Chlorophyll-a Outliers in the Banda Sea and its surroundings: Implications for Ecosystem Dynamics

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Abstract

Chlorophyll-a concentration is a critical indicator of marine ecosystem health, reflecting primary productivity and potential ecological changes. However, the occurrence of outlier data in the Banda Sea and its surroundings has not been sufficiently studied. This study aims to investigate the dynamics of chlorophyll-a concentration outliers in the Banda Sea, focusing on their spatial and temporal patterns from 2010 to 2022. Data were acquired from MODIS satellite imagery and analyzed using R Studio for time series decomposition, while spatial patterns were explored with ArcGIS 10.8 and Google Maps to pinpoint key hotspots of outlier activity. The findings reveal fluctuating chlorophyll-a outliers with extreme concentrations ranging from 14.39 to 81 mg·m $^{-3}$*. Temporally, these outliers are predominantly observed in the western Banda Sea during January to March and December, while in the eastern Banda Sea they occur from June to September. Spatially, these anomalies are concentrated in areas of significant human activity, particularly in Tolo Bay, suggesting a potential link between anthropogenic influences and ecological disruptions. Field monitoring in areas with persistent outliers is strongly recommended to verify actual conditions and assess their ecological impacts. While chlorophyll-a plays a vital role in marine productivity, excessive concentrations can disrupt ecosystems, potentially leading to harmful algal blooms or hypoxic conditions. This study underscores the importance of integrating remote sensing, field validation, and spatial analysis to effectively monitor and manage these anomalies. Enhanced understanding of these dynamics is critical for informed decision-making and sustainable marine management practices in the Banda Sea.*

Keywords: *Chlorophyll-a outliers, ecosystem dynamics, Banda Sea, FMA 714, machine learning*

Introduction

The Fisheries Management Area is a reference area set by the Ministry of Marine Affairs and Fisheries to support fisheries management policies in Indonesia (Habibullah *et al*., 2023). This policy aims to improve fisheries management sustainably (Purwanto *et al*., 2022). One of the WPPs with great potential is WPP 714, which covers the Banda Sea and its surroundings. This area is known as an area with sizeable pelagic fishery resources, especially tuna (Suharti *et al*., 2023). A deep understanding of oceanographic factors that affect fisheries productivity is needed to make the most of this potential. Oceanographic factors are known to have a major influence on fish catches (Villaseñor-Derbez *et al*., 2019; Manuhutu *et al*., 2021). By understanding the dynamics of oceanography, policies for protecting and managing marine resources can be designed more effectively (Scharffenberg *et al*., 2019; Sala *et al*., 2021). One of the important indicators used to evaluate the quality of aquatic ecosystems is the concentration of chlorophyll-a (Gittings *et al*., 2019; Pérez-Ruzafa *et al*., 2019; Safruddin *et al*., 2022).

Chlorophyll-a is a photosynthetic pigment that plays an important role in aquatic ecology. Its concentration reflects the health of aquatic ecosystems and is an important indicator for monitoring water quality (Xu *et al*., 2020; Pérez-Gómez *et al*., 2020; Alizamir *et al*., 2021). However, the distribution of chlorophyll-a is often uneven, resulting in outliers, *i.e*., data that are significantly higher or lower than the mean value (Xu *et al*., 2019; Alizamir *et al*., 2021). These outliers can be caused by various factors, including pollution, eutrophication, or natural fluctuations in phytoplankton populations (Carballeira *et al*., 2019; Lusiana *et al*., 2019). In this

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context, understanding the spatial and temporal outlier distribution of chlorophyll-a concentrations is essential to support the management of aquatic resources. However, research on seasonal patterns and ecosystem dynamics through time series analysis and decomposition function in chlorophyll-a outlier data is still limited, especially in the Banda Sea area and its surroundings.

Previous studies suggest that observations of chlorophyll-a concentration outliers can provide helpful information in monitoring water quality and understanding aquatic ecosystem dynamics (Pompêo *et al*., 2021). Another study also shows the importance of monitoring chlorophyll-a concentrations for marine resources and environmental management (Matus-Hernández *et al*., 2019; Tapilatu *et al*., 2022). However, studying ecosystem dynamics through time series and seasonal patterns through the 'decompose function' of chlorophyll-a outlier -was still limited.

This study aims to describe the dynamics of outlier data on chlorophyll-a concentrations in the Banda Sea and its surroundings from 2010–2022. The research focuses on the analysis of trends, seasonal patterns, and residuals of time series data, as well as their spatial and temporal distribution. With this approach, this research is expected to make a theoretical contribution to understanding aquatic ecosystem dynamics and practical benefits in supporting the sustainable management of aquatic resources. The data generated can also be an essential reference in formulating marine environmental management policies in WPP 714.

Several research questions are formulated to guide the analysis. First, what are the dynamics of outlier concentrations of chlorophyll-a in the Banda Sea and its surroundings in the period 2010–2022? Second, what are the trend, seasonal, and residual patterns of chlorophyll-a outlier data in time series analysis in this region? Third, what is the spatial and temporal distribution of the outlier of chlorophyll-a concentration, and what environmental factors affect it?

Materials and Methods

The research location in FMA 714, a designated location according to Marine Affairs and Fisheries Regulation No. 18/PERMEN-KP/2014 on the Republic of Indonesia Fishing Management Area (KKP, 2014), covering the waters of Tolo Bay and the Banda Sea (KKP, 2021b, 2021a), as shown in Figure 1.

Chlorophyll-a data retrieval

Chlorophyll-a concentration data for the Banda Sea and its surroundings was obtained from Aqua Modis at https://oceancolor.gsfc.nasa.gov (NASA Official, 2023).

Processing of chlorophyll-a raw data

Processing of chlorophyll-a raw data using Ocean Data View (ODV). The chlorophyll-a ocean color data used in this study has a resolution of 4 km from 2010 to 2022. The chlorophyll-a dataset from the ODV is tidied up through R Studio, and then the data frame is processed into a map via ArcGIS 10.8, visualized every month of the year.

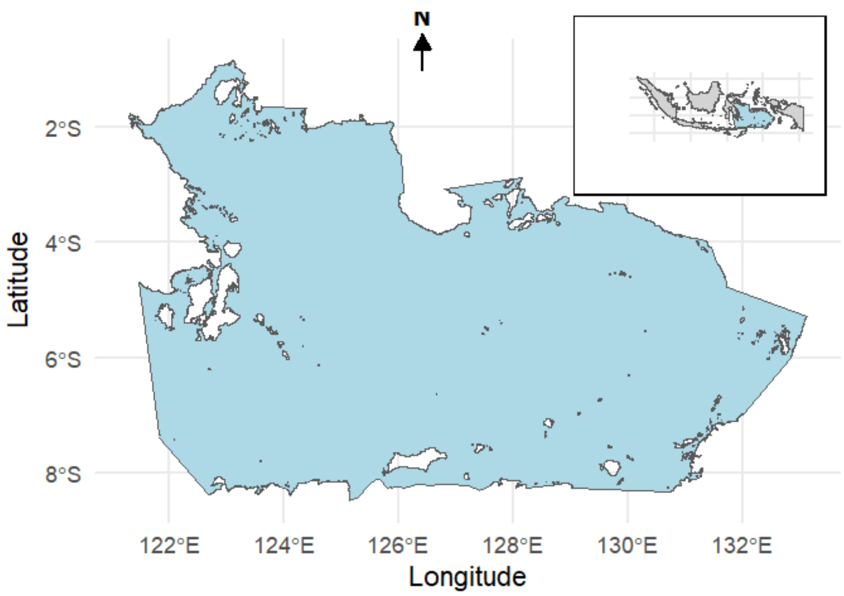

Figure 1. Study area

Chlorophyll-a dataset processing through Machine Learning

We have advanced data processing through the R Studio version 4.3.0. The initial processing of data is carried out by 1) Enabling the required libraries (Jeelani *et al*., 2022): library(dplyr), library(lubridate), library(forecast), library(tseries), library(TSstudio), library(ggplot2), and library(tidyr); 2) Operate R Studio functions for data wrangling and data cleaning.

Determination of chlorophyll-a outliers

Detection of outliers on chlorophyll-a concentration data using machine learning methods in R Studio. Outlier determination using the interquartile range (IQR) method. IQR scores are considered outliers. If below Q1 - 1.5*IQR or above Q3 + 1.5*IQR. IQR is the difference between Q3 and Q1 to measure data spread (Fernando and Wickramasuriya, 2021). This study limited the number of outliers to the top 120 data.

Data analysis

Machine learning methods were employed in this study to identify outliers, as they can handle complex data and high levels of noise (Du *et al*., 2023; Taghribi *et al*., 2023). Meanwhile, the spatial analysis describes the spatial distribution of outliers (Cai and Kwan, 2022; Sogacheva *et al*., 2022). The analysis results will provide helpful information for identifying changes in the condition of aquatic ecosystems and monitoring the quality of marine waters in the Banda Sea and its surroundings. Analysis of chlorophyll-a concentration data using time series and decompose methods to identify trend, seasonal, and residual patterns from the data (remainder). Next, the distribution of spatial outliers is analyzed using spatial analysis. Spatial analysis using ArcGIS 10.8. The analysis results were interpreted to comprehend the dynamics and distribution of chlorophyll-a concentration outliers within the Banda Sea and its surroundings. Details on the location of chlorophyll-a concentration outliers using Google Maps.

Results and Discussion

Chlorophyll-a data outliers checking

After data processing and cleaning, 4,815,096 rows were obtained, covering monthly chlorophyll-a concentration values from 2010 to 2022, with columns including Station, Longitude, Latitude, Moon (Date), and Chlo (Chlorophyll-a). Data representation was derived by detecting outliers in 120 out of 134 months across 30,866 stations. Based on quartile analysis, the outliers considered were values more significant than 0.44139, as no values below the lower limit of -0.07497 were found. From the outlier search results, several stations showed recurring outliers, including stations 30761, 878, 779, and 778, which were further analyzed using time series functions.

The distribution of chlorophyll-a by year shows that 2022 there were 11 outliers, with the highest concentrations recorded in August across six stations. In 2021, there were three outliers, while in 2020, there were 15 outliers, with the highest concentrations in December and April. In 2019, nine outliers were detected, mainly in September and July, whereas in 2018, three outliers were found in July. Similar patterns were observed in previous years, with the highest recorded value in 2010 at 81.09 mg·m^{-3}.

Overall, the spatial and temporal distribution of chlorophyll-a concentration outliers in the Banda Sea demonstrates significant annual and seasonal variation, which is essential for a deeper understanding of the dynamics of this aquatic ecosystem. This analysis is expected to support the development of more effective fisheries management policies in Indonesia.

There is a significant correlation between satellite data and field measurements of chlorophyll-a concentrations (Moutzouris-Sidiris and Topouzelis, 2021). Numerous studies show a correlation between ocean color data and field data (Lavigne *et al*., 2021; Zhang *et al*., 2022). Research results from Tang and Huang (2021) show that the correlation coefficients of the two are 0.8836, while according to Kusumawati *et al*. (2019), the correlation between the two shows R^2= 0.7851.

Time series of outlier's chlorophyll-a in the Banda Sea and its surroundings

The ten highest outliers were found at Stations 30761, 13385, 4699, 539, 540, 4698, 416, 476, 8638, and 8748, with chlorophyll-a concentration values (in mg·m^{-3}) of 81.09, 73.76, 57.93, 41.33, 41.33, 41.33, 41.33, 40.43, 40.43, 36.45, and 36.45, respectively. Meanwhile, the ten lowest outliers were recorded at Stations 879, 9380, 779, 683, 10272, 9379, 778, 11402, 683, and 780, with chlorophyll-a concentrations of 14.71, 14.67, 14.66, 14.65, 14.64, 14.62, 14.54, 14.53, 14.47, and 14.39 mg·m^{-3}, respectively. Figure 2 below is a time series graph showing chlorophyll-a concentration outlier data in the Banda Sea and its surrounding areas for the 2010-2022 period.

Outlier data on chlorophyll-a concentrations in the Banda Sea show significant differences between

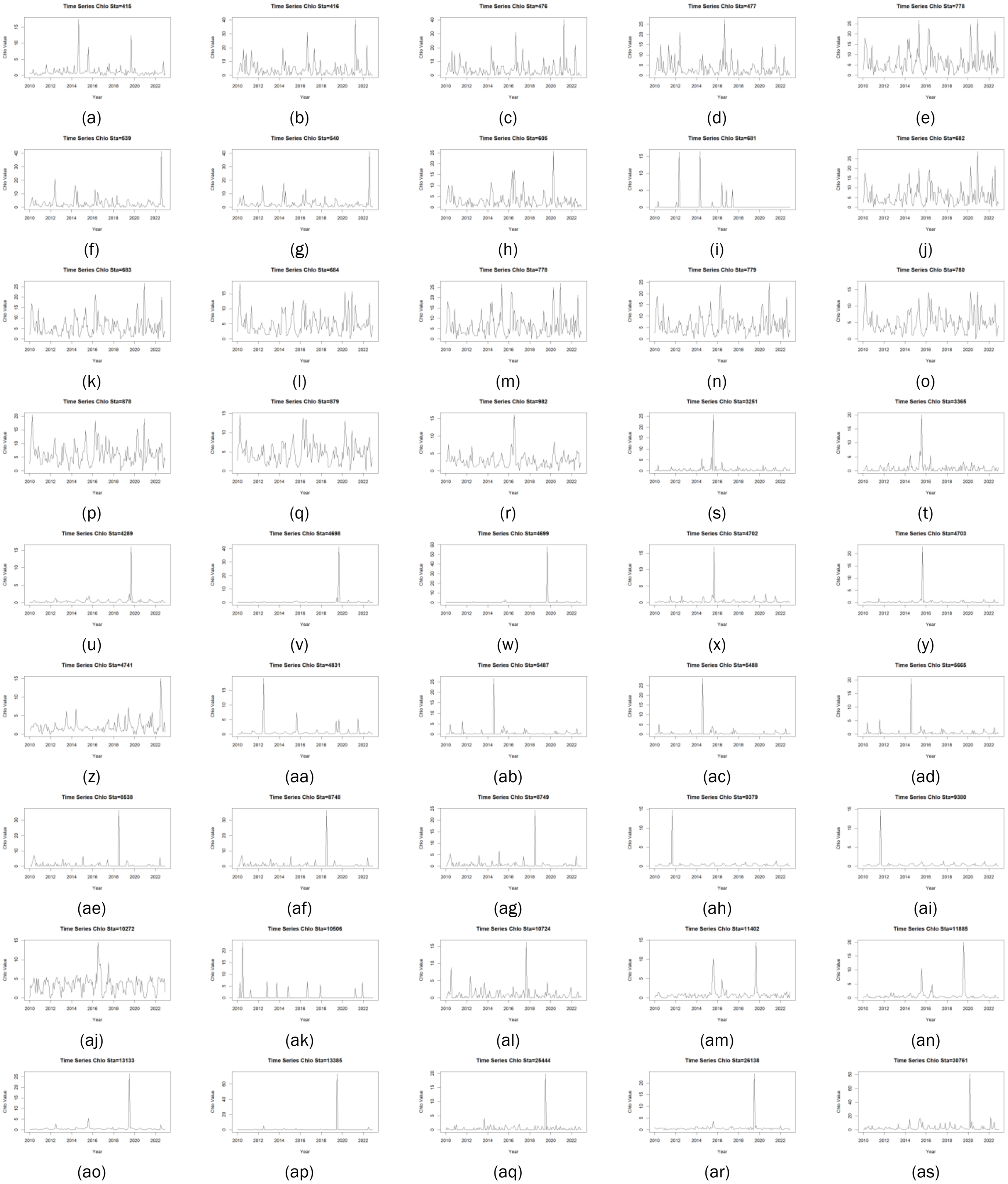

Figure 2. Time series outliers' graph of chlorophyll-a in the Banda Sea and its surroundings year 2010-2022: (a) Sta 415, (b) Sta 416, (c) Sta 476, (d) Sta 477, (e) Sta 478, (f) Sta 539, (g) Sta 540, (h) Sta 605, (i) Sta 681, (j) Sta 682, (k) Sta 683, (l) Sta 684, (m) Sta 778, (n) Sta 779, (o) Sta 780, (p) Sta 878, (q) Sta 879, (r) Sta 982, (s) Sta 3251, (t) Sta 3365, (u) Sta 4289, (v) Sta 4698, (w) Sta 4699, (x) Sta 4702, (y) Sta 4703, (z) Sta 4741, (aa) Sta 4831, (ab) Sta 5487, (ac) Sta 5488, (ad) Sta 5665, (ae) Sta 8538, (af) Sta 8748, (ag) Sta 8749, (ah) Sta 9379, (ai) Sta 9380, (aj) Sta 10272, (ak) Sta 10506, (al) Sta 10724, (am) Sta 11402, (an) Sta 11885, (ao) Sta 13133, (ap) Sta 13385, (aq) Sta 25444, (ar) Sta 26138, and (as) Sta 30761

the stations with the highest and lowest values, which can reflect the influence of environmental factors. Stations with the highest concentrations, such as 30761 and 13385, show high phytoplankton productivity, usually associated with seasonal phenomena such as upwelling and El Niño that increase nutrient supply in waters (Marpaung *et al*., 2020). In contrast, stations with the lowest concentrations, such as 879 and 9380, reflect less favorable environmental conditions, such as weaker circulation or low nutrient inputs during a given season (Rachman *et al*., 2020). Trends in satellite data corroborate that seasonal variability and global climate change play a role in the region's spatial and temporal distribution of chlorophyll-a (Park *et al*., 2022).

Graph of specific outliers of chlorophyll-a in the Banda Sea and its surroundings

Figure 2 is a time series plot showing changes in chlorophyll-a concentration values at observation stations over 13 years in the Banda Sea and surrounding areas. The differences between the raw data plot, trend, seasonal, and remainder components of chlorophyll-a concentration can be visually observed in the time series diagram in Figure 3.

The graphs in Figure 3 above show the seasonal pattern of chlorophyll-a concentration outliers, with the highest frequency in April (25 occurrences), May (24 occurrences), August (16 occurrences), and July (14 occurrences). Outliers most frequently occurred in May (6 times), followed by April (5 times), August and September (4 times each), and July (3 times) during the 2010–2022 period. Rarely occurring outliers were recorded in March, November, and December, each appearing only once.

Chlorophyll-a concentration outliers, as shown in Figure 3, show strong seasonal patterns, with the highest frequencies in April, May, August, and July. This pattern reflects the influence of a combination of environmental factors such as thermal stratification, nutrient supply, and sea surface temperature that contribute to the seasonal dynamics of chlorophyll-a concentrations, especially in subtropical and coastal waters that have striking spatial variations (Liu *et al*., 2020; Muskananfola *et al*., 2021). In coastal waters, the availability of light and changes in the stability of the water column also affect the concentration of chlorophyll-a, in contrast to offshore areas that are more environmentally stable (Wang and Gao, 2020).

In addition, meteorological factors such as ocean current patterns and human activities also determine the spatial and temporal variation of chlorophyll-a. These trends show the influence of seasonal variability and climate change, both at the local and global levels (Rousseaux *et al*., 2021). Pattern analysis through the decomposition function shows the existence of irregular fluctuations (remainder). Pattern analysis through the decomposition function shows the existence of irregular fluctuations (Lin *et al*., 2021). This combination underscores the complexity of the interaction between environmental factors and human activities on the distribution of chlorophyll-a.

The distribution of chlorophyll-a outliers in the Banda Sea and its surroundings: temporal and spatial

Based on the description above, outliers appear spatially and temporally distributed. To examine more specifically how the outliers are distributed, they are visualized spatially and temporally as the map per month in Figure 4 below using ArcGIS 10.8.

Based on this study, no outliers were found in January, February, and October. The selected outliers from 120 stations had values >14.39 mg·m^{-3}. Chlorophyll-a concentrations in the western Banda Sea and surrounding areas were higher from January to March and December, while the eastern region showed higher concentrations from June to September. These findings align with previous studies indicating that chlorophyll-a concentrations vary seasonally (Kotsiuba *et al*., 2022).

The location of outliers was identified using 'Sta' coordinates on Google Maps. Outliers in March (Sta 682, 683, 778, and 779), May (Sta 416, 476, 477, 478, 539, 605, 681, 682, 683, 778, 779, and 878), and June (Sta 477, 478, 539, 540, 682, and 778) were found in the waters of Tolo Bay, Central Sulawesi, adjacent to an industrial area. Additionally, an outlier was identified in the waters of Riangeba, East Nusa Tenggara (Sta 30761).

The distribution of outliers in July includes the waters of Tolo Bay, Bahubulu, Kolono, Bombana, Tanjung Kamponea, Onemea, Buru Island, Ungar Island, and Lutur Island. In August, outliers are spread across Tolo Bay, Mataindaha waters, Patinea, Osi Island, and Ambon Bay. Outliers in September appear in Tolo Bay, Napabale waters, Ereke, Botolino, Liang Ambon, and Haruku Island. Meanwhile, outliers in April, November, and December are in the waters of Tolo Bay.

These findings reveal higher chlorophyll-a concentrations than previous studies in the Madura Strait and East Nusa Tenggara, which reported chlorophyll-a levels around 0.18–3 mg·m^{-3} (Muskananfola *et al*., 2021). This study's high chlorophyll-a outlier values reinforce the view that

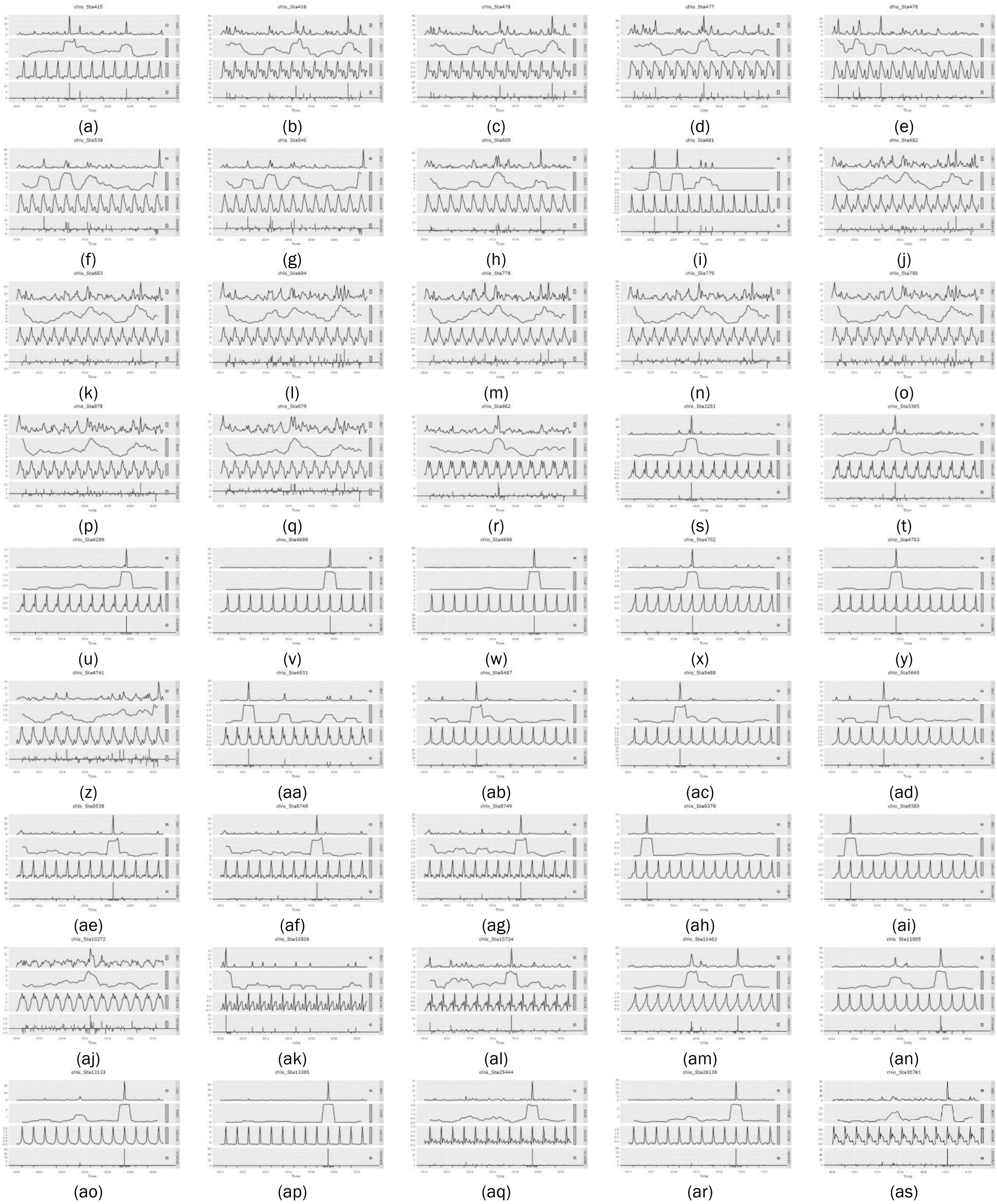

Figure 3. Graph of decomposed chlorophyll-a concentration in the Banda Sea and its surroundings: (a) Sta 415, (b) Sta 416, (c) Sta 476, (d) Sta 477, (e) Sta 478, (f) Sta 539, (g) Sta 540, (h) Sta 605, (i) Sta 681, (j) Sta 682, (k) Sta 683, (l) Sta 684, (m) Sta 778, (n) Sta 779, (o) Sta 780, (p) Sta 878, (q) Sta 879, (r) Sta 982, (s) Sta 3251, (t) Sta 3365, (u) Sta 4289, (v) Sta 4698, (w) Sta 4699, (x) Sta 4702, (y) Sta 4703, (z) Sta 4741, (aa) Sta 4831, (ab) Sta 5487, (ac) Sta 5488, (ad) Sta 5665, (ae) Sta 8538, (af) Sta 8748, (ag) Sta 8749, (ah) Sta 9379, (ai) Sta 9380, (aj) Sta 10272, (ak) Sta 10506, (al) Sta 10724, (am) Sta 11402, (an) Sta 11885, (ao) Sta 13133, (ap) Sta 13385, (aq) Sta 25444, (ar) Sta 26138, and (as) Sta 30761

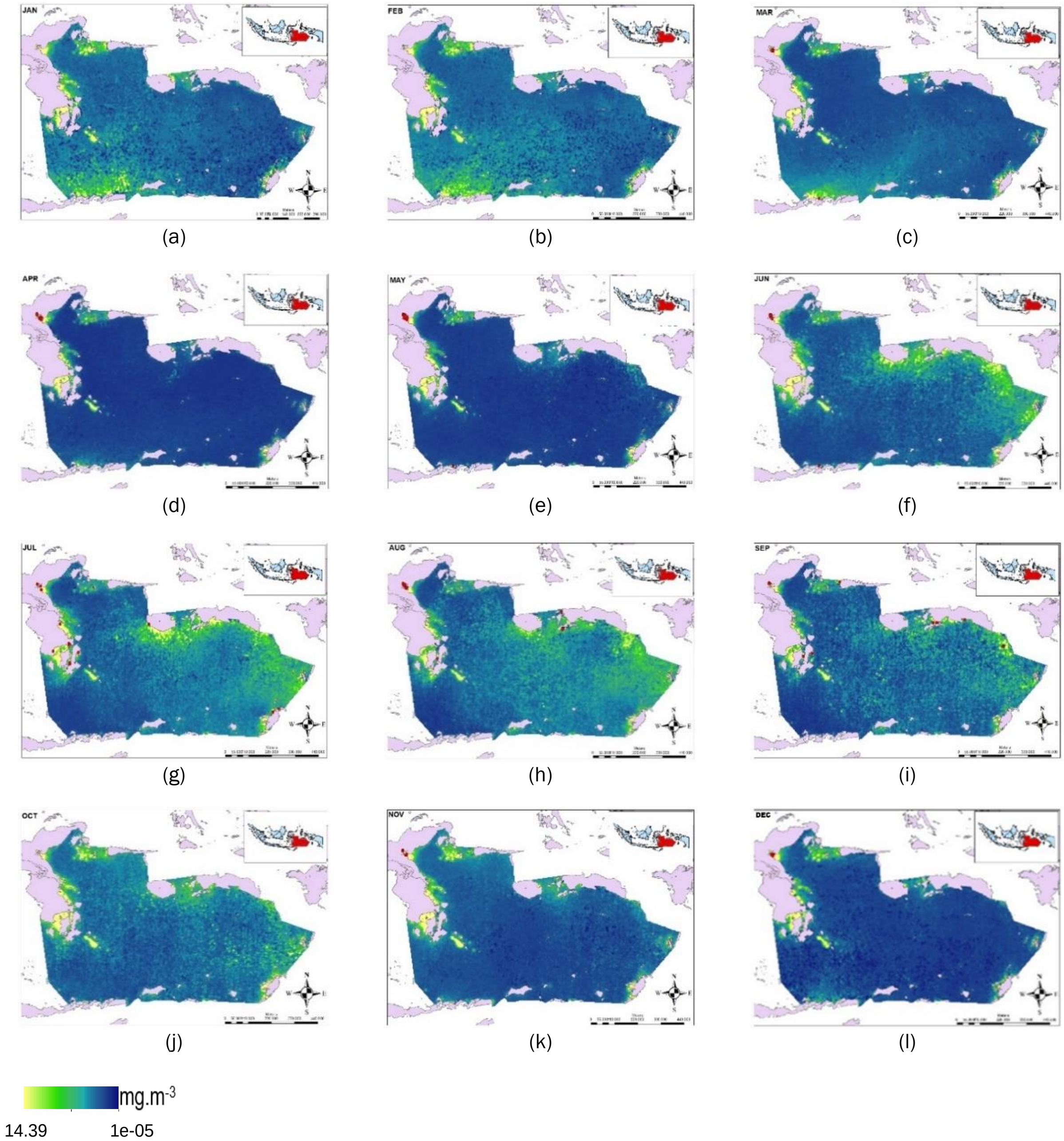

Figure 4. Horizontal distribution of chlorophyll-a in the Banda Sea and its surroundings in 2010-2022: (a) January, (b) February, (c) March), (d) April, (e) May, (f) June, (g) July, (h) August, (i) September) (j) October, (k) November, and (l) December

chlorophyll-a concentration anomalies are often associated with human activities, such as industrial or agricultural waste disposal, which can lead to marine pollution (Mandal *et al*., 2022).

Chlorophyll-a concentration outliers can serve as important indicators in understanding the quality of aquatic ecosystems and levels of primary productivity (Ahmadi *et al*., 2020). Increased chlorophyll-a outliers in waters near industrial or agricultural activity may indicate eutrophication risks, negatively affecting marine ecosystem health (Tishchenko *et al*., 2020). Therefore, continuous monitoring is necessary to maintain the balance of marine ecosystems.

This study is limited by satellite data and statistical analysis with the IQR method, which may not fully capture the complexity of marine environments. The historical data may also be subject to time bias, potentially affecting long-term trend interpretation (Shin *et al*., 2023). This limitation has also been noted in other studies that emphasize the need for direct observations to validate satellite data results (Owings *et al*., 2019).

Future research should incorporate field observations to verify satellite data results and identify additional factors contributing to increased outliers. Moreover, an approach that considers the long-term impact of climate change on chlorophyll-a variability can provide further insights into marine ecosystem adaptation (Punyapornwithaya *et al*., 2020).

Conclusion

This study successfully identified chlorophyll-a concentration outliers in the Banda Sea (2010–2022) using the IQR method, uncovering significant spatial and temporal variations influenced by seasonal factors and human activities. Outliers were more prominent in the western region during January to March and December, and in the eastern region during June to September, with concentrations reaching up to 81 mg·m^{-3}. These findings highlight the ecological implications of chlorophyll-a as an indicator of environmental disturbances, offering valuable insights into marine ecosystem quality. The practical application of this study lies in detecting outliers to monitor human impact, while its theoretical contribution emphasizes the importance of integrating satellite data into marine monitoring efforts. However, the study's reliance on historical satellite data and basic statistical methods presents limitations. Future research should address these gaps by incorporating field measurements and employing advanced analytical approaches for a deeper understanding of chlorophyll-a dynamics and their ecological significance.

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