Quantification of Climate Factors Contributing to Variation of Oil Palm Yield

Kuantifikasi Kontribusi Faktor Iklim Terhadap Variasi Produktivitas Tanaman Kelapa Sawit

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Abstract The yield of oil palm is heavily influenced by various climatic conditions, including rainfall (RF), radiation (Qs), temperature, and humidity. To quantify the impact of these factors, a study was conducted on a 15-year-old palm located in an oil palm estate in Pangkalan Lima Puluh Kota, West Sumatra, Indonesia. The study used climate data from 2011-2019 and yield data from 2015 and 2019. To determine the contribution of RF, Qs, and VPD / vapour pressure deficit, which was estimated from temperature and humidity, a computer-intensive importance metric developed by Lindemann, Merenda, and Gold (LMG metric) was utilized. The results showed that RF, Qs, and VPD collectively accounted for 42.29% of yield fluctuations at the study site. Furthermore, the contribution of climate factors on yield followed the order of VPD > Qs > RF.

Keywords: climate, oil palm, rainfall, solar radiation, vapour pressure deficit, yield

Abstrak *Produktivitas tanaman kelapa sawit sangat dipengaruhi oleh beberapa kondisi iklim, termasuk curah hujan (RF), radiasi (Qs), suhu, dan kelembaban udara. Untuk mengkuantifikasikan pengaruh faktor-faktor produksi tersebut, sebuah kajian telah dilakukan pada tanaman umur 15 tahun di sebuah perkebunan kelapa sawit di Pangkalan Lima Puluh Kota, Sumatera Barat, Indonesia. Kajian ini menggunakan data iklim kurun waktu 2011-2019 dan data produktivitas dari tahun 2015-2019. Untuk mengetahui kontribusi dari RF, Qs, dan vapour pressure deficit / VPD, yang diestimasikan dari data suhu udara dan kelembaban udara, telah digunakan Metode LMG metric yang dikembangkan oleh Lindemann, Merenda, and Gold. Hasil kajian menunjukkan bahwa RF, Qs, dan VPD secara bersamaan mempengaruhi 42.29% fluktuasi produktivitas di lokasi kajian. Lebih lanjut, kontribusi faktor iklim terhadap produktivitas tanaman kelapa sawit mengikuti urutan sebagai berikut VPD > Qs > RF.*

Kata kunci: *curah hujan, iklim, kelapa sawit, produktivitas, radiasi matahari, vapour pressure deficit*

INTRODUCTION

Oil palm is a crop that is highly sensitive to changes in climatic conditions (Kamil & Omar, 2016). Among the many climate factors influencing its growth and development, rainfall (RF), radiation (Qs), temperature, and humidity are considered the most crucial (Woittiez *et al.*, 2017). According to Corley & Tinker (2015), for optimal growth and development, oil palm requires an annual RF of between 2000 and 2500 mm/year. However, Darlan *et al.* (2016) and Pradiko *et al.* (2016) reported that when the crop experiences RF less than 1250 mm year^{-1}, water deficit of more than 200 mm/year, dry months (RF less than 60 mm/month) for more than three months, or dry spell more than 20 days, drought stress is likely to occur. Sujadi *et al.* (2020) also emphasized that excessive RF of over

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Penulis yang tidak disertai dengan catatan kaki instansi adalah peneliti pada Pusat Penelitian Kelapa Sawit

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3000 mm/year can have a detrimental effect on oil palm productivity due to increased soil erosion, nutrient leaching, and a decrease in solar Qs intensity caused by high levels of cloudiness.

Oil palm is a type of plant that requires direct sunlight to grow and develop optimally, hence, it is classified as a heliophyte (Darlan *et al*., 2016). To grow optimally, the plant requires a Qs intensity of 15-17 MJ/m2/day, but it can still tolerate an intensity ranging from 7-21 MJ/m^2/day. Moreover, Qs outside of this range is unsuitable for the plant (Rhebergen *et al*., 2016). According to Verheye (2010), the minimum sunshine duration required by oil palm is 4 hours/day. Darlan *et al.* (2016) & Woittiez *et al.* (2017) further found that insufficient solar Qs can disrupt its growth and productivity. In line with their study, Hasibuan & Pradiko (2018) explained that when oil palm experiences drought stress, the low reception of solar Qs can cause a decrease in oil yield. This is because the amount of photosynthetically active radiation (PAR) intercepted by plants strongly influences their biomass production (Henson I. E, 2000). The reduction in solar Qs reception can be caused by several factors, such as haze disturbances (Hasibuan & Pradiko, 2018), shading, high cloudiness levels, and RF. High levels of cloudiness are typically observed in highland areas where the sunshine duration can be lower than 4 hours/day in some cases (Darlan *et al*., 2017).

The optimal air temperature for oil palm is 24-33°C, although in extreme cases, it can survive in a temperature range of 15-38°C (Paterson *et al*., 2015; Pirker *et al*., 2016). When exposed to higher temperatures, the plant undergoes photorespiration (Ibrahim *et al*., 2010), while at low temperatures, it experiences a slowed growth phase (Darlan *et al*., 2017). Moreover, air temperature affects the duration of oil palm bunch development. In some studies, air temperature cannot be considered in isolation, as it is closely linked to air humidity, and the two variables are combined into a vapor pressure deficit (VPD) variable. According to Pradiko *et al.* (2023), the VPD is a dominant climatic factors affecting the transpiration rate of oil palm.

The quantitative contribution of climate factors, particularly solar Qs, RF, and VPD, to oil palm productivity, which is measured in tons of FFB/ha, has not been extensively discussed. Therefore, this study attempts to quantify the impact of these three factors on the plant's productivity. Ultimately, this study seeks to identify the dominant climatic factors influencing oil palm production. The results of this study are expected to serve as a basis for planters to anticipate negative impacts due to climate and weather anomalies.

MATERIALS AND METHODS

Study Location

This study was conducted in one of oil palm plantations in Lima Puluh Kota Regency, West Sumatra as shown in Figure 1. The main focus was on a 15-year-old oil palm that was planted in 2005. The soil types in this location include Typic Hapludults, Psammentic Paleudult, and Typic Ochraquults, all of which had relatively low fertility. In terms of topography, the land was flat to undulating, with an altitude ranging from 180-450 meters a.s.l.

Climate Condition

The average solar (Qs) for 2011-2019 was 10.13 MJ/m^2. The data was obtained from Direct Normal Irradiance (DNI), measuring the amount of solar Qs that directly hits the earth's surface. It is important to note that the solar Qs reaching the earth's atmosphere consists of both DNI and Diffuse Horizontal Irradiance (DHI). In particular, DHI is the Qs reflected by the ground and clouds. This implies that the DNI value is influenced by the level of cloud cover. In this study, the DNI data were obtained from the website of www.toolkit.solcast.com.au.

Figure 2 presents the solar Qs (MJ/m^2/day) at the study site. The direct solar Qs was generally under optimal conditions, which is 17 MJ/m^2/day, it often fell below the minimum threshold for oil palm plantations, namely 7 MJ/m^2/day. Furthermore, the location experiences a high average rainy day, which reaches 183 days/year, indicating high cloudiness levels. According to Harjupa (2013), these high cloudiness levels are caused by high RF and local circulation, especially the orographic effects triggered by the Barisan Mountains.

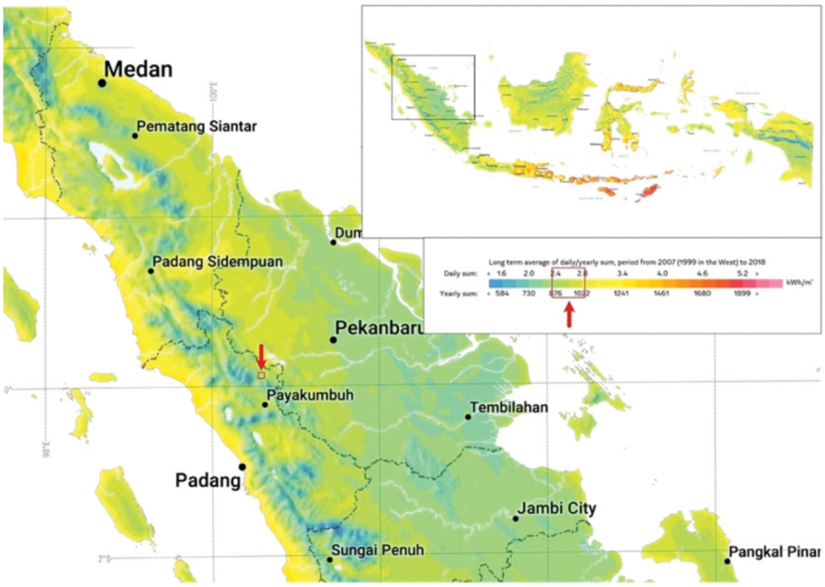

Figure 1. Map of the study site and the estimation of solar energy received per year

Gambar 1. Peta lokasi penelitian dan estimasi penerimaan energi matahari per tahun

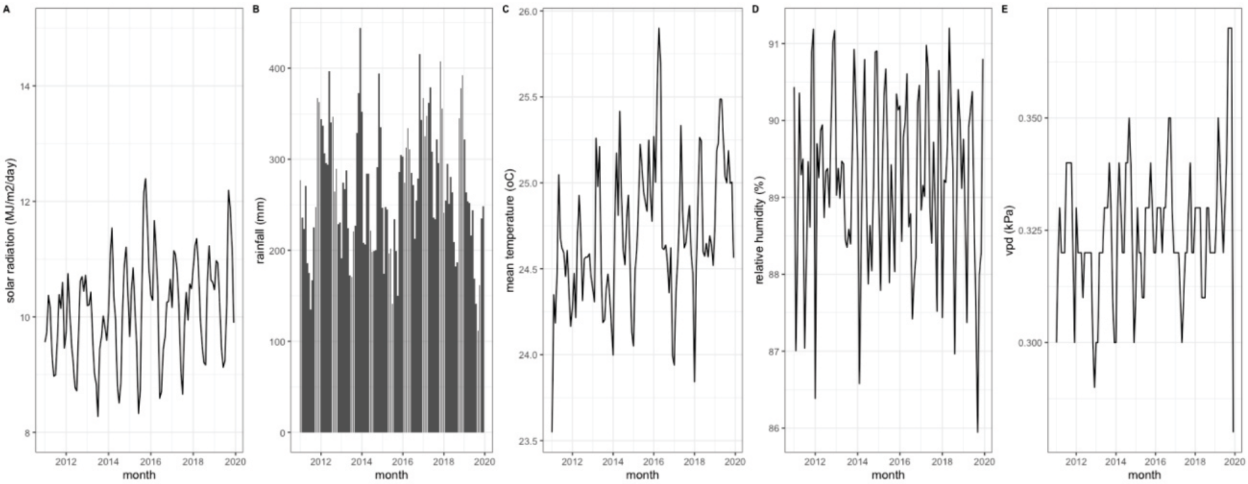

Figure 2. Monthly average solar Qs (A), RF (B), mean temperature (C), relative humidity (D), and VPD (E) at the study site for the period of 2011-2019

Gambar 2. Rerata radiasi matahari bulanan Qs (A), RF (B), rerata suhu udara (C), kelembaban relatif (D), dan VPD (E) pada lokasi kajian kurun waktu 2011-2019

The average RF from 2011 to 2019 was 3213 mm/year, and the average rainy day is 183 days/year. RF at the study site exhibited an equatorial pattern with two peaks, typically occurring in March and November. The average daily temperature was 24.70°C, with the maximum and minimum temperatures being 29.63°C and 20.61°C, respectively, while the average air humidity was 89.22%. Subsequently, the average air temperature and humidity were used to estimate the VPD by applying the equation postulated by Murray (1967). Due to limited availability, these data were obtained from secondary data gridded NASA-POWER (NASA, 2020).

Yield Data

In addition to the aforementioned data, monthly yield data (tons of FFB/ha) was utilized for this study, specifically from 2015 to 2019. Previous data were excluded due to their incompleteness and lack of separation based on the year of planting, which can have compromised accuracy. Figure 3 illustrates the average monthly yield (tonnes/ha). Endogenous and exogenous factors can cause monthly fluctuations in palm oil production. Endogenous factors, or endogenous cycles, are characterized by low production after the previous period of very high production. Environmental conditions and agronomic practices generally influence exogenous factors (Monzon *et al.*, 2022).

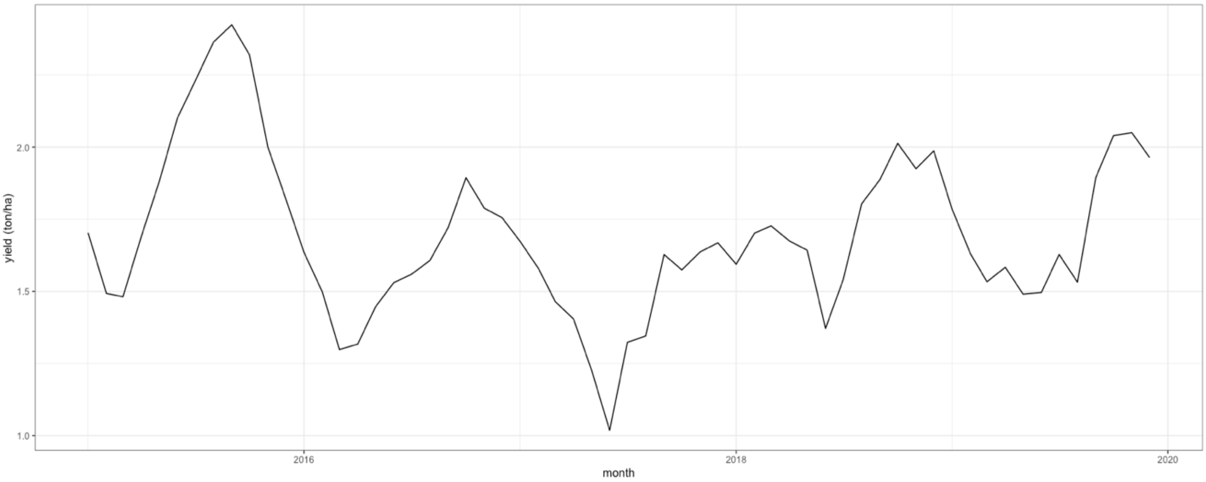

Figure 3. The monthly yield (tonnes/ha) of the study site for the period of 2015-2019
Gambar 3. Produktivitas bulanan (ton/ha) pada lokasi kajian kurun waktu 2015-2019

Data Analysis

Figure 4 outlines the various steps of this study, including the initial stage of data analysis. The first step in this process involved conducting a Pearson correlation test to establish the relationship between climate variables (Qs, RF, and VPD) and productivity. To assess this relationship accurately, a correlation test between climate variables and yield was carried out at lag-0 to lag-43 months. This time frame was selected as it aligns with the duration required for bunch formation and development, which can take up to 3.5 years (Woittiez *et al.*, 2017). Specifically, the correlation test between Qs and yield was conducted between January 2015 to December 2019 (lag-0). Meanwhile, for the lag-43, the correlation test was conducted between Qs for June 2011-May 2016 and yield for January 2015-December 2019. In total, each pair of variables tested for correlation value yielded 43 coefficients.

The correlation test was primarily concerned with identifying critical phases during bunch development, namely critical phases I, II, and III. Critical phase I corresponds to the period when sex differentiation occurs, which was 22-35 months before the bunches ripen. Phase II was the inflorescence abortion phase, which occurred 10-15 months before the bunches ripen. Meanwhile, phase III was the bunches failure stage, which occurred 3-6 months before they were harvested (Woittiez *et al.*, 2017). To delve deeper into the analysis, the highest mean absolute value of the correlation coefficient (r) between the three climate variables and yield during the same lag was selected for further investigation. Among these highest values, it was cross-checked whether the partial correlation value followed the provisions that it has a positive correlation with Qs and RF. In contrast, with VPD, it has a negative correlation. Furthermore, the time lag with the highest Pearson correlation value and fit to the criteria mentioned before was then chosen as the basis for multilinear regression analysis. Multilinear regression analysis was carried out to re-examine whether the direction of the correlation of the variables complied with predetermined criteria. When it was unsuitable, the re-analysis needed to be done using the following best data.

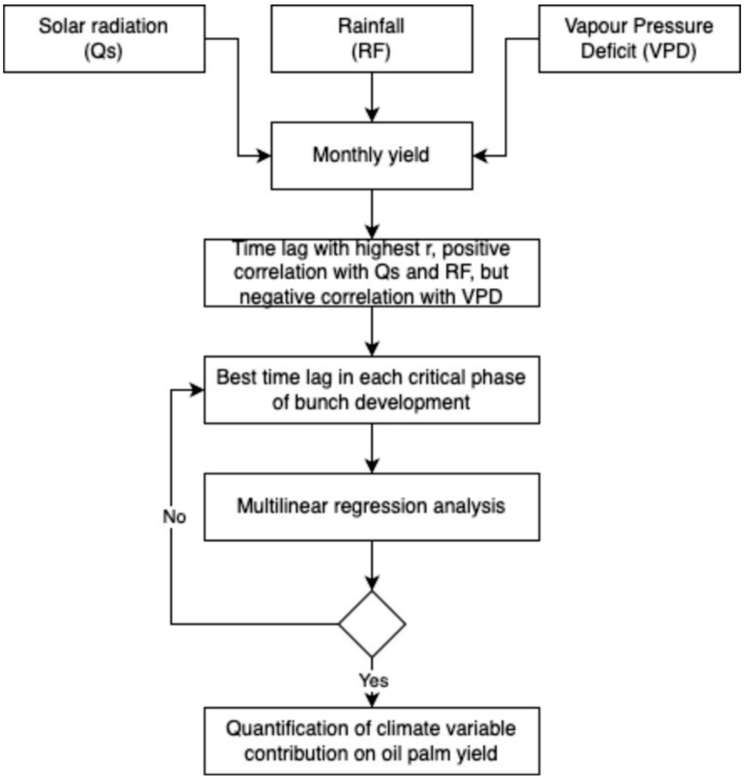

Figure 4. Flowchart of data analysis
Gambar 4. Diagram alir proses analisis data

Further analysis was carried out to quantify the contribution of each climate variable to yield. This was accomplished by utilizing computer-intensive relative importance metrics, specifically, the LMG metric developed by Lindemann, Merenda, and Gold (Grömping, 2006; Grömping, 2015). The R-software was employed to calculate the LMG metric, and the relaimpo package, which contains the LMG calculation package, was downloaded from http://prof.beuth-hochschule.de/groemping/software/relaimpo/.

RESULTS AND DISCUSSIONS

Partial Correlation of Climate Factors on Yield

The influence of climate variables, namely Qs, RF, and VPD, on oil palm yield in the study area was presented in Figure 5. It was observed that the correlation between climate factors and yield varied widely, as indicated by the coefficient ranging from -0.680 to 0.509 (please find Supplementary Material 1 for more detail information). However, among the three phases, only critical phase I at lag-34 conforms to the theoretical relationship between climate factors and yield. Solar radiation and rainfall in the optimal range positively correlate with oil palm yield. While large VPD negatively correlates with oil palm yield (Monzon *et al.*, 2022; Pradiko *et al.*, 2023). This study observed a positive correlation between Qs vs. yield and RF vs. yield, while VPD vs. yield showed a negative correlation at lag-34. Moreover, it can be concluded that the best mean correlation between the three climate factors and yield occurred at lag-34.

Plants rely primarily on solar Qs as their source of energy to carry out photosynthesis. However, they also depend on other climatic factors, such as VPD, which affects their transpiration rates (Pradiko *et al.*, 2023). For example, in the case of oil palm, insufficient sunshine hours (<4 hours/day) have been found to lead to lower production levels (Henson, 2000). This was evident in a study conducted in North Sumatra, where the plant was cultivated at an altitude of 600-900 meters a.s.l, receiving an average of only 3.7 hours/day. Consequently, yield was lower than the potential yield of a marginally suitable land class (Wahyuni, 2021).

RF is an important climatic factors and the primary source of water for oil palm plantations. In general, higher amounts of RF are associated with increased production levels. The optimal monthly RF range for its cultivation is between 40-490 mm/month, which correlates with increased production. The average annual rainfall at the study site is 2088 mm (Pradiko *et al.* 2017). However, excessive RF (>3000 mm/year) can have adverse effects on oil palm plantations (Sujadi *et al.*, 2020).

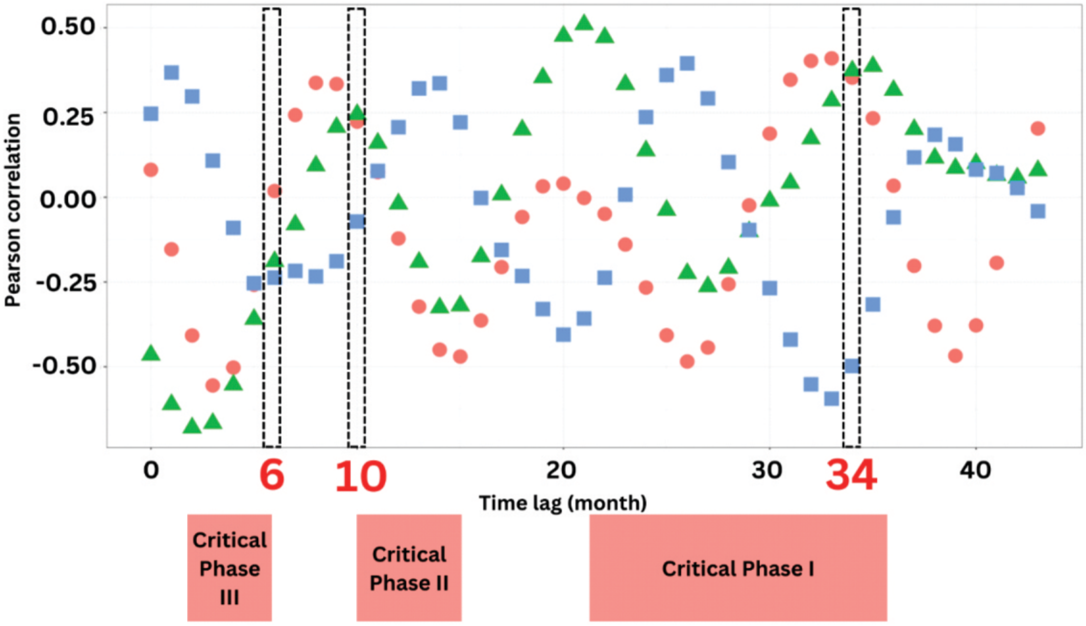

Figure 5. Correlation coefficients of Qs vs. yield (circle), RF vs. yield (triangle), and VPD vs. yield (rectangle) at lag-0 to lag-43 months before harvest. Best correlation between climate variable and yield in critical phase I occurred in lag-34, critical phase II at lag-10, and critical phase III at lag-6. The multilinear equation of each critical phase is attached in Supplementary Material 2.

Gambar 5. Koefisien korelasi antara Qs vs produktivitas (tanda bulat), RF vs produktivitas (tanda segitiga), dan VPD vs produktivitas (tanda kotak) pada lag-0 hingga 43 sebelum panen. Korelasi terbaik antara variabel iklim dan produksi di fase kritis I terjadi pada lag-34, fase kritis II pada lag-10, dan fase kritis III pada lag-6. Persamaan korelasi multilinear dari masing-masing fase kritis disajikan di Supplementary Material 2.

Pradiko *et al.* (2023) stated that VPD contributed significantly to oil palm transpiration. The study found a positive correlation between VPD and transpiration rate until its value reached 2.1 kPa. Beyond this threshold, VPD was negatively correlated with transpiration rate. In this condition, photosynthesis also decreased, thereby affecting oil palm production. According to Monzon *et al.* (2022), productivity is lower in areas with an average VPD >0.6 kPa compared to regions with a lower value. Similarly, Carr (2011) found that an increase in VPD without adequate water supply can lead to a decrease in production. On the other hand, Brum *et al.* (2020) argued that providing adequate water supply during ENSO droughts can increase oil palm yield by up to 35% compared to crops without adequate irrigation.

Although Figure 5 provides partial correlation information between each climatic factors and yield, it does not present a complete picture of the impact of climate factors on oil palm production. This is because the various climate factors interact with each other, thereby influencing the plant's production collectively. For example, Oettli *et al.* (2018) discovered that during El Nino, RF decreased and air temperature increased, leading to reduced oil production compared to normal conditions. Furthermore, Pradiko *et al.* (2023) stated that when the solar Qs is <10 MJ/m^2/day and the VPD is <0.5 kPa, the transpiration of the plants declines, and frequent occurrences of this condition can lead to a decrease in the photosynthesis rate, ultimately reducing oil palm production.

Quantification of Qs, RF, and VPD on Oil Palm Yield

Figure 6 displays the results of the contribution analysis of climate factors to yield, with detailed information presented in Supplementary Materials 3. Based on the outcome, the three climate factors accounted for 42.29% of yield fluctuations. Among factors, VPD was the most dominant, contributing 22.95% of the 42.29% total, while RF had the smallest contribution. Furthermore, it was observed the non-climate factors had a significant impact as they accounted for 57.71% of production fluctuations.

The findings that VPD has the most significant impact on oil palm production aligned with previous studies conducted by Monzon *et al.* (2022) and Brum *et al.* (2020). Pradiko *et al.* (2023) and Bayona-Rodriguez & Romero (2016) also identified that VPD was the dominant climatic factors affecting the transpiration of the plant. Typically, an increase in the value leads to increased transpiration and reduced water use efficiency in most crops (Kemanian *et al.*, 2005). However, in oil palm, when the value is increased above a certain threshold, it can trigger partial stomatal closure (Waite *et al.*, 2019). This means the dominant contribution of VPD to yield in this study indirectly indicated that temperature and relative humidity contributed significantly to determining yield.

The low yield was found to be related to the low VPD value. The average daily VPD in the study locations ranged from 0.28-0.37 (Figure 2E). Lower VPD caused the transpiration rate not to be maximal. This condition was also compounded by the frequent low solar radiation at the study site (<7 MJ/m^2/day). It was consistent with the previous finding of Pradiko *et al.* (2023), stating that transpiration was lower when VPD <0.5 kPa and solar Qs <10 MJ/m^2/day. This condition would cause the oil palm photosynthesis to be less than optimal so that the oil palm yield would be low.

Solar radiation (Qs) is the second climatic factors affecting oil palm yield in this study. The contribution of Qs on oil palm yield was 14.56%. Interestingly, the contribution of climate factors to yield fluctuations was lower compared to transpiration. The contribution of Qs (Figure 6) was different from the previous study reported by Pradiko *et al.* (2023), stating that it can reach up to 80% in transpiration. This indicated that oil palm has a buffering ability to environmental changes (Legros *et al.*, 2009). Furthermore, the low VPD and Qs at the study site lead to the RF contribution being insignificant. Consequently, high RF was not matched by high Qs and VPD, causing the photosynthesis process to be disrupted.

The less significant contribution of RF to production fluctuations was similar to the study conducted by Monzon *et al.* (2022). It was discovered that the most significant correlation between RF and the components of oil palm production was not more than 0.3. Despite this result, an average annual RF of >3000 mm/year can still cause a decrease in production under certain conditions. Generally, areas with high rainfall also have high cloudiness levels. It would reduce sunshine hours. In addition, high rainfall would also affect the harvesting process, especially in unfavorable harvest road conditions. Both factors could cause a decrease in palm oil yield.

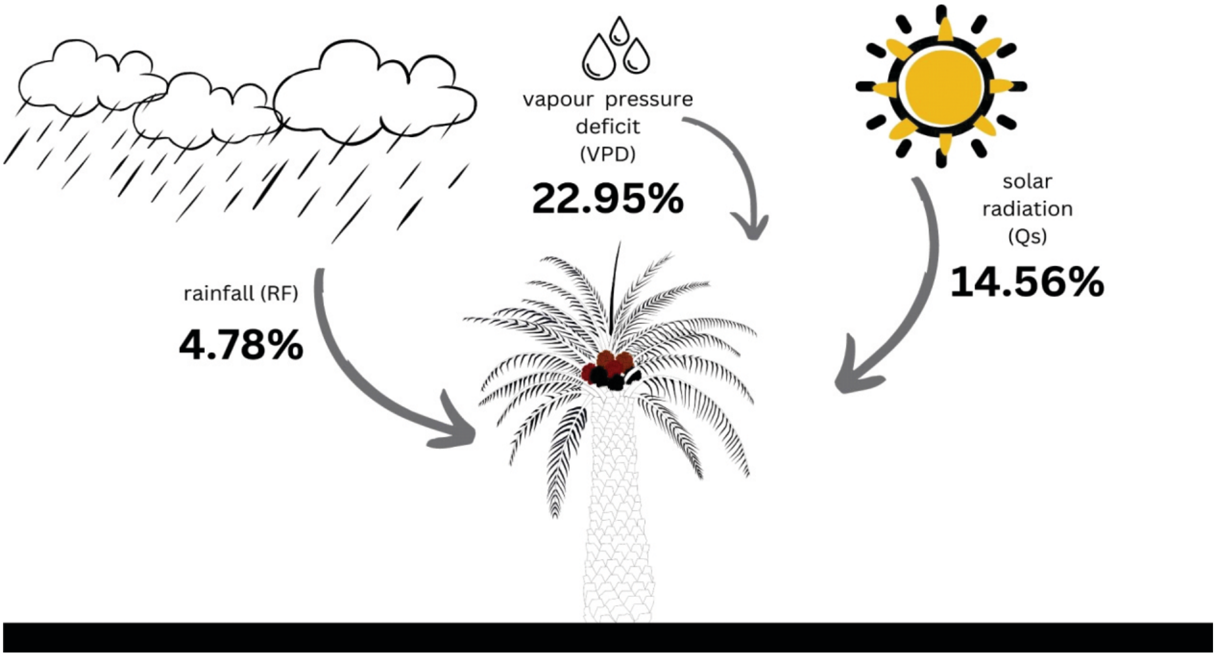

Figure 6. The percentage of Qs, RF, dan VPD contribution to oil palm yield

Gambar 6. Persentase kontribusi Qs, RF, dan VPD terhadap produktivitas tanaman kelapa sawit

CONCLUSION

The correlation between climate factors and yield varied widely. Among the three critical phase of bunch formation and development, only phase I (sex differentiation) conforms to the theoretical relationship between climate factors and yield. A positive correlation was observed between Qs vs. yield and RF vs. yield, while VPD vs. yield showed a negative correlation. It can be concluded that the highest mean correlation between the three climate factors and yield occurred at lag-34.

In critical phase I, specifically 34 months before harvest, the climatic factors of solar Qs, RF, and VPD showed the most remarkable correlation with yield. These three climatic factors accounted for 42.29% of the production fluctuations. Moreover, the VPD has the most significant contribution to yield fluctuations.

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Supplementary Material 1: Partial correlation index between climate variables and oil palm yield between lag-0 and lag-43 month.

Critical Phases	Time Lag (month)	Partial Correlation Index			Average Correlation Index	Note
		Qs vs yield	RF vs yield	VPD vs yield		
	lag-0	0.081	- 0.465	0.246	0.264	
	lag-1	- 0.154	- 0.611	0.368	0.377	
	lag-2	- 0.408	- 0.680	0.297	0.462	
III	lag-3	- 0.555	- 0.667	0.108	0.443	
	lag-4	- 0.502	- 0.553	- 0.090	0.382	
	lag-5	- 0.258	- 0.360	- 0.254	0.290	
	lag-6	0.018	- 0.189	- 0.237	**0.148**	*best time lag for critical phase III since no one meets the criteria*
	lag-7	0.242	- 0.081	- 0.217	0.180	
	lag-8	0.337	0.093	- 0.234	0.221	
	lag-9	0.334	0.207	- 0.189	0.243	
II	lag-10	0.223	0.245	- 0.072	**0.180**	*best time lag for critical phase II*
	lag-11	0.074	0.160	0.078	0.104	
	lag-12	- 0.122	- 0.019	0.207	0.116	
	lag-13	- 0.323	- 0.191	0.321	0.278	
	lag-14	- 0.450	- 0.326	0.336	0.371	
	lag-15	- 0.470	- 0.320	0.221	0.337	
	lag-16	- 0.364	- 0.175	- 0.002	0.180	
	lag-17	- 0.206	0.008	- 0.156	0.123	
	lag-18	- 0.058	0.199	- 0.232	0.163	
	lag-19	0.032	0.353	- 0.330	0.238	
	lag-20	0.040	0.475	- 0.405	0.307	
	lag-21	- 0.002	0.509	- 0.358	0.290	
I	lag-22	- 0.049	0.472	- 0.237	0.253	
	lag-23	- 0.139	0.333	0.008	0.160	
	lag-24	- 0.266	0.137	0.236	0.213	
	lag-25	- 0.407	- 0.038	0.360	0.269	
	lag-26	- 0.485	- 0.225	0.395	0.368	
	lag-27	- 0.443	- 0.263	0.291	0.333	
	lag-28	- 0.257	- 0.209	0.104	0.190	
	lag-29	- 0.024	- 0.101	- 0.097	0.074	
	lag-30	0.188	- 0.011	- 0.268	0.155	
	lag-31	0.347	0.042	- 0.420	0.269	
	lag-32	0.402	0.173	- 0.552	0.376	
	lag-33	0.410	0.285	- 0.594	0.430	
	lag-34	0.353	0.373	- 0.498	**0.408**	*best time lag for critical phase I*
	lag-35	0.233	0.386	- 0.316	0.312	
	lag-36	0.034	0.316	- 0.059	0.136	
	lag-37	- 0.202	0.200	0.118	0.173	
	lag-38	- 0.379	0.116	0.184	0.226	
	lag-39	- 0.468	0.086	0.156	0.237	
	lag-40	- 0.378	0.100	0.082	0.186	
	lag-41	- 0.194	0.065	0.072	0.110	
	lag-42	0.029	0.057	0.027	0.038	
	lag-43	0.203	0.079	- 0.041	0.108	

Supplementary Material 2: Equation of the best time lag at each critical phase.

Critical phase I: Lag-6

`Equation: y = 5.159732 - 0.007520*Qs - 0.001579*RF - 9.082152*VPD`

where y is monthly yield (ton/ha); Qs is average solar irradiance (MJ/m^2/month); RF is monthly rainfall (mm/month); VPD is average vapour pressure deficit (kPa/month)

Detailed information:

```
Call:
lm(formula = yield ~ ., data = yield6)

Residuals:
     Min       1Q   Median       3Q      Max 
-0.65691 -0.15785 -0.05567  0.14718  0.68177 

Coefficients:
             Estimate Std. Error t value Pr(>|t|)    
(Intercept)  5.159732   1.091494   4.727 1.58e-05 ***
rad         -0.007520   0.039960  -0.188  0.85141    
rain        -0.001579   0.000590  -2.676  0.00975 ** 
vpd         -9.082152   3.236814  -2.806  0.00689 ** 
---
Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1

Residual standard error: 0.2593 on 56 degrees of freedom
Multiple R-squared:  0.1845,	Adjusted R-squared:  0.1409 
F-statistic: 4.224 on 3 and 56 DF,  p-value: 0.009207
```

Critical phase I: Lag-10

`Equation: y = 0.8517676 + 0.0719517*Qs + 0.0008843*RF - 0.4409568*VPD`

where y is monthly yield (ton/ha); Qs is average solar irradiance (MJ/m^2/month); RF is monthly rainfall (mm/month); VPD is average vapour pressure deficit (kPa/month)

Detailed information:

```
Call:
lm(formula = yield ~ ., data = yield10)

Residuals:
     Min       1Q   Median       3Q      Max 
-0.54968 -0.18737 -0.06324  0.14048  0.62013 

Coefficients:
              Estimate Std. Error t value Pr(>|t|)  
(Intercept)  0.8517676  1.1508572   0.740   0.4623  
rad          0.0719517  0.0403957   1.781   0.0803 .
rain         0.0008843  0.0006038   1.465   0.1486  
vpd         -0.4409568  3.4372798  -0.128   0.8984  
---
Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1

Residual standard error: 0.2675 on 56 degrees of freedom
Multiple R-squared:  0.1326,	Adjusted R-squared:  0.08616 
F-statistic: 2.854 on 3 and 56 DF,  p-value: 0.04524
```

Critical phase I: Lag-34

`Equation: y = 3.857e+00 + 1.167e-01*Qs + 4.142e-04*RF - 1.068e+01*VPD`

where y is monthly yield (ton/ha); Qs is average solar irradiance (MJ/m2/month); RF is monthly rainfall (mm/month); VPD is average vapour pressure deficit (kPa/month)

Detailed information:

```
Call:
lm(formula = yield ~ ., data = yield34)

Residuals:
     Min       1Q   Median       3Q      Max
-0.39088 -0.16250 -0.01906  0.11114  0.51036

Coefficients:
              Estimate Std. Error t value Pr(>|t|)
(Intercept)  3.857e+00  8.267e-01   4.665 1.96e-05 ***
rad          1.167e-01  3.027e-02   3.857 0.000298 ***
rain         4.142e-04  4.442e-04   0.932 0.355141
vpd         -1.068e+01  2.343e+00  -4.558 2.84e-05 ***
---
Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1

Residual standard error: 0.2182 on 56 degrees of freedom
Multiple R-squared:  0.4229,    Adjusted R-squared:  0.392
F-statistic: 13.68 on 3 and 56 DF,  p-value: 8.3e-07
```

Supplementary Material 3: Quantification of climate variable contribution on oil palm yield using LMG metric

```
Call:
lm(formula = yield ~ ., data = yield34)
Residuals:
     Min       1Q   Median       3Q      Max
-0.39088 -0.16250 -0.01906  0.11114  0.51036

Coefficients:
              Estimate Std. Error t value Pr(>|t|)
(Intercept)  3.857e+00  8.267e-01   4.665 1.96e-05 ***
rad          1.167e-01  3.027e-02   3.857 0.000298 ***
rain         4.142e-04  4.442e-04   0.932 0.355141
vpd         -1.068e+01  2.343e+00  -4.558 2.84e-05 ***
---
Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1

Residual standard error: 0.2182 on 56 degrees of freedom
Multiple R-squared:  0.4229,   Adjusted R-squared:  0.392
F-statistic: 13.68 on 3 and 56 DF,  p-value: 8.3e-07

> anova(linmod34)
Analysis of Variance Table

Response: yield
          Df  Sum Sq Mean Sq F value    Pr(>F)
rad        1 0.64998 0.64998 13.6569 0.0005004 ***
rain       1 0.31441 0.31441  6.6062 0.0128494 *
vpd        1 0.98898 0.98898 20.7796 2.843e-05 ***
Residuals 56 2.66525 0.04759
---
Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1

> reverse <- anova(lm(yield ~ rad + rain + vpd, data = yield34))

> calc.relimp(linmod, type = c("lmg"), rela = TRUE)

trying URL 'https://cran.rstudio.com/bin/macosx/contrib/4.2/mitools_2.4.tgz'
Content type 'application/x-gzip' length 269521 bytes (263 KB)
==================================================

> calc.relimp(linmod34, type = c("lmg"), rela = FALSE)
Response variable: yield
Total response variance: 0.07828185
Analysis based on 60 observations

3 Regressors:
rad rain vpd
Proportion of variance explained by model: 42.29%
Metrics are not normalized (rela=FALSE).

Relative importance metrics:

            lmg
```

```
rad  0.14563880
rain 0.04776145
vpd  0.22953446

Average coefficients for different model sizes:

                 1X           2Xs           3Xs
rad    0.110634498  1.114960e-01  1.167493e-01
rain   0.001228763  8.600337e-04  4.141725e-04
vpd  -10.829239481 -1.057151e+01 -1.067991e+01

> calc.relimp(linmod34, type = c("lmg"), rela = TRUE)
Response variable: yield
Total response variance: 0.07828185
Analysis based on 60 observations

3 Regressors:
rad rain vpd
Proportion of variance explained by model: 42.29%
Metrics are normalized to sum to 100% (rela=TRUE).



Relative importance metrics:

           lmg
rad  0.3443529
rain 0.1129287
vpd  0.5427184

Average coefficients for different model sizes:

                 1X           2Xs           3Xs
rad    0.110634498  1.114960e-01  1.167493e-01
rain   0.001228763  8.600337e-04  4.141725e-04
vpd  -10.829239481 -1.057151e+01 -1.067991e+01

> bootresult <- boot.relimp(linmod34, b = 1000, type = c("lmg", "last",
"first"), fixed = FALSE)
> booteval.relimp (bootresult, typesel = c("lmg"), level = 0.9,bty = "perc",
nodiff = TRUE)


Confidence interval information ( 1000 bootstrap replicates, bty= perc ):
Relative Contributions with confidence intervals:

                           Lower  Upper
          percentage 0.9 0.9    0.9
rad.lmg  0.1456      ABC 0.0696 0.2403
rain.lmg 0.0478      _BC 0.0106 0.1331
vpd.lmg  0.2295      AB_ 0.0966 0.3757

Letters indicate the ranks covered by bootstrap CIs.
 (Rank bootstrap confidence intervals always obtained by percentile method)
```

```
CAUTION: Bootstrap confidence intervals can be somewhat liberal.
Warning message:
In matrix(cbind(x@lmg, x@pmvd, x@last, x@first, x@betasq, x@pratt,  :
  data length differs from size of matrix: [9 != 3 x 1]
```