as the basis for projecting oil palm productivity during the period 2026–2035 under the RCP 4.5 and RCP 8.5 climate change scenarios.

Projected Impacts of Climate Change on Oil Palm Productivity

The developed multiple linear regression model was subsequently used to project oil palm productivity at PT Kumala Jambi Prakasa during the period 2026–2035 under the RCP 4.5 and RCP 8.5 climate change scenarios. The projections were conducted to evaluate potential changes in oil palm productivity under moderate and extreme climate change conditions.

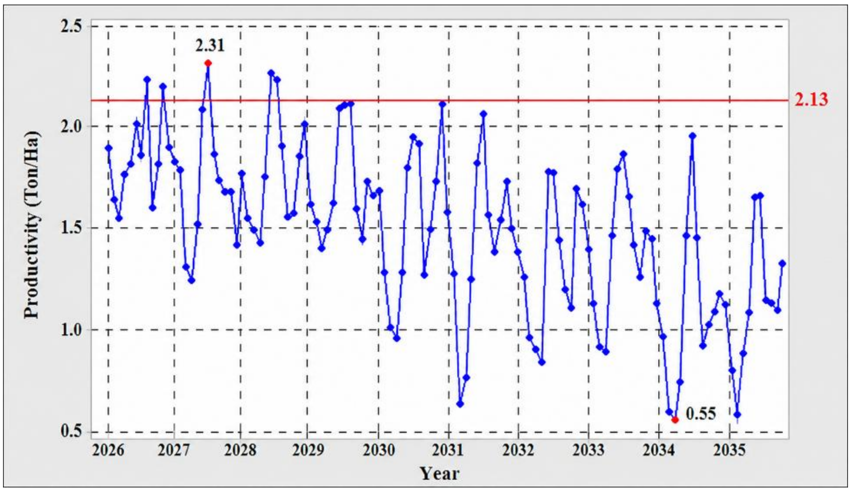

Figure 6. Projected Monthly Oil Palm Productivity Trends under the RCP 4.5 Scenario (2026–2035)

Based on the projection results presented in Figure 6, oil palm productivity under the RCP 4.5 scenario exhibited a fluctuating pattern with a declining trend throughout the period 2026–2035. Productivity ranged from 0.55 to 2.31 tons/ha, compared to the historical average productivity of 2.13 tons/ha during the period 2016–2025. The highest productivity was projected to occur in 2027, while the lowest productivity was projected to occur in 2034. In addition, most productivity values after 2030 were below the historical average, indicating a declining productivity trend toward the end of the projection period. These results suggest that climate change under the RCP 4.5 scenario has the potential to reduce the stability of oil palm productivity in the study area in the future.

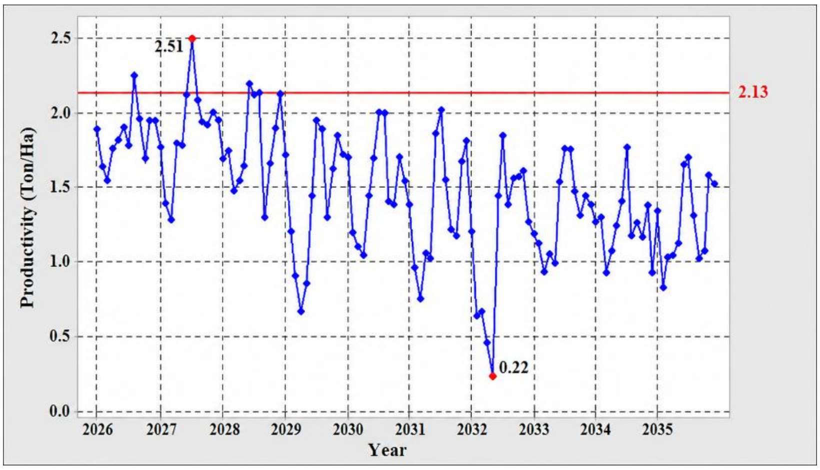

Figure 7. Projected Monthly Oil Palm Productivity Trends under the RCP 8.5 Scenario (2026–2035)

Under the RCP 8.5 scenario, oil palm productivity also exhibited a fluctuating pattern with a declining trend. Productivity ranged from 0.22 to 2.51 tons/ha, with the lowest productivity projected to occur in 2032. Most productivity values after 2030 were below the historical average, indicating a decline in future productivity. Changes in rainfall patterns, increasing air temperatures, and decreasing humidity have the potential to reduce water availability for plants, thereby triggering environmental stress that affects oil palm productivity.

Table 4
Summary of Differences in Oil Palm Productivity under RCP 4.5 and RCP 8.5 Relative to Actual Conditions

Year	Difference between RCP 4.5 and Actual (%)	Difference between RCP 8.5 and Actual (%)	Difference between RCP 4.5 and RCP 8.5 (%)
2026	-12.98%	-13.47%	-0.12%
2027	-20.04%	-11.83%	11.66%
2028	-16.38%	-15.79%	0.86%
2029	-20.28%	-33.15%	-16.56%
2030	-27.72%	-28.84%	-0.05%
2031	-33.19%	-35.63%	-1.50%
2032	-37.64%	-45.92%	-15.96%
2033	-34.64%	-37.83%	-3.73%
2034	-48.97%	-41.94%	23.79%
2035	-46.51%	-40.65%	13.93%

Based on Table 4, both the RCP 4.5 and RCP 8.5 scenarios consistently showed a decline in oil palm productivity compared to actual conditions during the period 2026–2035. Under the RCP 4.5 scenario, productivity declines ranged from -12.98% to -48.97%, whereas under the RCP 8.5 scenario, the declines ranged from -11.83% to -45.92%. These results indicate that climate change has the potential to negatively affect future oil palm productivity, although the magnitude of the decline varies across periods and emission scenarios.

Practical Plantation Management Adaptation Strategies

Based on the projected oil palm productivity for the period 2026–2035 under the RCP 4.5 and RCP 8.5 scenarios, long-term adaptation strategies are required to enhance the resilience of plantation management systems to climate change. The adaptation strategies proposed in this study were developed based on the projected patterns of productivity decline and the climate risk characteristics faced by PT Kumala Jambi Prakasa. A summary of the practical plantation management adaptation strategies is presented in Table 8.

Table 5
Pillars of Practical Adaptation Strategies for Oil Palm Plantation Management

Strategic Pillar	Focus of Action	Data-Based Justification
Permanent water management reform	Development of permanent ponds/reservoirs, deep wells, and fixed irrigation systems; maintenance of optimal water table levels throughout the year	Productivity differences relative to actual conditions have been negative since 2026 (-12.98% and -13.47%) and continue to worsen, indicating that water deficits are chronic rather than seasonal
Variety transformation in replanting programs	Accelerated adoption of drought- and heat-tolerant varieties as the standard for replanting rather than as an additional option	Productivity declines reaching -48.97% (RCP 4.5, 2034) and -45.92% (RCP 8.5, 2032) indicate that incremental agronomic improvements alone will be insufficient
Revision of production targets and business planning	Re-forecasting annual production based on RCP projections and integrating loss scenarios into investment planning	Consistent declining trends under both scenarios require projection-based business planning rather than historical data extrapolation
Monitoring differences between RCP 4.5 and RCP 8.5 as a priority signal	Years with substantial differences (2029, 2032, and 2033) receive additional mitigation measures, while other years remain under observation	Inconsistent inter-scenario differences indicate that seasonal combinations of rainfall, temperature, and humidity are more influential than emission magnitude alone

Overall, the proposed adaptation strategies emphasize the structural transformation of plantation management systems and resource governance, in line with the progressive and persistent nature of the projected productivity decline. This approach is expected to slow the rate of decline in oil palm productivity at PT Kumala Jambi Prakasa during the period 2026–2035 while providing a more realistic planning framework for addressing climate uncertainty in the coming decades.

Conclusion

This study demonstrated that oil palm productivity at PT Kumala Jambi Prakasa does not respond instantaneously to climate change, but rather through a time lag effect of approximately 4 months for air temperature and 8 months for rainfall and relative humidity. The integration of time lag effects with the plant age factor produced a regression model capable of explaining 29.23% of the variation in oil palm productivity. Productivity projections for the period 2026–2035 under the RCP 4.5 and RCP 8.5 climate change scenarios indicated a declining trend in productivity compared to the historical average. Productivity reductions during certain periods may reach nearly half of the actual conditions. Comparisons between the two scenarios revealed inconsistent patterns from year to year, indicating that the combination of rainfall, air temperature, and relative humidity during specific periods exerts a greater influence on productivity than emission magnitude alone. Overall, the findings indicate that the challenge faced is not merely ordinary seasonal fluctuations, but rather gradual climatic pressures whose impacts become apparent several months after their occurrence. Therefore, understanding the time lag effect is an important aspect in developing adaptation strategies and managing oil palm plantations in the future.

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