Maritime Technology and Society
Vol. 5(1): 117-126, February 2026
https://doi.org/10.62012/mp.vi.48201

Regular Research Article

Analysis of the Relationship between Chlorophyll-a Concentration Variability and Sea Surface Temperature on ENSO and IOD Phenomena in the Waters of Sumenep, Madura Island

Zacky Maulana Alfaridzi[1], Inayatul Lailiyah[1*], Aries Dwi Siswanto[1], Ilham Cahya[1] and Anita Kusuma Wardhani[2]

[1]Program Studi Ilmu Kelautan, Jurusan Kelautan Dan Perikanan, Fakultas Pertanian, Universitas Trunodjoyo Madura, Indonesia
[2]Departemen Teknik Kelautan Fakultas Teknologi Kelautan, Institut Teknologi Sepuluh November, Indonesia

*inayatul.lailiyah@trunojoyo.ac.id

Abstract: Indonesia's marine environment is highly sensitive to global climate variability, particularly El Niño–Southern Oscillation (ENSO) and the Indian Ocean Dipole (IOD). This study analyzes the spatial and temporal variability of sea surface temperature (SST) and chlorophyll-a concentration and their relationship with ENSO and IOD in Sumenep waters, Madura Island. SST and chlorophyll-a data were derived from Aqua MODIS satellite observations for the period 2014–2024, while ENSO and IOD were represented by the Oceanic Niño Index (ONI) and Dipole Mode Index (DMI). Data were analyzed using temporal trend analysis, spatial mapping, and Pearson correlation. The results show that SST fluctuated between 28.01 and 30.75 °C, with higher temperatures during El Niño phases and lower temperatures during La Niña phases. Chlorophyll-a exhibited relatively stable minimum values (0.178–0.217 mg/m³), while maximum values varied between 0.499 and 0.782 mg/m³, peaking in 2020. Pearson correlation analysis indicates a strong relationship between ENSO and SST (r = 0.791) and a very strong relationship with chlorophyll-a (r = 0.898). In contrast, IOD shows very weak correlations with SST (r = 0.074) and chlorophyll-a (r = 0.211). These findings confirm that ENSO is the dominant driver of SST and chlorophyll-a variability in Sumenep waters, with important implications for regional marine productivity.

Keywords: Chlorophyll-a, Sea Surface Temperature (SST), ENSO, IOD, Sumenep Waters

1. Introduction

Indonesia is the largest archipelagic country in the world with a strategic geographical position, flanked by the Indian Ocean to the west and the Pacific Ocean to the east [1]. The waters of Sumenep in northern Madura Island have oceanographic conditions that are sensitive to ENSO and IOD fluctuations [2]. Global climate phenomena such as the El Niño Southern Oscillation (ENSO) and the Indian Ocean Dipole (IOD) are major factors influencing oceanographic variability in tropical waters. The changes caused by ENSO and IOD can have a significant impact on sea surface temperature (SST) and the distribution of chlorophyll-a concentration related to primary productivity, which is directly influenced by these two climate phenomena [3].

Global climate phenomena such as ENSO and IOD play an important role in regulating tropical ocean dynamics. ENSO in the El Niño phase tends to increase sea surface temperature (SST) and decrease chlorophyll-a, while La Niña does the opposite, decreasing SST and increasing primary productivity [4]. The IOD also affects water conditions, with the positive

Received: 2025-11-10; Accepted: 2026-01-01

phase promoting upwelling that enriches chlorophyll-a, while the negative phase weakens marine productivity [5]. Changes in SST and chlorophyll-a have a direct impact on marine ecosystems and the fisheries sector. Understanding the effects of ENSO and IOD is essential to understanding water variability [6].

The variability of SST and chlorophyll-a in Indonesian waters is very complex because it is influenced by the interaction of the global ENSO phenomenon in the Pacific Ocean and the IOD in the Indian Ocean [7]. Both parameters undergo spatial and temporal changes due to climate influences [8]. This study analyzes the relationship between SST and chlorophyll-a with ENSO and IOD in the waters of Sumenep, Madura Island, with differences in location and study period compared to previous studies in the Flores Sea. The objective of this study is to analyze the spatial and temporal variability of sea surface temperature (SST) and chlorophyll-a concentration and their relationship with the global climate phenomena El Niño–Southern Oscillation (ENSO) and Indian Ocean Dipole (IOD) in the waters of Sumenep, Madura Island.

2. Materials and Methods

2.1 Study Area

Research on “Analysis of the Relationship between Chlorophyll-a Concentration Variability and Sea Surface Temperature in ENSO and IOD Phenomena in the Waters of Sumenep, Madura Island.” This research was conducted in Sumenep Regency, Madura, East Java. The research location is shown in Figure 1 below, which displays the study area marked with a red box on a topographic map and satellite image with a resolution of 4 km, directly covering the area between 113.479°–116.812° E and 7.604°–5.062° S.

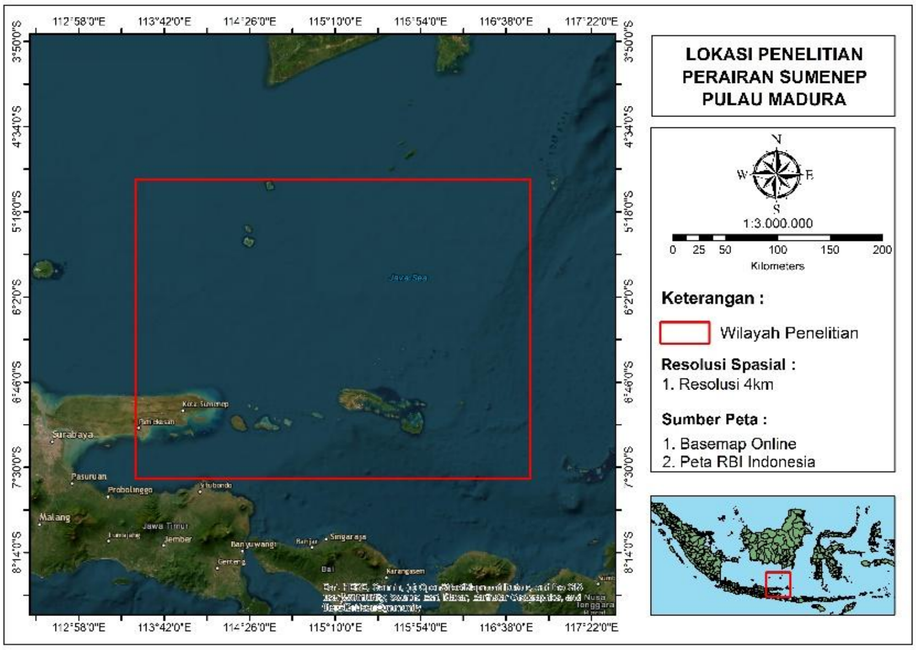

Figure 1. Study Area

2.2 Data Collection and Processing

This study was conducted through several systematic stages, including research preparation, data processing, data analysis, and report writing.

During the preparation stage, sea surface temperature (SST) and chlorophyll-a data were obtained from Level-3 Aqua MODIS monthly composite satellite imagery with a spatial resolution of 4 km. Climate indices representing the El Niño–Southern Oscillation (ENSO) and the Indian Ocean Dipole (IOD) were derived from the Oceanic Niño Index (ONI) and the Dipole Mode Index (DMI), respectively.

The data processing stage employed SeaDAS, Microsoft Excel, SPSS, and ArcGIS software. In SeaDAS, satellite data were subjected to spatial subsetting based on the study area, quality control procedures to eliminate invalid pixels, and spatial averaging. Monthly mean values were then calculated to synchronize SST and chlorophyll-a data with the ENSO and IOD indices. This temporal averaging approach reduces short-term variability and enhances the identification of climate-driven signals.

The analysis stage consisted of temporal trend analysis, spatial distribution mapping, and statistical correlation analysis. The results were subsequently compared with relevant literature to support interpretation and discussion.

2.3 Data Analysis

2.3.1 Monthly Average Calculations

Data analysis began with the collection of global climate index data for ENSO (Niño 3.4 Index) and IOD (Dipole Mode Index), along with satellite-derived sea surface temperature (SST) and chlorophyll-a concentration data for the period 2014–2024. All datasets were transformed into monthly time series to ensure temporal synchronization.

According to previous studies [9], monthly averages were calculated by summing all daily values of a given parameter, such as SST or chlorophyll-a concentration, over one month and dividing the total by the number of days in that month. The calculation formula is expressed as follows:

$$(X) = \frac{\sum_{i=1}^{n} Xi(x,y,t)}{n} \qquad (1)$$

where X is the average value of a parameter in one month. This value is obtained from the i-th daily data (Xi(x,y,t))(Xi(x,y,t))(Xi(x,y,t)) in that month, which is then summed and divided by the number of days in that month (nnn). The number of days in a month can vary, namely 28, 29, 30, or 31 days, depending on the calendar.

2.2.1 Temporal Analysis

The processed data is then visualized in the form of seasonal and interannual trend graphs. Temporal analysis is carried out by looking at monthly, seasonal, and annual fluctuation patterns to identify long-term trends and anomalies, such as increases in sea surface temperature during certain periods when El Niño occurs.

2.2.2 Spatial Analysis

Spatial analysis is performed by compiling maps of SPL and chlorophyll-a distribution to observe differences in distribution between locations. For example, chlorophyll-a concentrations decrease or increase depending on oceanographic conditions influenced by climate phenomena.

2.2.3 Pearson Correlation

Pearson correlation is used to determine the direct relationship between ENSO and IOD on SPL and chlorophyll-a. Correlation values (r) and significance (p-value) are the basis for determining whether ENSO or IOD have a significant effect. This analysis is also used to assess which factor is more dominant in controlling SPL and chlorophyll-a variability in Sumenep waters.

Table 1. Pearson Correlation Criteria

Nilai r	Interpretasi
0,00 – 0,19	Very Low
0,20 – 0,39	Low
0,40 – 0,59	Moderate
0, 60 – 0,79	Strong
0,80 – 1,00	Very Strong

According to research [10], Pearson's correlation is a statistical method used to measure the strength and direction of a linear relationship between two variables, with a correlation coefficient r ranging from 0 to 1. A large value indicates a very strong relationship, a small value indicates a very weak relationship, while a value close to zero indicates no strong linear relationship, in accordance with the formula provided.

$$r = \frac{n\sum xy - (\sum x)(\sum y)}{\sqrt{[n\sum x^2 - (\sum x)^2]\,[n\sum (y)^2 - (\sum y)^2]}} \qquad (2)$$

where the value r indicates the correlation between two variables. The symbol n represents the number of pairs of x and y. The symbol $\sum x$ represents the total number of x variables, while $\sum y$ represents the total number of y variables. The symbol $\sum x^2$ represents the total number of x variables squared, and $\sum y^2$ represents the total number of y variables squared.

2.4. Statistical Analysis

Data processed using Seadas and Excel was analyzed and illustrated using OriginPro software to visualize the temporal trends of sea surface temperature and chlorophyll-a in relation to the El Niño -Southern Oscillation (ENSO) and Indian Ocean Dipole (IOD) phenomena. To visualize the results spatially, ArcGis software can be used to create spatial maps of sea surface temperature and chlorophyll-a, and Pearson's correlation can be used to test the relationship between all parameters.

3. Results

3.1 Temporal Analysis of Sea Surface Temperature

Figure 2 shows that sea surface temperature (SST) in Sumenep Waters during the 2014–2024 period fluctuated between 27–31 °C, with a sharp increase to 30–31 °C during the El Niño phase (2015–2016, 2023–2024) and a decrease to 27–28 °C during the La Niña phase (2017–2018, 2022). During the positive IOD phase (2019, 2021), the SPL tended to be warm (29–30 °C), while during the negative IOD phase (2022–2023) the temperature was relatively lower. Normal ENSO–IOD conditions are characterized by a stable SPL in the range of 28–29 °C.

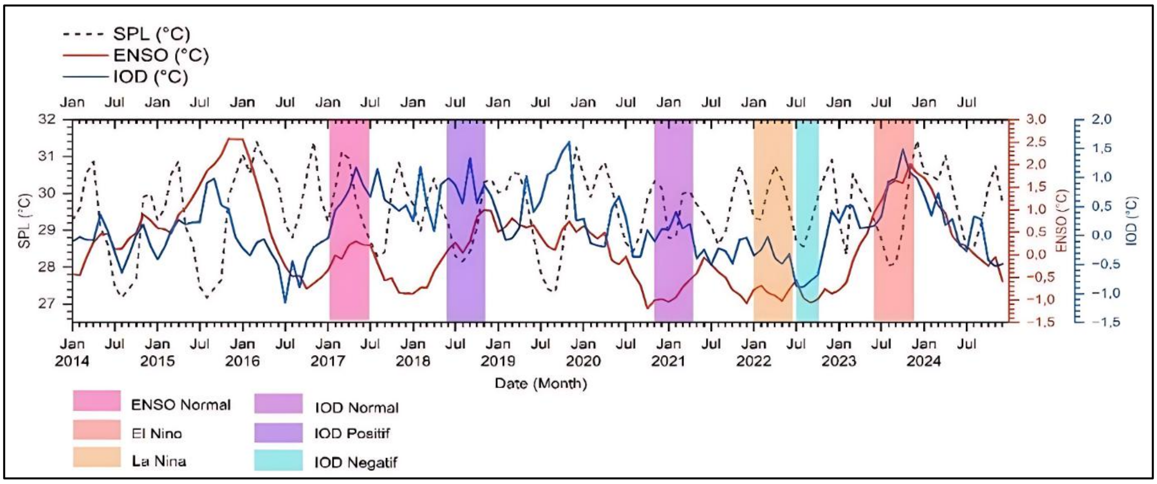

Figure 2. Temporal Variability of Sea Surface Temperature (°C)

3.2 Temporal Analysis of Chlorophyll-a

Figure 3 illustrates the temporal variability of chlorophyll-a concentration in relation to ENSO phases. During the strong El Niño event of 2015–2016, characterized by an ENSO index of approximately 2.5 °C, chlorophyll-a concentrations declined markedly from about 0.5 to 0.2 mg/m³. In contrast, the La Niña episode of 2020–2021, with an index of around −1.2 °C, was associated with a pronounced increase in chlorophyll-a, reaching approximately 0.6 mg/m³. This pattern suggests that ENSO-driven changes in sea surface temperature play a significant role in regulating phytoplankton productivity in the study area.

A similar response was observed in relation to the Indian Ocean Dipole (IOD). During the positive IOD phase in 2019, when the index reached approximately 1.2 °C, chlorophyll-a concentrations decreased to around 0.2 mg/m³. Conversely, negative IOD events in 2016 and 2022, with index values near −0.8 °C, coincided with elevated chlorophyll-a concentrations exceeding 0.5 mg/m³. These findings indicate that both ENSO and IOD exert a substantial influence on the temporal dynamics of chlorophyll-a, likely through their modulation of regional oceanographic conditions such as upwelling intensity and nutrient availability.

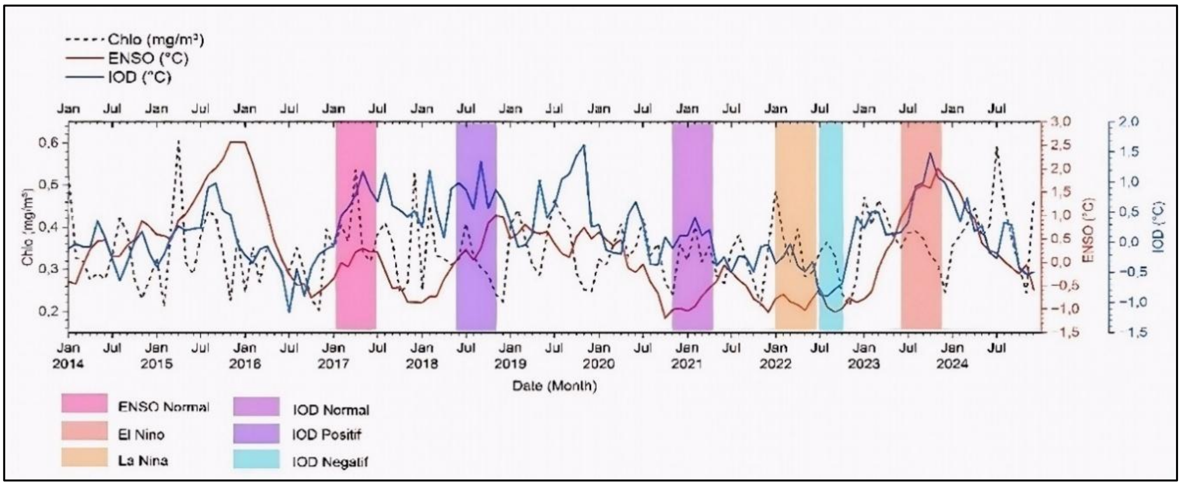

Figure 3. Temporal Variability of Chlorophyll-a (mg/m³)

3.3 Spatial Analysis of Sea Surface Temperature

Figure 4 illustrates that sea surface temperature (SST) in Sumenep waters during the 2014–2024 period fluctuated within a range of 28.01–30.75 °C, indicating notable interannual variability. The lowest SST values were recorded in 2015 (28.01–28.19 °C), followed by a sharp increase in 2016, when SST reached its maximum range of 29.68–30.75 °C. This warming phase coincided with a strong El Niño event, suggesting a clear linkage between elevated SST and ENSO-induced atmospheric–oceanic anomalies.

During the subsequent period from 2017 to 2020, SST exhibited moderate fluctuations between 28.22 and 30.45 °C, with a distinct cooling tendency observed in 2018–2019 that corresponded to La Niña conditions. In contrast, the 2021–2024 period was characterized by relatively stable SST values ranging from 28.96 to 30.28 °C, reflecting near-normal climatic conditions. These temporal SST patterns demonstrate that ENSO acts as the primary driver of thermal variability in Sumenep waters, while the Indian Ocean Dipole (IOD) provides secondary modulation by influencing regional heat distribution and ocean–atmosphere interactions.

In parallel, the spatial distribution of chlorophyll-a consistently reveals higher concentrations in coastal waters compared to offshore areas throughout the study period. This persistent pattern is strongly associated with local coastal processes, including nutrient enrichment from terrestrial runoff, shallow bathymetry, and intensified vertical and horizontal mixing in nearshore zones. Such conditions enhance nutrient availability in surface waters and support phytoplankton growth, particularly during La Niña phases when cooler SST conditions further stimulate primary productivity. Together, the spatial correspondence between SST and chlorophyll-a highlights the critical role of coastal dynamics in regulating biological productivity in Sumenep waters, emphasizing the coupled influence of large-scale climate forcing and local environmental processes.

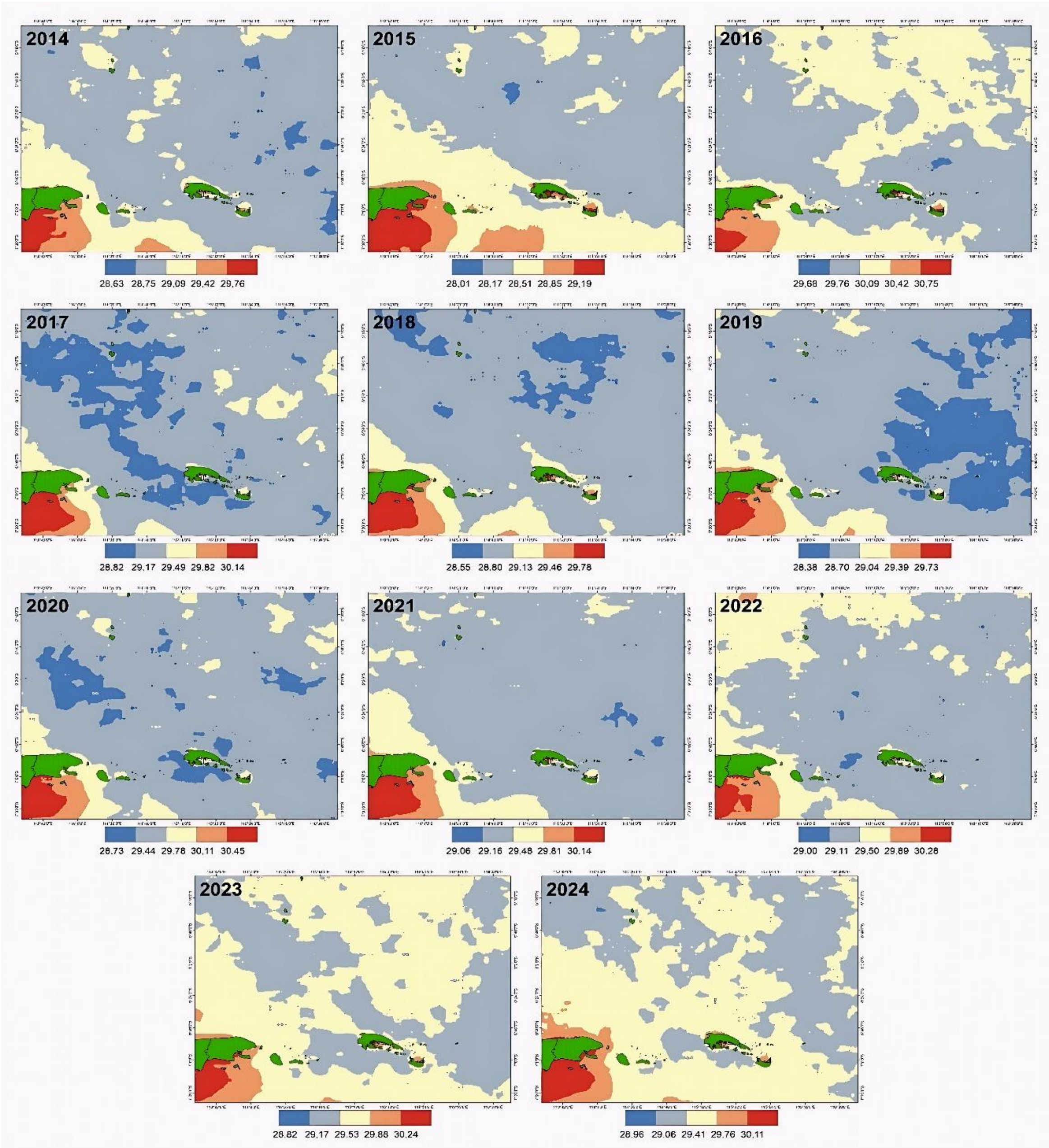

Figure 4. Spatial Distribution of Sea Surface Temperature (°C)

3.4 Spatial Analysis of Chlorophyll-a

Figure 5 shows that chlorophyll-a concentrations in Sumenep waters during the 2014–2024 period fluctuated within the range of 0.166–0.782 mg/m³, reflecting notable spatial and temporal variability in primary productivity. The highest concentrations were observed in 2020 (0.180–0.782 mg/m³), indicating highly fertile waters, whereas the lowest values occurred in 2016 (0.178–0.499 mg/m³), coinciding with reduced productivity conditions. An increasing trend was evident during 2017–2019, with a peak in 2017 reaching approximately 0.677 mg/m³, followed by a relatively stable decline in 2021–2022. In the most recent period (2023–2024), chlorophyll-a concentrations increased again to 0.217–0.670 mg/m³, confirming that the productivity of Sumenep waters remains generally high despite interannual fluctuations. Spatially, chlorophyll-a concentrations were consistently higher in coastal areas compared to offshore waters. This pattern is strongly associated with land-derived nutrient inputs, shallow bathymetry, and enhanced coastal mixing processes that increase nutrient availability in surface waters.

These local coastal processes amplify the response of chlorophyll-a to climate variability, particularly during La Niña periods, when cooler sea surface temperatures further support phytoplankton growth. The combined temporal and spatial patterns highlight the dominant role of coastal dynamics in regulating primary productivity in Sumenep waters and underscore the resilience of this coastal ecosystem under varying climatic conditions.

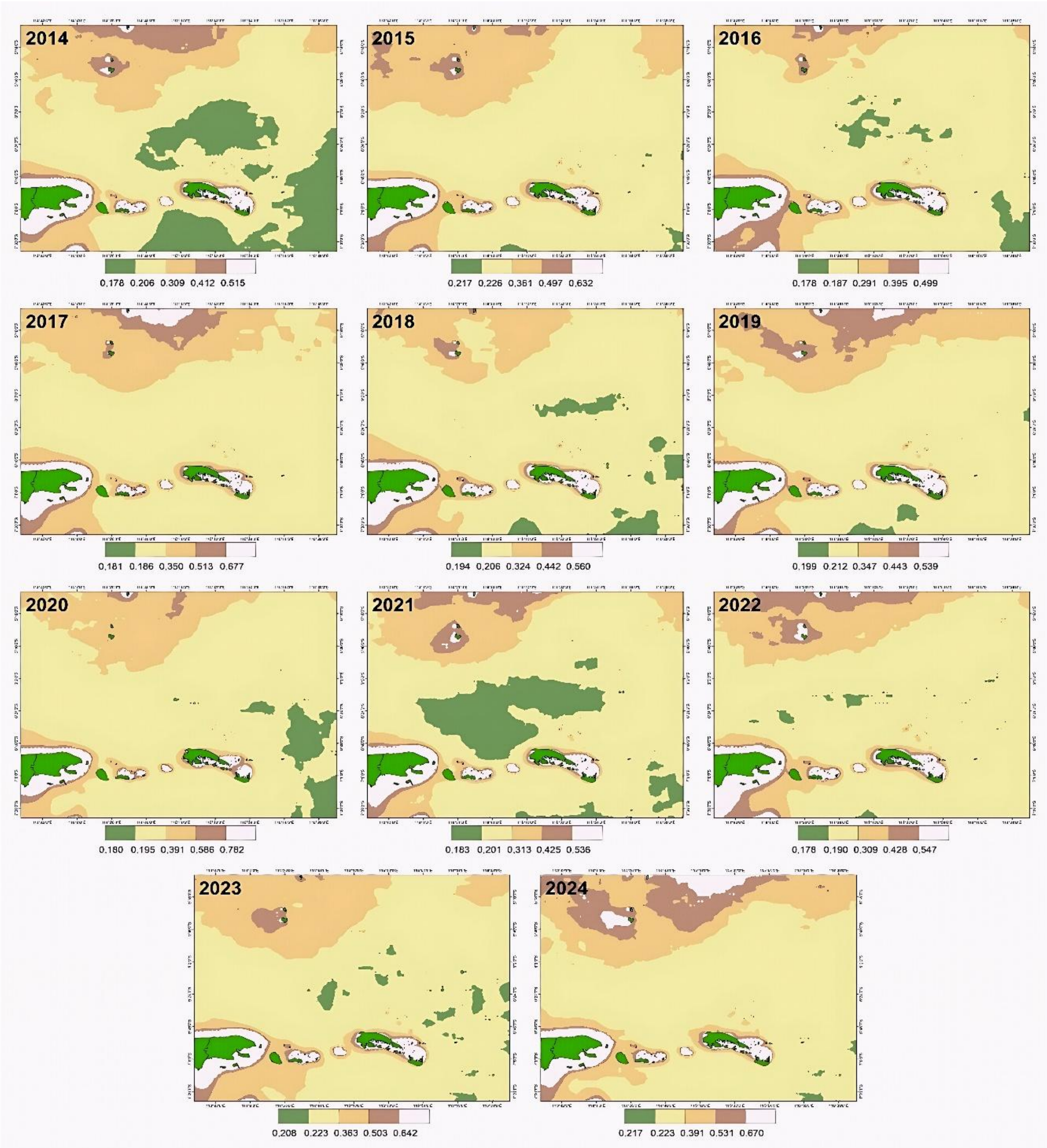

Figure 5. Spatial Distribution of Chlorophyll-a (mg/m³)

3.5 Pearson Correlation

Pearson correlation analysis shows that oceanographic variability in Sumenep waters is more influenced by ENSO than IOD. Sea surface temperature has a strong correlation with ENSO (r = 0.791) but a very low correlation with IOD (r = 0.074), while chlorophyll-a concentration has a very strong correlation with ENSO (r = 0.898) and a low correlation with IOD (r = 0.211). These results confirm that ENSO is the dominant factor controlling changes in SST and chlorophyll-a in the region, as shown in Table 2.

Table 2. Correlation of SST and Chlorophyll-a

with ENSO and IOD

Parameters	Correlation	
	ENSO	IOD
Sea Surface Temperature	0,791	0,074
Chlorophyll-a concentration	0,898	0,211

4. Discussion

Sea surface temperature (SST) variability in the waters of Sumenep during the 2014–2024 period shows pronounced fluctuations primarily driven by large-scale climate variability. SST ranged between 27 and 31 °C, with significant warming during El Niño events in 2015–2016 and 2023–2024, when temperatures reached 30–31 °C. In contrast, La Niña phases in 2017–2018 and 2022 were associated with cooler SST conditions of approximately 27–28 °C. The Indian Ocean Dipole (IOD) also influenced SST variability, although its impact was comparatively minor; positive IOD phases in 2019 and 2021 slightly elevated SST, while negative phases in 2016 and 2022 caused modest cooling. These SST fluctuations are ecologically important, as elevated temperatures may suppress biological productivity, whereas cooler conditions generally promote more fertile marine environments.

Chlorophyll-a concentration, used as a proxy for primary productivity, exhibited clear temporal and spatial variability consistent with SST dynamics. During the strong El Niño period of 2015–2016, chlorophyll-a concentrations declined from approximately 0.5 mg/m³ to 0.2 mg/m³, indicating reduced phytoplankton productivity. Conversely, during La Niña conditions in 2020–2021, chlorophyll-a increased to around 0.6 mg/m³, reflecting enhanced nutrient availability and more productive waters. Spatially, chlorophyll-a concentrations were consistently higher in coastal areas than in offshore waters, influenced by terrestrial nutrient inputs, shallow bathymetry, and intensified nearshore mixing processes. These characteristics highlight the Sumenep coastal zone as a key center of primary productivity supporting the base of the marine food web and potential fishing grounds.

The linkage between climate variability and oceanographic parameters is further supported by Pearson correlation analysis. ENSO shows a strong correlation with SST (r = 0.791) and a very strong correlation with chlorophyll-a (r = 0.898), whereas IOD exhibits a very weak correlation with SST (r = 0.074) and a low correlation with chlorophyll-a (r = 0.211). These results confirm that ENSO is the dominant driver of oceanographic variability in Sumenep waters, while the influence of IOD is limited. This limited IOD impact can be attributed to the geographical position of Sumenep waters in the northern part of Madura Island, which reduces direct exposure to Indian Ocean processes. In contrast, ENSO-related atmospheric and oceanic teleconnections from the Pacific Ocean exert broader and more persistent effects across Indonesian waters. Variations in SST and chlorophyll-a therefore have direct implications for fisheries, as La Niña conditions tend to enhance productivity and fish availability, while El Niño events may reduce catches. Continuous monitoring of these parameters is thus essential to support adaptive and climate-informed fisheries management in Sumenep waters.

5. Conclusions

Sea surface temperature (SST) in Sumenep waters during the 2014–2024 period varied between 28.01 and 30.75 °C, with distinct warming during El Niño phases and cooling during La Niña events. Chlorophyll-a concentrations showed relatively stable minimum values ranging from 0.178 to 0.217 mg/m³, while maximum values varied between 0.499 and 0.782 mg/m³, with the highest peak observed in 2020. Elevated chlorophyll-a concentrations were consistently concentrated in coastal waters adjacent to nutrient-rich islands, underscoring the critical role of coastal processes in sustaining primary productivity. Pearson correlation analysis confirms that ENSO is the dominant driver of oceanographic variability in Sumenep waters, as reflected by its strong correlation with SST (r = 0.791) and very strong correlation with chlorophyll-a (r = 0.898). In contrast, the influence of the Indian Ocean

Dipole (IOD) is comparatively weak, exhibiting very low correlation with SST (r = 0.074) and low correlation with chlorophyll-a (r = 0.211). These results indicate that SST and chlorophyll-a dynamics in Sumenep waters are primarily regulated by ENSO, with important implications for fisheries potential, given the strong sensitivity of fish resources to changes in thermal conditions and primary productivity.

This study is limited to examining the relationships between SST, chlorophyll-a, and large-scale climate indices (ENSO and IOD) and does not explicitly account for other oceanographic drivers such as wind forcing, ocean circulation, vertical mixing, or nutrient fluxes that may influence local variability. Future research incorporating integrated physical and biogeochemical processes, supported by in situ observations, is therefore recommended to provide a more comprehensive understanding of climate–ocean interactions in Sumenep waters and to strengthen climate-adaptive fisheries management strategies.

Acknowledgments

The authors would like to express their gratitude to the Research and Community Service Institute (LPPM), Universitas Trunodjoyo Madura, for research support. Special thanks are also extended to academic supervisors and colleagues who provided valuable assistance during data processing and manuscript preparation.

References

[1] A. Soemarmi, E. Indarti, P. Pujiyono, and A. Diamantina, “Konsep negara kepulauan dalam upaya perlindungan wilayah pengelolaan perikanan Indonesia,” *Masal. Huk.*, vol. 48, no. 3, pp. 241–248, 2019.

[2] A. Y. Yuliardi, H. A. Rachman, R. J. Sari, D. A. Rahmalia, A. T. Nugroho, and L. M. Prayogo, “Analisis Variasi Musiman Suhu, Salinitas, dan Arus Permukaan di Perairan Madura,” *Indones. J. Oceanogr.*, vol. 6, no. 4, pp. 292–305, 2024.

[3] S. Maharani, H. I. Ratnawati, and A. M. Lubis, “Hubungan ENSO-IOD terhadap Curah Hujan dan Suhu Permukaan Laut di Perairan Bengkulu,” *Bul. Oseanografi Mar.*, vol. 14, no. 2, pp. 284–298, 2025.

[4] M. Ariska, H. Akhsan, M. Muslim, S. Sudirman, and K. Kistiono, “Pengaruh el niño southern oscillation (enso) dan indian ocean dipole (iod) terhadap curah hujan dan korelasinya dengan consecutive dry days (cdd) provinsi sumatera selatan dari tahun 1981-2020,” *J. Ilmu Fis. dan Pembelajarannya*, vol. 6, no. 2, pp. 31–41, 2022.

[5] M. F. K. Almunawir, A. Wirasatriya, and R. Widiaratih, “Pengaruh Fenomena IOD Positif Kuat 2019 Terhadap Karakteristik Upwelling di Perairan Nusa Tengggara,” *Indones. J. Oceanogr.*, vol. 6, no. 1, pp. 72–83, 2024.

[6] D. S. Graha, K. Kunarso, and M. Zainuri, “Variabilitas antar tahunan suhu permukaan laut dan klorofil-A terhadap hasil tangkapan ikan kembung (Rastreligger sp.) di perairan Demak,” *Indones. J. Oceanogr.*, vol. 6, no. 2, pp. 148–158, 2024.

[7] M. Z. Alamsyah, G. Handoyo, and Y. J. Wijaya, “Analisis Pengaruh Indian Ocean Dipole Terhadap Suhu Permukaan Laut Dan Klorofil-a Di Selat Karimata Pada Tahun 2008-2022,” *Indones. J. Oceanogr.*, vol. 6, no. 3, pp. 257–265, 2024.

[8] A. Nagi, G. Napitupulu, I. M. Radjawane, S. Nurdjaman, D. Supriadi, and D. Nurhayati, “Pemetaan zona potensial penangkapan ikan tongkol di Perairan Teluk Banten,” *Bul. Oseanografi Mar.*, vol. 12, no. 3, pp. 379–394, 2023.

[9] H. A. Rachman, Z. Hidayah, and A. Y. Yuliardi, “Dinamika Suhu Permukaan Laut dan Konsentrasi Klorofil-a di Perairan Laut Flores Hubungannya dengan Fenomena ENSO dan IOD,” *J. Kelaut. Trop.*, vol. 28, no. 1, pp. 53–62, 2025.

[10] A. L. Latifah, S. Y. Wulandari, and K. Kunarso, “hubungan suhu permukaan laut (SPL) dan klorofil-a terhadap hasil tangkapan yellowfin tuna (Thunnus albacares) yang didaratkan di Pelabuhan Tamperan, Pacitan,” *Indones. J. Oceanogr.*, vol. 6, no. 3, pp. 197–208, 2024.

[11] F. G. Fofied, A. Hartoko, and S. W. Saputra, "Analisis Sebaran Suhu Permukaan Laut, Klorofil-a, dan Zona Potensial Penangkapan Ikan Cakalang di Perairan Jayapura," *Bul. Oseanografi Mar.*, vol. 13, no. 3, pp. 409–423, 2024.