INFLUENCE OF SEA SURFACE TEMPERATURE AND CHLOROPHYLL-A ON MACKEREL PRODUCTIVITY IN BANTEN BAY, INDONESIA: ANALYSIS USING AQUA MODIS DATA (2014–2023)

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ABSTRACT

Banten Bay, located in Banten Province near Java Island's northwestern tip, supports abundant mackerel populations (*Rastrelliger sp.*), a primary fishing commodity impacting coastal communities' livelihoods. Mackerel migratory patterns are sensitive to oceanographic conditions, making them indicators of marine ecosystem health. This study investigates the impact of these conditions on mackerel catches in Banten Bay waters using Aqua Moderate Resolution Imaging Spectroradiometer (Aqua MODIS) data from 2014 to 2023, combined with catch records from the Nusantara Fishery Harbor (NFH) Karangantu and analyzed using the Generalized Additive Model (GAM). The results indicate increased mackerel productivity, particularly during the west season (October to December), coinciding with upwelling-driven Chlorophyll-a (Chl-a) rises. Sea Surface Temperature (SST) distribution analysis revealed seasonal fluctuations (29.33°C - 31.32°C), supporting mackerel aggregation in warmer waters. Chl-a levels peaked during upwelling seasons, enhancing mackerel food availability. Sea depth analysis showed successful catches at depths around 50-60 m. GAM analysis confirmed SST and Chl-a as significant factors, with SST having a dominant influence. The combined effect of SST and Chl-a best-explained mackerel distribution patterns provides insights for sustainable fisheries management.

Key-words: *Mackerel; Banten bay waters; Oceanographic; Aqua MODIS; SST and Chl-a.*

1. INTRODUCTION

As an archipelagic country rich in natural resources, Indonesia holds immense biodiversity potential (Yulius et al., 2021). Among these resources is Banten Bay waters, which is located in Banten Province, near the northwestern tip of Java Island in Indonesia and is recognized for its ecosystem that supports abundant mackerel populations (*Rastrelliger sp.*) (Rachmad et al., 2022). The oceanographic features of Banten Bay waters, such as the upwelling events in this area, play a crucial role in enhancing water productivity and providing a stable phytoplankton supply, the primary food source for pelagic fish (Belkin, 2021). Upwelling, as detailed by Uiboupin et al. (2012) is an essential oceanographic process that transports nutrient-rich, cold water from the depths to the surface layer, promoting increased water column productivity.

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In addition to the upwelling phenomenon, the oceanographic conditions of Banten Bay are also influenced by a complex current system as a result of the interaction of local and regional circulation, salinity variations determined by freshwater input from surrounding rivers, and anthropogenic influences such as large-scale industrial, agricultural, and fisheries activities that directly affect habitat quality and nutrient distribution (Arifin et al., 2025). These unique characteristics distinguish Banten Bay from other coastal areas around Java and make it an interesting natural laboratory for understanding coastal water dynamics.

Mackerel was selected as the focus of this study due to its significant economic importance to the fishing communities of Banten Bay. As one of the area's primary fishing commodities, mackerel availability greatly impacts coastal communities' financial well-being (Meliyana et al., 2024). In addition to its economic value, mackerel species (*Rastrelliger spp.*) also have distinctive morphological and biological characteristics. For example, mackerel are known for their fusiform bodies, small, smooth scales, and pectoral fins close to the head, allowing efficient swimming in certain ocean currents. They are also pelagic fish that form large schools, have clear spatial migrations, and reproductive patterns sensitive to environmental conditions (Nasri et al., 2024). Their streamlined morphological characteristics and their ability to move following oceanographic conditions make mackerel a good indicator species for detecting changes in the aquatic environment (Kasinath et al., 2024). Moreover, the migratory patterns of mackerel are highly sensitive to oceanographic conditions, making them key indicators of marine ecosystem health (Lubis et al., 2019). According to Tanto et al. (2016), oceanography is the science that encompasses various physical parameters of the ocean, with ongoing advancements as research progresses.

This study specifically focuses on a few parameters related to coastal dynamics, such as Sea Surface Temperature (SST), Chlorophyll-a (Chl-a), and sea depth. Suhartono et al. (2013) identified through Cobb-Douglas regression analysis that the variables SST, Chl-a, and sea depth significantly affect mackerel catch in Pangkep Regency waters, with probability values of 0.01, 0.007, and 0.001, respectively all of which are below 0.1. Research by Setyamarta et al. (2024) similarly demonstrated that variations in SST, Chl-a, and sea depth strongly impact skipjack tuna catches, emphasizing the critical role of oceanographic factors in determining fish abundance and distribution. A positive relationship between Chl-a levels and tuna catch was also found by Heriati et al. (2018), highlighting that favorable oceanographic conditions support fish abundance. While previous studies have examined the impact of oceanographic factors on mackerel catches across various areas, limited research has focused on Banten Bay waters, indicating a gap in knowledge regarding mackerel distribution and abundance in this specific area.

Unlike previous studies that generally focus on other waters in Indonesia or generally discuss oceanographic parameters, this study specifically explores how the unique oceanographic conditions in Banten Bay with a combination of currents, salinity, and anthropogenic influences correlate with the dynamics of mackerel stocks. Thus, this study has added value in filling the information gap that has not been widely discussed in previous studies.

Satellite-based remote sensing technology is an effective method for monitoring phenomenal changes in the atmosphere, land and ocean by utilizing electromagnetic waves to obtain information without physical contact, enabling data recording in wide coverage and repetition in the same area in each satellite orbit, so that environmental changes can be observed in different periods (Itsarawisut et al., 2024). In this research, this technology was applied to assess the impact of oceanographic conditions on mackerel catches in the waters of Banten Bay through analysis of Aqua Moderate Resolution Imaging Spectroradiometer (Aqua MODIS) data from 2014 to 2023. By exploring the relationship between environmental dynamics and mackerel abundance in Banten Bay waters, this study aims to provide critical insights into the sustainable management of fisheries in this important region. The novelty of this research lies in its decade-long Aqua MODIS dataset utilization to assess the impact of oceanographic factors on mackerel populations in Banten Bay waters an area not extensively studied in prior research. The results of this study are expected to contribute valuable data to support sustainable fisheries management practices within the area.

2. DATA AND METHODS

2.1. Research Location

This study is conducted in Banten Bay waters, part of Fisheries Management Area (FMA) 712 (Nagi et al., 2023). Banten Bay waters is situated at coordinates 5°7′50″-7°1′11″ South Latitude and 105°1′11″-106°7′12″ East Longitude, covering approximately 150 km² of sea, which includes the Serang coastline within Banten Province (Rahmania et al., 2021). For further visual context, refer to **Figure. 1** below.

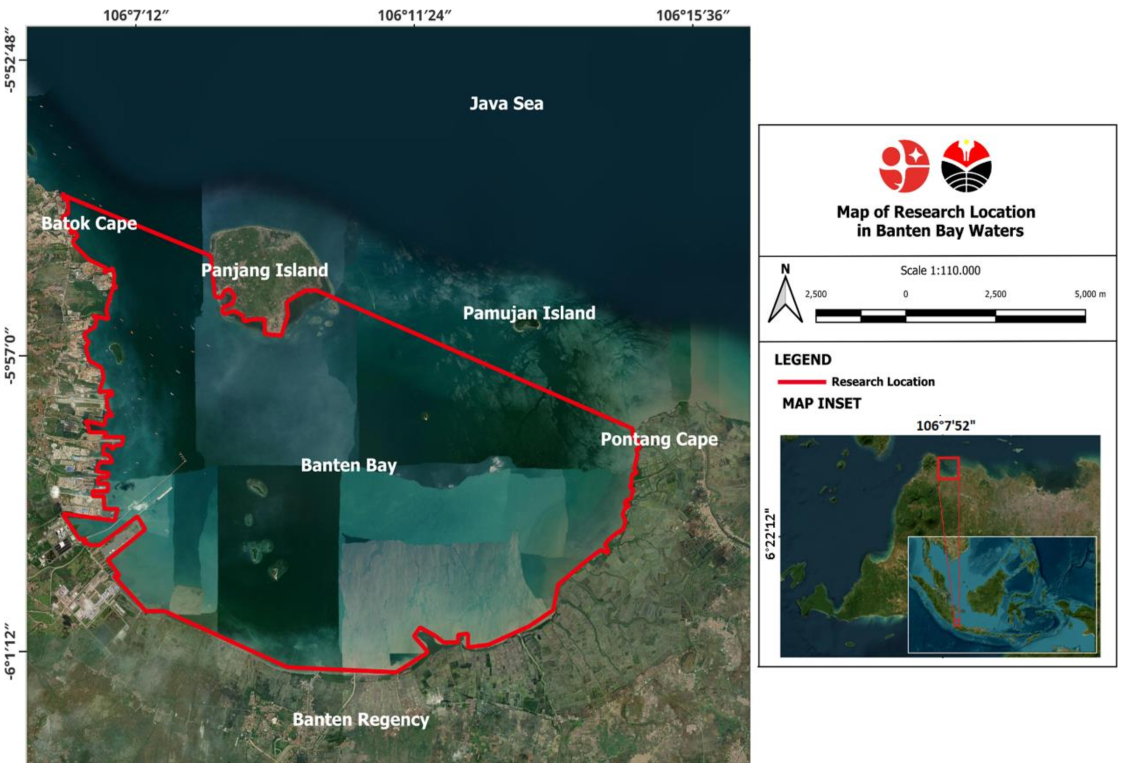

Fig. 1. Map of research location in Banten Bay waters.

The boundaries of Banten Bay waters are defined by two headlands (Pontang to the east and Batok to the west). Within this boundary lie two small islands (Panjang and Pamujan) which play a crucial role in supporting the coastal ecosystem of Banten Bay (Gorlinski, 2024).

2.2. Data

Satellite imagery obtained from the Aqua MODIS sensor provides highly detailed and comprehensive data, facilitating an in-depth examination of spatial and temporal variations in Chl-a concentrations and SST across regional seas (Doydee et al., 2010). By capturing large-scale environmental patterns over prolonged periods, this technology offers invaluable insights into the shifting conditions of marine ecosystems. In this study, we combine Aqua MODIS data with mackerel catch records from the Nusantara Fishery Harbor (NFH) Karangantu, covering the period from 2014 to 2023 (see **Table 1**). This method allows for a detailed exploration of the relationship between oceanographic factors and fishery productivity, contributing to a more comprehensive understanding of how environmental conditions influence mackerel populations in Banten Bay waters.

Table 1.

Data sources utilized in this study.

Data	Month	Years	Resolution	Source
SST and Chl-a	9	2014-2023	4 km	https://oceancolor.gsfc.nasa.gov/
Sea Depth (Bathymetry)	-	2023	6 arcsec	http://tides.big.go.id/DEMNAS/
Mackerel catch results	-	2014-2023	-	NFH Karangantu

The use of Aqua MODIS data to map SST and Chl-a concentrations in September is aimed at analyzing seasonal patterns associated with low mackerel catch rates. The selection of September (part of Transition Season II, namely the September–November period) was based on the existence of unique oceanographic phenomena in Banten Bay, especially the peak upwelling event that increases nutrient content and Chl-a concentration. Although theoretically, these conditions can increase the availability of fish resources, historical catch data show anomalies, where the level of mackerel caught in that month is not always in line with the high concentration of Chl-a. In other words, this period was chosen because its existence raises scientific questions about the relationship between oceanographic parameters and fish catches that are not always linear. September falls within Transition Season II, spanning from east to west (September to November) in Banten Bay waters, which coincides with the peak period of upwelling. This upwelling process greatly enhances nutrient levels and Chl-a concentrations due to increased phytoplankton growth (Wisha et al., 2015; Pranowo et al., 2005). While this increase in Chl-a theoretically suggests a potential boost in fish abundance, catch data for September often reveals anomalies, where high Chl-a levels do not correlate with greater fish productivity. In addition, to ensure data consistency in interpreting SST and Chl-a trends, this study utilizes secondary data from related observation years. However, if very specific cross-year comparative data are limited or unavailable, this will be mentioned as one of the limitations of the study. Thus, interpretation of the results will include consideration of the availability and quality of the secondary data. For this analysis, a laptop equipped with spatial data processing software such as the SeaWiFS Data Analysis System (SEADAS), ArcMap 10.3, Surfer, and Jupyter Notebook (Python 3.12) was used to process and interpret the satellite imagery data.

2.3. Methods

This study examines the relationship between fish catches and the variations in oceanographic parameters, particularly SST and Chl-a, by employing the Generalized Additive Model (GAM) statistical approach (Safruddin et al., 2018). As Puspito (2022) explains, GAM is an extension of general linear models that captures relationships between response and explanatory variables through smooth, flexible functions, accommodating non-linear patterns for a more nuanced data representation. According to Rezaei et al. (2019), GAM is extensively applied in species distribution modeling and environmental management due to its capacity for non-linearity. The specific model applied in this study is as follows:

$$g(\mu i) = \alpha 0 + s1\ (SST) + s2\ (Chl\text{-}a) + \varepsilon$$

where: $g(\mu i)$= dependent variable
$\alpha 0$ = constant
sn = smoothing function
βn = free variable (oceanography parameter)
ε = standard error

In designing this methodological approach, this study refers to a variety of relevant literature. For example, a study by Rabbi et al. (2024) used geospatial analysis and satellite data to predict potential fishing areas, emphasizing the importance of combining oceanographic and acoustic data. Furthermore, a study by Woods et al. (2023) applied a statistical modeling approach to oceanographic data to predict pelagic fish distribution, while Kuiper et al. (2023) highlighted the importance of integrating remote sensing data to understand fisheries habitat dynamics.

Badger et al. (2023) showed how statistical models can be used to capture spatial and temporal variability in fish stock distributions, and Puspita et al. (2023) introduced the basic concept of GAMs that underpins many current ecological and fisheries analyses. In addition, McDonnell et al. (2024) described the relationship between oceanographic parameters and tuna abundance, highlighting the relevance of variables such as SST and Chl-a in understanding fisheries resource distribution. Thus, these references play an important role in forming the analytical framework used in this study.

The methodology for analyzing the impact of oceanographic parameters on mackerel catch in Banten Bay begins with a comprehensive literature review. This first step builds a foundation by evaluating prior studies on the relationships between SST, Chl-a, and mackerel catch productivity, helping to identify research gaps and shape the study framework. Following the literature review, the research advances to the GIS mapping phase, where spatial data is processed to create visual representations of SST, Chl-a concentrations, and bathymetry. These maps are essential for showing the spatial distribution of mackerel populations within their environmental context. The next phase involves data analysis. GAM and correlation analysis examine the relationships between oceanographic factors and mackerel catches, thereby deepening the understanding of how SST and Chl-a influence mackerel catch productivity. The final stage synthesizes findings to provide insights into the sustainable management of mackerel fish in Banten Bay waters.

3. RESULTS AND DISCUSSIONS

3.1. Mackerel catch results

The mackerel catch data from 2014 to 2023, illustrated in graphs of **Figure 2**, reveals an overall trend of increasing productivity after September in many of the observed years. Particularly in 2022, there was a pronounced peak in catches between October and December (during the west season), with a noticeable rise in productivity levels.

This pattern in graphs of **Figure 2** above indicates a migratory movement of mackerel toward areas with higher Chl-a concentrations, which generally begin to increase in September due to upwelling. The migration and adaptation period for mackerel likely contributed to the elevated catch numbers observed in the latter part of the year. The mackerel catch data from 2014 to 2023 indicates a general trend of increased productivity following September in several observed years. Increased productivity often occurs in the west season (October to December), which is the rainy season and is characterized by the upwelling phenomenon. In this period, nutrient-rich air rises from the depths of the ocean to the surface, resulting in higher concentrations of Chl-a due to the primary productivity of phytoplankton. This upwelling is usually identified through low sea surface temperatures, which indicate the emergence of nutrient-rich deep sea air masses to the surface (Alfarizi et al., 2023). As findings by Kizhakudan et al. (2023), elevated Chl-a levels are vital in attracting pelagic fish like mackerel, which depend on phytoplankton as a key food source. A similar observation was made by Largier (2020), who found that upwelling can impact the spatial distribution of fish in coastal zones, with pelagic species often congregating in areas with high Chl-a levels.

In 2022, a significant peak in mackerel catch productivity was observed from October to December, suggesting a possible migratory shift of mackerel toward regions with higher Chl-a concentrations. Kuletz et al. (2024) described fish migration as an adaptive response to resource availability, especially with seasonal changes and rising phytoplankton levels. This trend may also explain the catch rate increase observed in 2023, though it was slightly less pronounced than in 2022. Prakash (2021) noted that seasonal climate variations can directly impact nutrient levels in marine environments, thus enhancing fishery productivity during certain months. Additionally, the late-year increase in catches might be attributed to mackerel's seasonal adaptations to shifting marine conditions. Moore & Schindler (2022) emphasize the critical role of adaptation in the resilience of pelagic species in variable coastal ecosystems. This upward productivity trend indicates a strong relationship between environmental factors, especially upwelling, and mackerel migration patterns, supporting findings from previous studies.

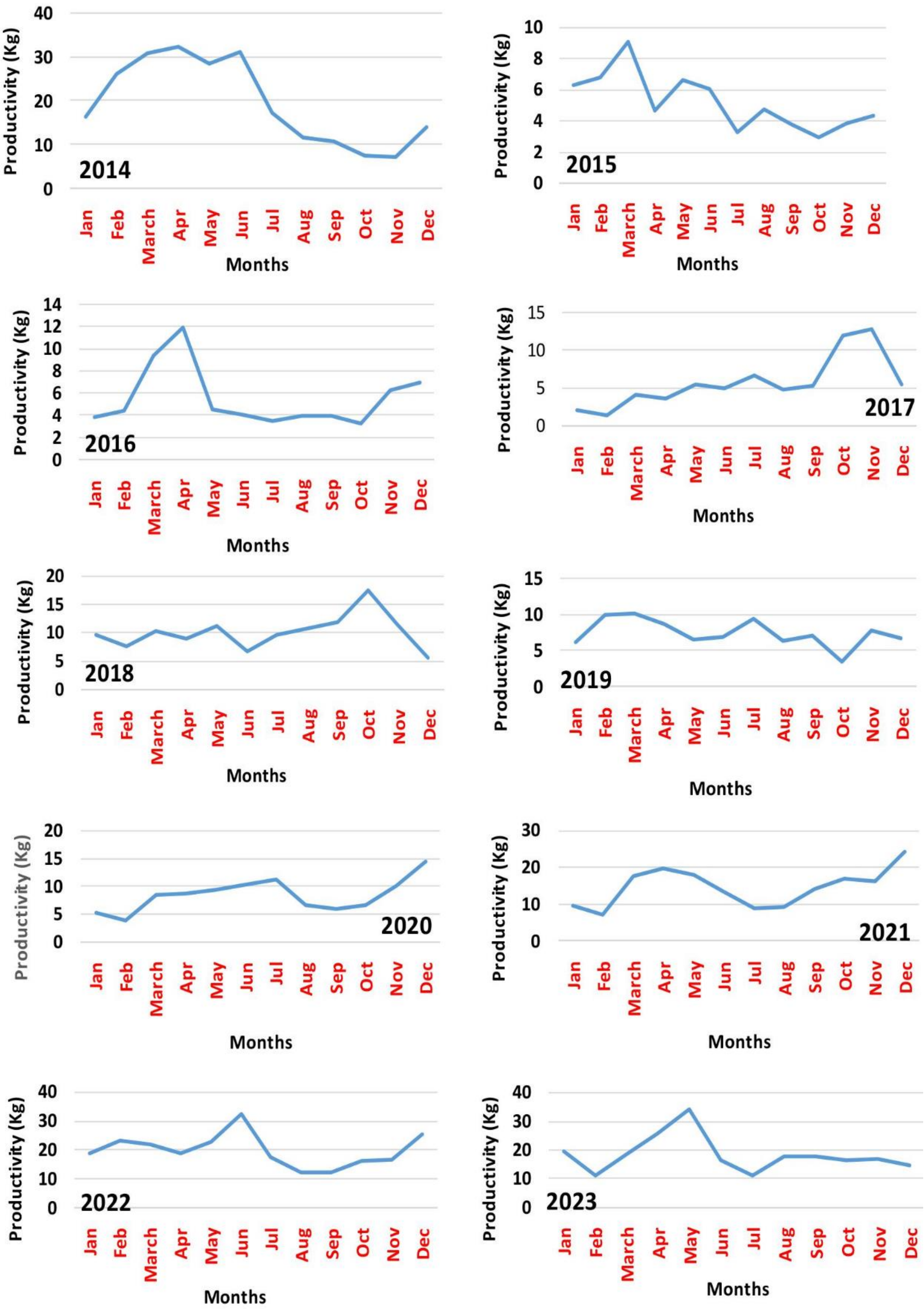

Fig. 2. Productivity graphs of mackerel catch in Banten Bay waters from 2014-2023.

In comparison, open seas such as the Indian Ocean have an average depth of around 3,890 meters (Phillips et al., 2021), while the depth of coastal waters in the open sea usually ranges from 50-100 meters before dropping drastically to the deep sea zone. This condition creates different oceanographic dynamics, where currents in the Indian Ocean are more stable but poorer in nutrients compared to island waters such as Banten Bay, which are rich in nutrients due to sedimentation and upwelling in shallow waters. This difference supports the findings in this study, the productivity and distribution of mackerel (spindle) are greatly influenced by shallow water conditions and specific oceanographic processes such as upwelling, which are not always present in the open sea environment. In addition to natural processes, anthropogenic activities here defined as " anthropogenic inputs" including nutrient-rich agricultural runoff, urban wastewater, and coastal development effluents–may also influence productivity patterns. Such human-driven nutrient enrichment can exacerbate or alter natural cycles of phytoplankton growth, potentially elevating Chl-a concentrations and affecting the seasonal distribution and abundance of mackerel. Future research could quantify these anthropogenic influences by comparing regions or periods with differing levels of human impact, thereby clarifying their role in shaping productivity trends.

3.2. Sea Surface Temperature (SST) in Banten Bay (2014-2023) based on Aqua MODIS data

The SST distribution in Banten Bay waters from 2014 to 2023, visualized using Aqua MODIS data, is shown in **Figure 3**. SST values are represented on a color scale ranging from yellow to dark red, with darker red shades indicating higher SST across Banten Bay waters. Each map in **Figure 3** displays the annual SST variations, allowing for a comparative analysis of temperature changes over the study period. Significant fluctuations in both the intensity and spatial distribution of SST are observed throughout Banten Bay waters, reflecting seasonal influences such as monsoon cycles. These variations contribute to changes in marine productivity and affect fish distribution across the Bay.

Using Aqua MODIS data, the SST distribution pattern reveals significant seasonal impacts, aligning with the observations of Lahiri & Vissa (2022), who highlight the influence of monsoon-driven SST shifts on upwelling strength. These upwelling events bring nutrient-rich waters to the surface, creating favorable conditions that attract species such as mackerel to high-productivity areas. The warmer, red-colored zones on SST maps indicate areas with elevated temperatures, supporting findings by Cook et al. (2022), who noted that coastal zones often exhibit higher SST due to limited water mixing and shallower depths. These warmer regions are likely to provide suitable habitats for mackerel, particularly during the west season, when productivity reaches its peak. In years like 2018, 2021, and 2023, higher SST values suggest changes in both oceanographic and atmospheric conditions. Hsiao et al. (2024) suggest that SST shifts associated with El Niño and La Niña events can impact coastal productivity and ecosystem stability, thereby affecting mackerel catch rates by altering their habitat preferences. Furthermore, Wang et al. (2021) point out that coastal productivity, including mackerel aggregation, responds to SST variations, influencing migratory behaviors and catch volumes. The elevated SST levels observed in 2021 and 2023 correlate with global warming trends highlighted by Qhadafi et al. (2018), implying that climate change may be affecting mackerel migration. As mackerel are drawn to nutrient-rich waters, rising SST and altered upwelling patterns may lead to increased catch rates in specific areas of Banten Bay waters. This warming trend might also shift the timing and locations of mackerel aggregations, prompting fishers to adapt their practices accordingly.

In the long term, SST changes associated with global warming may shift upwelling patterns, affect nutrient availability, and indirectly reshape the population dynamics of mackerel in Banten Bay. Increasing SST can weaken or shift the position of upwelling, reducing the supply of nutrients from deep water layers (Satar et al., 2023). As a result, long-term mackerel populations may be affected due to the decline in the main food source, namely phytoplankton. These implications are highly relevant for fisheries management, where adaptation strategies are needed to ensure the sustainability of stocks and fishing practices that take into account the impacts of climate change.

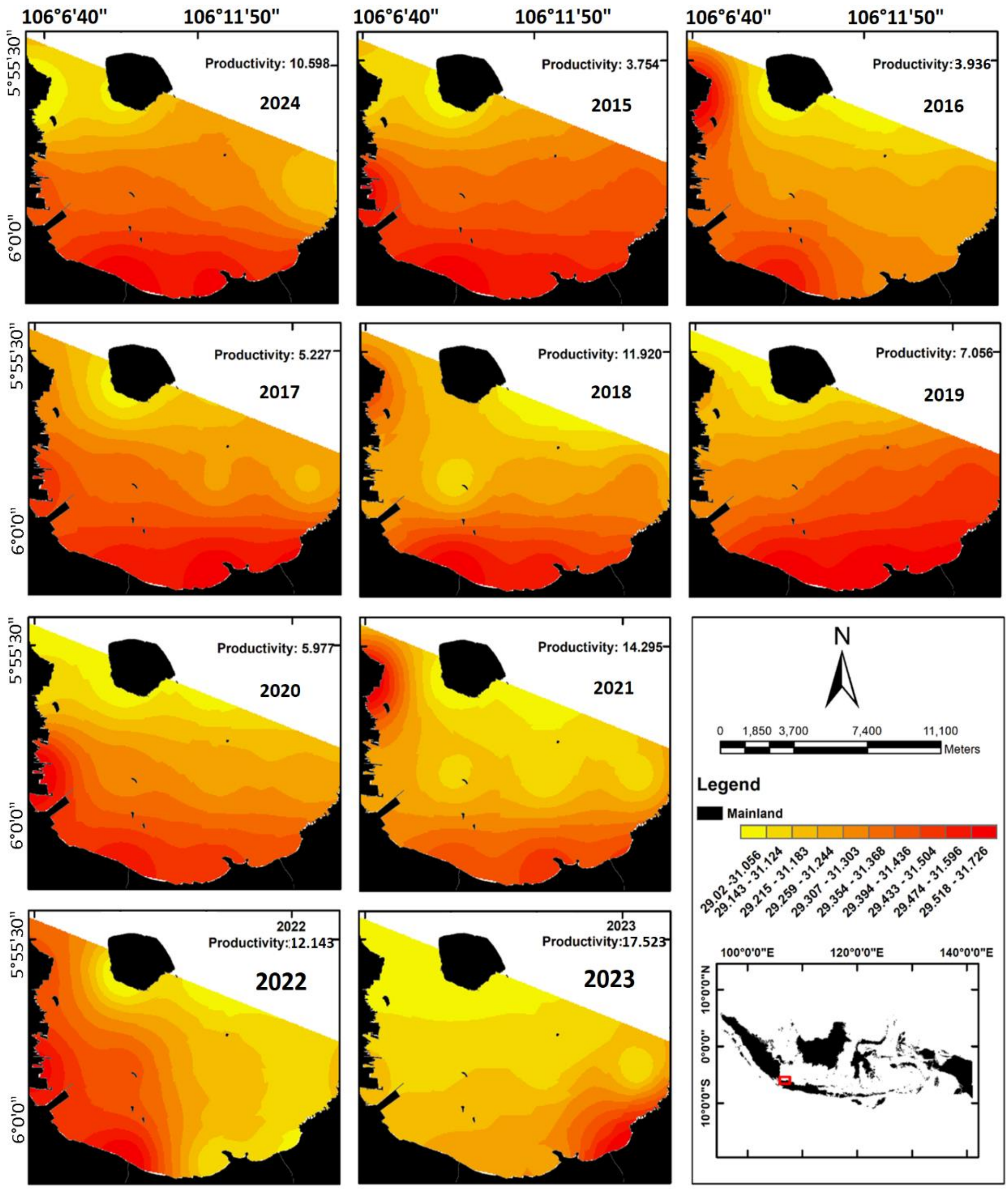

Fig. 3. Annual SST distribution in Banten Bay waters based on Aqua MODIS data.

Overall, the recent SST distribution (**Figure 3** above) reveals a dynamic thermal environment in Banten Bay waters, shaped by annual variability and broader climate trends. **Figure 4** illustrates these spatial and temporal SST variations, which are essential for understanding the ecological factors driving mackerel migration and productivity patterns. The seasonal peak from October to December demonstrates the strong link between catch rates and thermal-nutrient dynamics in coastal waters, highlighting the need for adaptive fisheries management in response to these evolving conditions. The graph in **Figure 4** displays the relationship between SST and mackerel productivity in Banten Bay waters from 2014 to 2023, showing annual SST fluctuations alongside variations in catch rates.

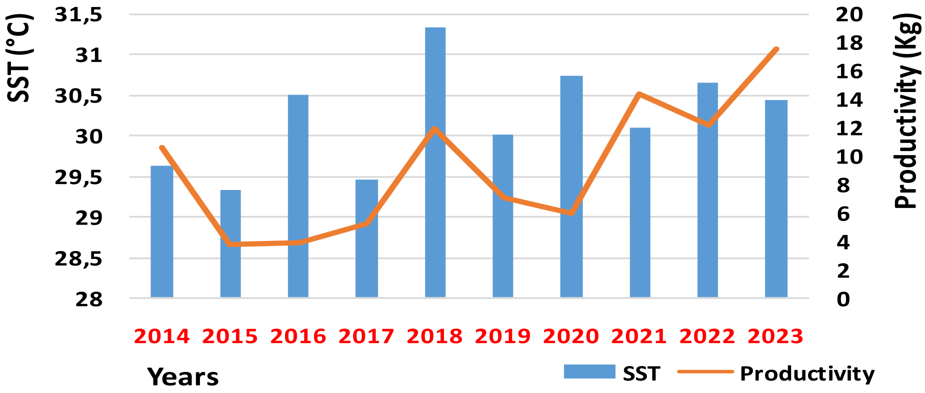

Fig. 4. Fluctuation of SST and mackerel productivity (2014-2023).

The distribution of SST in Banten Bay waters from 2014 to 2023 demonstrates notable annual variations, as seen in the graph in **Figure 4** above. SST values fluctuate within a range of 29.33°C - 31.32°C, consistent with research results by Ramawijaya et al (2012), which documented typical water temperatures in Banten Bay waters between 29.5°C and 30.6°C. A significant temperature rise occurred in 2018, reaching a peak of 31.32 °C, the highest recorded SST during this period. This spike in temperature is likely due to the maximum solar isolation that occurs in September, particularly during the equinox, which results in increased solar radiation being absorbed by the sea surface layer. Following the 2018 peak, SST dropped to 30.01°C in 2019 but gradually rose again, reaching 30.43 °C by 2023. These variations in SST are illustrated by the blue bars on the graph, reflecting an overall warming trend across the decade. This warming trend seems to correlate with mackerel productivity, represented by the orange line. As SST values increased, there was a corresponding rise in productivity, with substantial peaks in 2021, 2022, and particularly in 2023, when productivity reached its highest at 18 kg. This suggests that mackerel are influenced by temperature changes, favoring warmer waters that likely create more favorable conditions for feeding and aggregation. The peaks in productivity coincide with periods of higher SST, supporting the idea that water temperature is a crucial factor in mackerel distribution and catch rates. However, it should be noted that oceanographic conditions are not only influenced by SST and Chl-a. Other environmental factors such as salinity, current patterns, and wind patterns can also interact with SST and Chl-a, forming more complex conditions for aquatic ecosystems. The interaction between salinity and currents, for example, can affect plankton distribution and fish migration, while seasonally varying wind patterns can trigger large-scale changes in upwelling processes and nutrient distribution (Schmid et al., 2023). Therefore, further studies that include these variables will provide a more holistic picture of the factors controlling the distribution and productivity of mackerel in Banten Bay. For future studies should explore additional oceanographic factors, such as currents and salinity, to gain a deeper understanding of environmental influences on mackerel behavior and habitat preferences.

3.3. Chlorophyll-a (Chl-a) in Banten Bay (2014-2023) based on Aqua MODIS data

The distribution of Chl-a from 2014 to 2023, visualized using Aqua MODIS data, is shown in **Figure 5**. Chl-a levels are represented on a color scale from light to dark green, with darker green shades indicating higher concentrations across Banten Bay waters. Each map in **Figure 5** illustrates the annual variations in Chl-a concentrations, allowing for a comparative analysis of productivity changes over the study period. Significant fluctuations in both the intensity and spatial distribution of Chl-a are observed throughout Banten Bay waters. These fluctuations likely reflect seasonal and interannual changes in nutrient availability, influenced by factors such as upwelling, river discharge, and local climate patterns, which contribute to the productivity of the marine ecosystem and directly impact mackerel feeding grounds and aggregation.

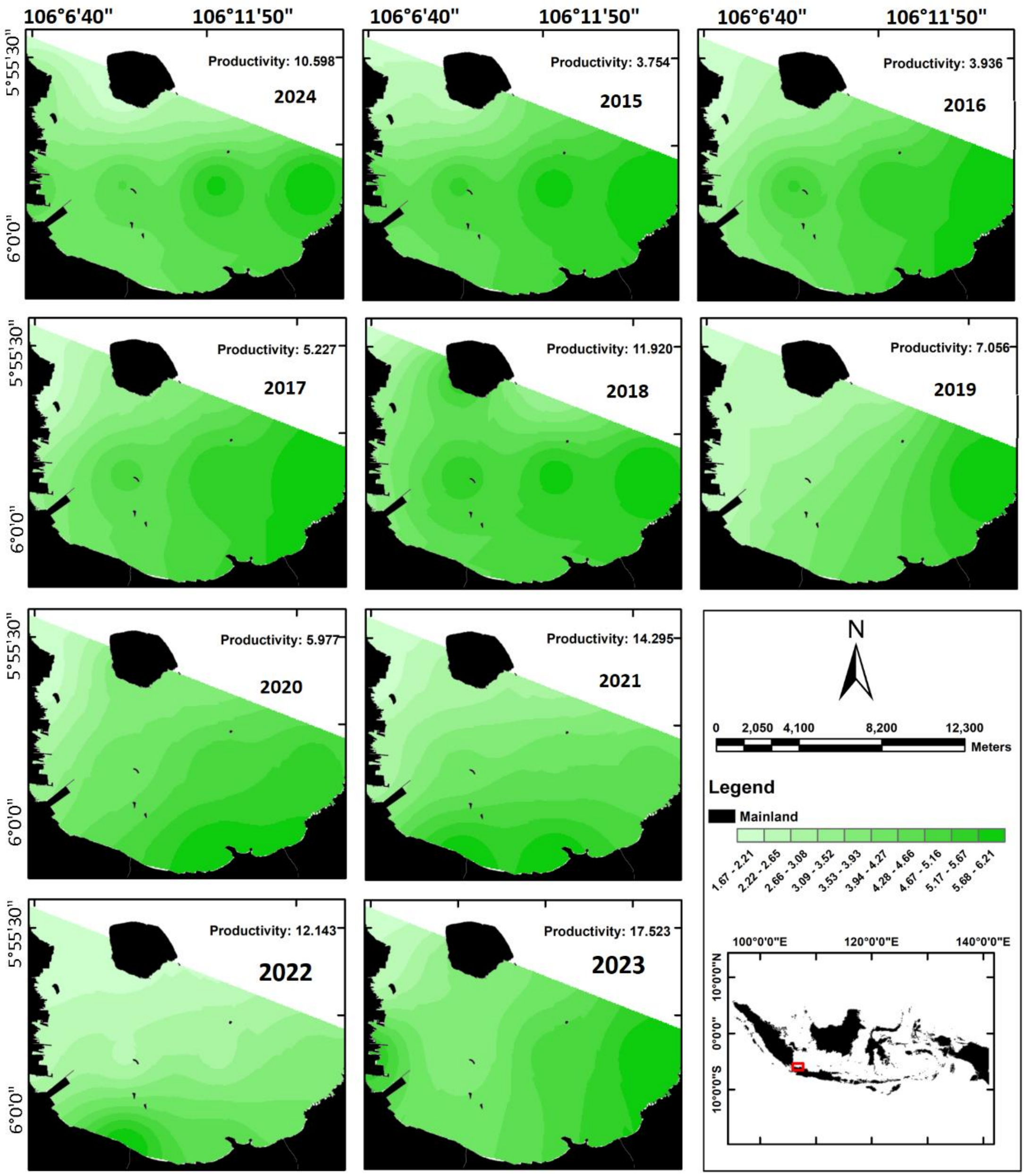

Fig. 5. Annual Chl-a distribution in Banten Bay waters based on Aqua MODIS data.

Using Aqua MODIS data, the Chl-a distribution from 2014 to 2023 reveals considerable variations in productivity levels, likely shaped by multiple ecological and oceanographic factors. The spatial patterns shown in **Figure 6** align with the findings of Mackey et al. (2010), who emphasized the role of seasonal nutrient cycles in influencing Chl-a levels in coastal waters, where high productivity is typically associated with nutrient-rich upwelling zones. This trend is particularly noticeable in years like 2018, 2021, and 2023, when productivity reached significant peaks, suggesting favorable conditions for phytoplankton growth and support for the local food chain in the study area. According to Wiggert et al. (2002), variations in Chl-a concentrations are often linked to seasonal monsoon dynamics and temperature shifts. The productivity map reflects a similar trend, particularly with recent productivity increases that may relate to fluctuations in monsoon intensity and changes in SST. This pattern supports the theory that temperature and monsoon dynamics collectively shape Chl-a's spatial distribution and concentrations. The observed productivity rise from 2020 to 2023 could partly be attributed to increased human activities along the coast, which elevate nutrient levels and drive higher Chl-a concentrations. These anthropogenic inputs likely impact productivity trends, especially near coastal areas, as suggested by the denser color gradient. Couto et al. (2013) proposed that fluctuations in Chl-a concentrations may reflect broader ecological changes, potentially linked to climate events like El Niño and La Niña. The productivity peaks in 2018 and 2023 may correspond with these climate events, implying that regional climate conditions significantly impact nutrient availability and biological productivity. The significant productivity surge in 2023, as depicted in **Figure 6**, may indicate broader climate trends influencing marine ecosystems. Such warming trends can enhance productivity in specific areas, potentially altering marine biodiversity and affecting fishing practices.

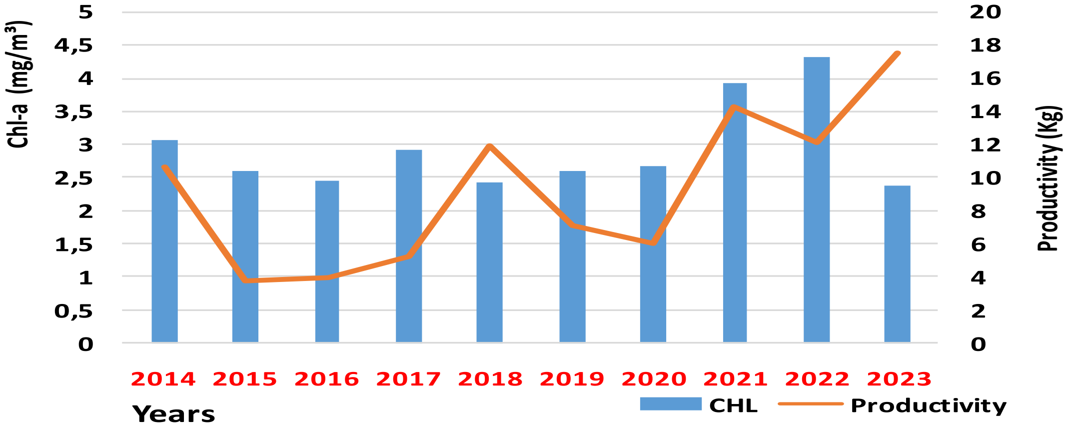

Fig. 6. Fluctuations of Chl-a concentration and mackerel productivity (2014-2023).

The pattern of Chl-a concentration and mackerel productivity from 2014 to 2023 shows notable annual variation, as illustrated in the graph above. Chl-a values range from approximately 2.5 to 4.5 mg/m³, reflecting shifts in nutrient availability and primary production within the study area. The blue bars represent Chl-a levels, with significant increases in 2021 and 2023, indicating enhanced phytoplankton growth during these years. In line with Chl-a fluctuations, mackerel productivity, represented by the orange line, also shows an upward trend, particularly in 2021, and 2022, and peaking in 2023 at 17.5 kg. This productivity peak aligns with high Chl-a levels, suggesting that greater phytoplankton presence provides an abundant food source for mackerel, thereby supporting higher catch rates. In the context of fisheries management, the increasing trend in Chl-a suggests that waters with higher nutrient availability may support mackerel rotation.

However, long-term changes in nutrient availability, for example, due to the influence of climate change on upwelling, may alter mackerel migration patterns and require more flexible fishing strategies. Fishers need to integrate Chl-a distribution to identify locations of higher catch potential, while fisheries managers can use this information to establish policies that ensure sustainable use of the resource. Nixon (1986) supports this, emphasizing that Chl-a concentrations are crucial for fish productivity in nutrient-rich marine environments. The observed variability in Chl-a and productivity is likely also influenced by climate factors such as monsoon cycles and temperature changes. The substantial productivity increase in 2023 may reflect these environmental factors, creating optimal conditions for mackerel aggregation and high catch yields. Overall, these trends reveal a strong link between mackerel productivity and Chl-a levels, where Chl-a serves as an indicator of marine productivity.

Smith (2023) indicates that coastal productivity rises with nutrient availability, as evidenced by increased mackerel catches in high Chl-a areas. This underscores the importance of Chl-a monitoring, as it directly impacts fisheries by identifying periods of high productivity. Productivity peaks occurring alongside high Chl-a levels indicate that phytoplankton abundance plays a critical role in supporting mackerel populations and influencing catch rates.

3.4. Relationship between SST, Chl-a, and mackerel catch

The September data for Chl-a, SST, and mackerel catch from 2014 to 2023 offers insights into how Chl-a and SST variations relate to fish catch fluctuations over this period. In graph of **Figure 7** shows the variation in SST, Chl-a, and productivity from 2018 to 2020. The peak catch was recorded in 2023 at 17,523 kg, with an SST of 30.43°C, which aligns with Harahap et al. (2020), who noted that an SST range of 29-31°C is optimal for pelagic fish habitats. This finding supports the study's results, revealing an interesting pattern where increases in fish catch productivity often follow rises in SST, particularly from 2017 to 2019. Although SST fluctuates, there is a positive correlation between rising sea temperatures and productivity in several years, such as 2016 and 2018, where higher temperatures coincided with increased productivity. However, in 2020 and 2022, high SST did not correspond with increased productivity, indicating that SST alone does not entirely determine productivity. For more details, refer to graph in **Figure 7** below.

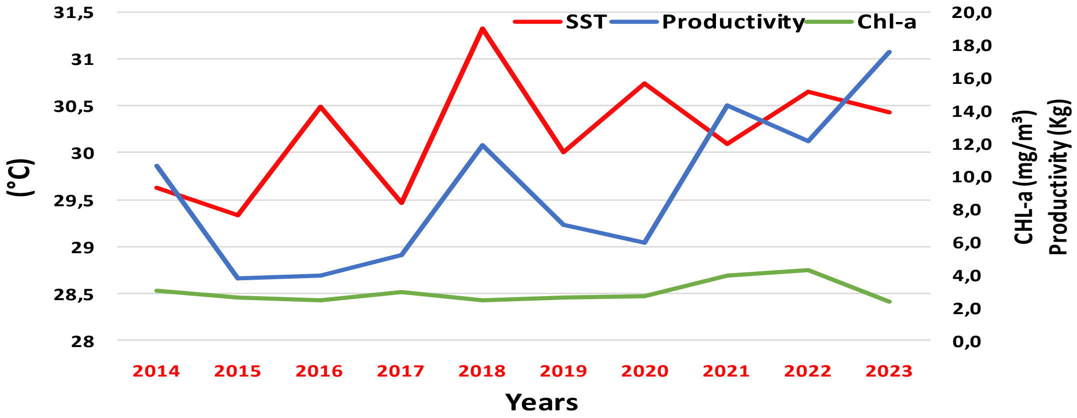

Fig 7. Relationship between SST, Chl-a, and mackerel productivity (2014–2023).

Chl-a concentration shows a generally stable upward trend compared to SST, even with a notable dip in 2023. This decrease in Chl-a concentration did not consistently correlate with reduced fish catch productivity, indicating a potentially more stable relationship between the two variables. In a study by Suaib et al. (2024), laboratory analysis of seawater samples in the Makassar Strait found that mackerel are frequently caught in areas where Chl-a concentrations range from 0.6 mg/m³ to 2.80 mg/m³. This range aligns with productivity in 2023, when the highest Chl-a concentration reached 2.38 mg/m³, and the catch totaled 17,523 kg. While a positive trend is observed between Chl-a and productivity, this correlation does not appear consistently strong. This implies that other factors, besides Chl-a, may influence fish productivity in Banten Bay waters. This view is supported by Larasati et al. (2024), who noted that mackerel, as a pelagic species, may not be directly influenced by Chl-a concentrations in the water. In the graph of **Figure 7** above illustrates the relationship between SST (°C), mackerel catch productivity (kg), and Chl-a concentration (mg/m³) from 2014 to 2023. The red line shows SST changes, the blue line represents catch productivity, and the green line indicates Chl-a concentration. Although a pattern exists between Chl-a and productivity, SST also seems to significantly impact mackerel productivity variation.

3.5. Analysis results based on Sea Depth

This map in **Figure 8** illustrates the bathymetry of Banten Bay waters in highlighting the variations in Sea Depth across the region. Darker-colored (blue) areas represent deeper waters, exceeding 45 m, while lighter-colored (blue) areas indicate shallower depths, from the surface down to approximately 5 m. This map offers essential insights into the seabed structure of Banten Bay waters, which can impact fish distribution and fishing practices in the area. Mackerel catch rates are closely linked to these depth variations, as mackerel typically inhabit nutrient-rich zones at optimal depths, often around 50-60 m (Kuriyama et al. 2023) in this area.

The bathymetry map of Banten Bay waters illustrates sea depth variations relevant to mackerel catch yields (see **Figure 8** above). The study by Suaib et al. (2024) found that mackerel are often caught at depths of 50-60 m. A similar study by Suhartono et al. (2013) also identified the optimal mackerel fishing zone to be between 55.03 and 60.04 m below the sea surface. During the transition season (September-November), Setyaningrum et al. (2023) observed that shifts in wind speed caused by the seasonal change from east to west also affect fishing locations in Banten Bay waters. This condition is further supported by findings from Wisha et al. (2015), who noted that surface currents moving offshore during ebb tides can trigger upwelling, whereby nutrient-rich water rises from the seabed to the surface. This upwelling enriches coastal waters, attracting pelagic fish like mackerel to migrate westward within Banten Bay waters in search of food. Thus, this bathymetry map not only provides insights into sea depth but also serves as a foundation for identifying optimal mackerel fishing zones in Banten Bay waters, particularly at depths conducive to upwelling and high nutrient availability. In addition, increasingly apparent climate change can affect upwelling dynamics. With reduced frequency or intensity of upwelling due to increased SST, the trophic chain can be disrupted, reducing the supply of phytoplankton and subsequently affecting the distribution and productivity of mackerel. In the long term, this condition can demand changes in fishing times, operational areas, and more adaptive fishing sizes to maintain the sustainability of mackerel stocks and the welfare of local fishermen.

3.6. Statistical analysis of oceanographic parameters on mackerel catch

Mackerel usually congregates within a specific range of SST and Chl-a values. The influence of these oceanographic parameters was analyzed using the GAM method, as shown in **Table 2** below. The results indicate that the combination of SST and Chl-a provides the lowest Akaike Information Criterion (AIC) value of 32.041, with a Cumulative Deviance Explained (CDE) of 36.7%, suggesting that this combination explains the variability in mackerel productivity more effectively than SST or Chl-a alone.

Table 2.

The GAM for the productivity of mackerel, with values AIC and CDE.

Prototype	*p*-value	AIC	CDE (%)
SST	5.43e-01	36.139	31.1
Chl-a	3.24e-01	33.696	13
SST + Chl-a	3.08e-01	32.041	36.7

Based on **Table 2**, it can be observed that the SST parameter alone has a significant influence on the distribution and abundance of mackerel in the waters of Banten Bay waters, contributing 31.1% to the CDE. This suggests that SST plays a more dominant role in mackerel distribution compared to Chl-a, which accounts for only 13%. This finding is consistent with research by Wang et al (2020), which suggests that SST is an effective indicator for identifying fishing areas, serving as the primary environmental factor for estimating fishing locations in Beibu Bay waters. The relatively low contribution of Chl-a (13%) to mackerel distribution may be due to the seasonal migration patterns of mackerel, as September marks the beginning of Transition Season II, during which mackerel migrate from east to west in search of areas with higher Chl-a concentrations. The most effective predictive model for mackerel presence was obtained by combining SST and Chl-a, resulting in a CDE of 36.7%.

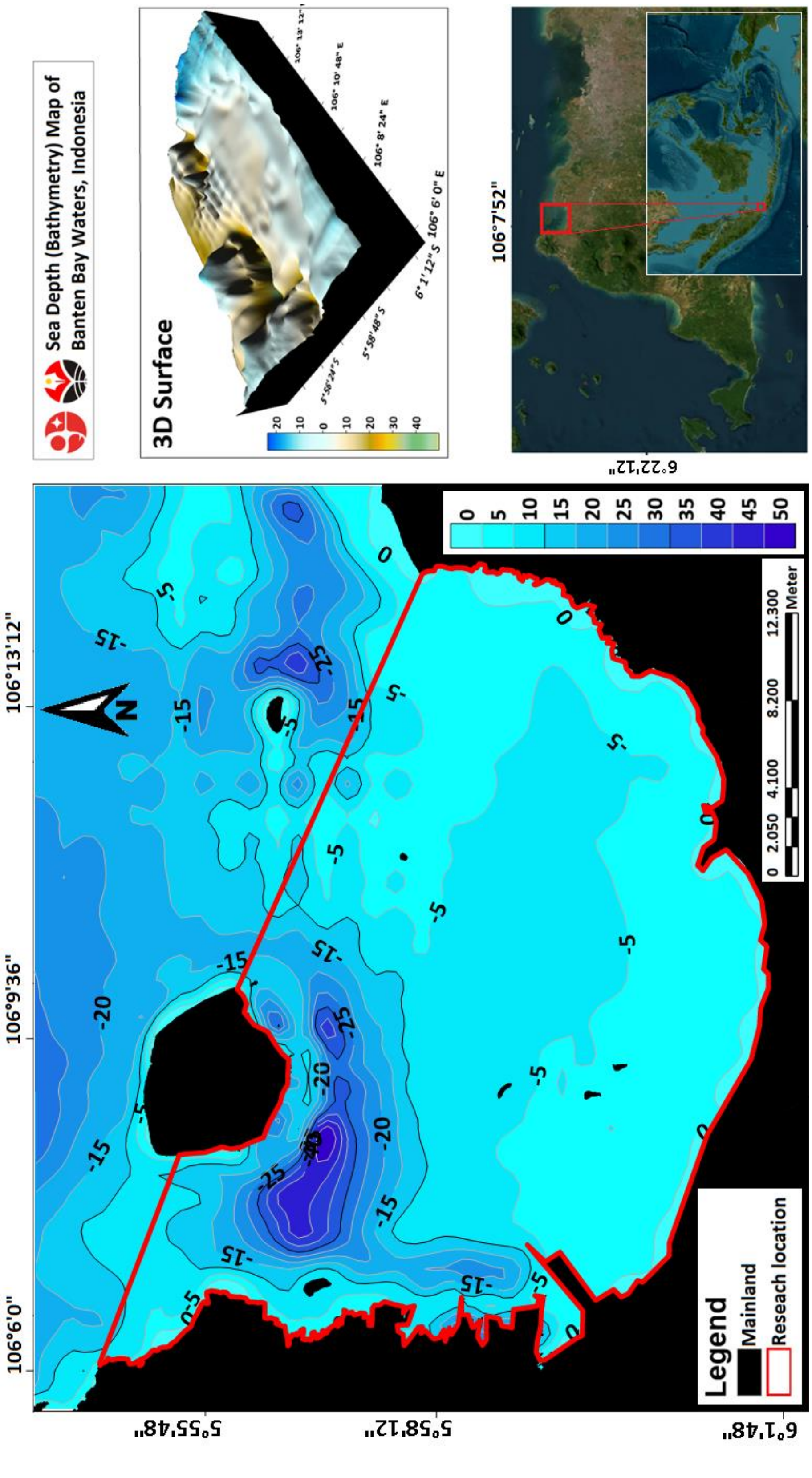

Fig. 8. Sea Depth (Bathymetry) map and 3D surface of Banten Bay Waters.

This indicates that the interaction between these two parameters provides a more comprehensive understanding of mackerel distribution. According to Das (2024), the relationship between SST and Chl-a may be influenced by seasonal rainfall variations, which affect the availability of nutrients and plankton, and consequently impact fish distribution. However, it is crucial to consider other factors outside the scope of this study that may also affect mackerel distribution and abundance in Banten Bay waters.

In addition to the results presented, comparing our GAM findings (AIC and CDE) with those from similar studies helps validate the effectiveness of our model. For example, Akter et al. (2024) demonstrated that incorporating both SST and Chl-a in their GAMs for predicting fish distributions resulted in lower AIC values and explained more than 30% of deviance, aligning closely with our CDE of 36.7%. Similarly, Oliveira et al (2024) reported that a two-parameter GAM including SST and chlorophyll concentration yielded an AIC reduction of up to 25% compared to single-parameter models, reinforcing our conclusion that combining variables enhances predictive power. Further supporting this, Suaib et al. (2024) found that integrative models using multiple oceanographic parameters (including SST and Chl-a) consistently achieved higher explanatory power (CDE > 35%) than simpler models. These comparisons with Wang et al. (2020); Das (2024); Suaib et al. (2024) underscore the robustness and effectiveness of our GAM approach.

The alignment of our AIC and CDE results with these studies confirms that integrating SST and Chl-a data provides a more reliable framework for identifying suitable mackerel habitats. This consistency across different marine ecosystems and species further validates our model's applicability and supports the adoption of similar integrative modeling strategies in future fisheries management and conservation research. The optimal oceanographic conditions for mackerel productivity were further analyzed using the GAM, as illustrated in **Figure 9**. Graph (a) shows the relationship between SST and mackerel abundance, while Graph (b) illustrates the influence of Chl-a concentration on mackerel distribution.

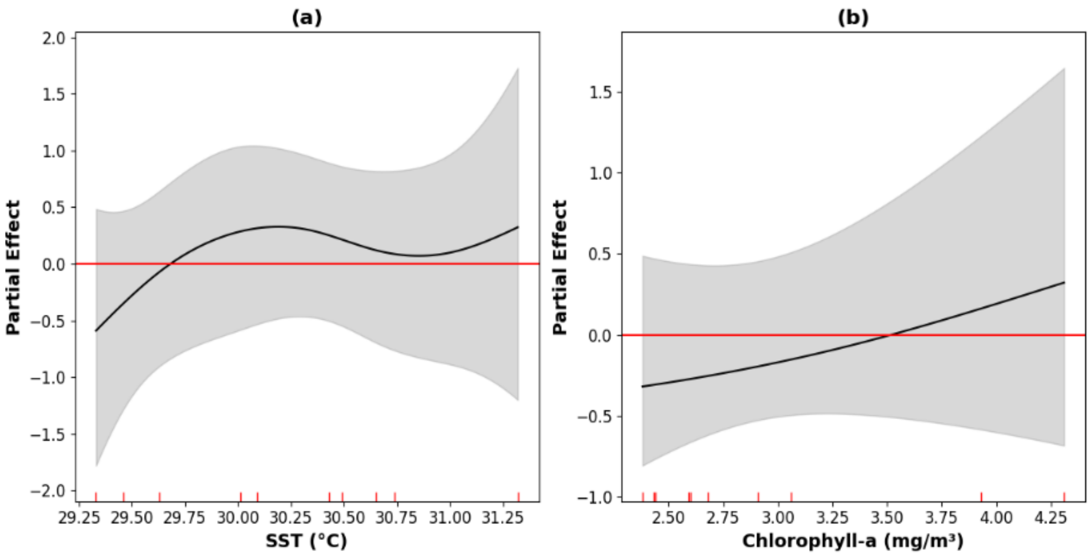

Fig. 9. Optimal oceanographic conditions for mackerel based on GAM analysis results, for (a) SST, and (b) Chl-a.

Figure 9 shows the influence of SST and Chl-a on mackerel distribution (*Rastrelliger sp.*) in Banten Bay waters. In Graph (a), the increase in SST from 29.5°C to 31.0°C is positively related to fish abundance, but abundance decreases at higher temperatures, indicating a preference for an optimum temperature range.

This suggests that mackerel are likely to aggregate within specific SST values, beyond which their abundance declines, possibly due to physiological stress or reduced prey availability in warmer waters. Meanwhile, graph (b) shows a positive relationship between Chl-a concentration and fish abundance, with increasing abundance at Chl-a concentrations up to 4.0 mg/m³, reflecting high primary productivity that may support greater prey availability for mackerel. After 4.0 mg/m³, the relationship appears to plateau, suggesting that extremely high Chl-a levels may not further increase mackerel presence.

The combination of SST and Chl-a parameters provides important insights and significantly contributes to understanding the spatial distribution pattern of mackerel in Banten Bay waters. These findings highlight that both SST and Chl-a are key environmental factors in predicting suitable habitats for mackerel, aiding in effective fisheries management and conservation strategies.

4. CONCLUSIONS

Based on the data analysis, SST within the range of 29.5°C to 31.0°C is positively correlated with mackerel abundance. However, abundance declines at temperatures beyond this range, indicating a preference for optimal temperature conditions. Chl-a also exhibits a positive relationship with mackerel abundance, with increased abundance observed at Chl-a concentrations up to 4.0 mg/m³, suggesting that these areas are regions of high primary productivity. Both SST and Chl-a are critical factors influencing the distribution and abundance of mackerel in Banten Bay waters, with SST emerging as the more dominant factor, contributing the highest GAM value of 31.1%, compared to Chl-a's contribution of 13%. This discrepancy may be attributed to the seasonal migration patterns, as September marks the start of Transition Season II, during which mackerel migrate from east to west in search of areas with higher Chl-a concentrations. Although higher SST and Chl-a levels are generally associated with increased catch productivity, this relationship is not consistently observed every year, as evidenced by fluctuations in 2020 and 2023.

Furthermore, the combination of SST and Chl-a provides the most accurate predictions for mackerel presence, highlighting the value of these parameters in developing habitat suitability models. Nevertheless, it is important to consider that additional environmental factors beyond this study, such as rainfall, wind, and ocean currents, also play significant roles in shaping mackerel distribution patterns in Banten Bay waters. In the context of fisheries management and conservation, these findings have several practical implications. First, by understanding the optimal temperature range and Chl-a concentration for mackerel abundance, local fishers can adjust their fishing times and locations more efficiently and sustainably. This can help avoid overfishing in certain areas and minimize negative impacts on fish populations.

Second, stakeholders and policymakers can use this information to develop more appropriate fisheries regulations, such as setting catch quotas, improving catch monitoring systems, and developing ecosystem-based conservation strategies. The study's contribution to broader conservation efforts is also seen in its potential to support sustainable marine management while strengthening science-based fisheries management initiatives that can be used by resource managers, government agencies, and non-governmental organizations in developing long-term management plans.

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