Egyptian Journal of Aquatic Biology & Fisheries
Zoology Department, Faculty of Science,
Ain Shams University, Cairo, Egypt.
ISSN 1110 – 6131
Vol. 29(5): 1553 – 1574 (2025)
www.ejabf.journals.ekb.eg

Spatio-Temporal Correlation of Sea Surface Temperature and Chlorophyll-a with East Seasonal Upwelling in the Bali Strait Using Aqua-MODIS Data

Windra Neka[1], Soemarno[2], Daduk Setyohadi[3], Rita Parmawati[4]*

[1]Doctoral Student Program in Agricultural Sciences, Faculty of Agriculture, Brawijaya University, Malang, 65145, Indonesia

[2]Soil Department, Faculty of Agricultural, Brawijaya University, Malang, 65145, Indonesia;

[3]Fisheries Resources Utilization Department, Faculty of Fisheries and Marine Science, Brawijaya University, Malang, 65145, Indonesia

[4]Doctoral in Postgraduate School, Postgraduate School, Brawijaya University, Malang, 65145, Indonesia

***Corresponding Author: windra.neka@gmail.com**

ARTICLE INFO

Article History:
Received: July 2, 2025
Accepted: Sep. 5, 2025
Online: Sep. 30, 2025

Keywords:
Sea surface temperature,
Chlorophyll-a,
Upwelling,
Sardin

ABSTRACT

The Bali Strait is a critical fishing ground for the *Sardinella lemuru* (sardine fish) fishery. This study analyzed the spatiotemporal dynamics of sea surface temperature (SST) and chlorophyll-a (Chl-a) in the strait and their relationship with sardine fish productivity using Aqua-MODIS satellite data from February (rainy season) and July (dry season) 2025. Results revealed significant seasonal variations driven by monsoon-induced upwelling. During the July east monsoon, intense upwelling lowered SST to 26°C and elevated Chl-a to 11.14 mg/m³ south of Banyuwangi and Jembrana, indicating high biological productivity. In contrast, February conditions showed warmer SST (28.12–34.49°C) and lower Chl-a, consistent with reduced upwelling. A strong inverse correlation was observed between SST and Chl-a, confirming upwelling's role in enhancing fertility. These oceanographic conditions directly influenced lemuru abundance, with optimal catch yields occurring at SSTs of 25–26°C. The study concludes that remote sensing of SST and Chl-a is vital for monitoring Potential Fishing Zones (PFZs) and promoting sustainable fisheries management in the Bali Strait amid increasing fishing pressure and climate variability.

INTRODUCTION

Sea surface temperature (SST) is a critical indicator of environmental change and a primary driver of various oceanic and atmospheric phenomena. Increasing SST has been correlated with multiple impacts on marine ecosystems, weather patterns, and climate change dynamics. A detailed assessment of SST trends reveals profound implications for ecological dynamics, especially in the context of climate change and marine heatwaves (MHWs).

SST is recognized as a fundamental parameter in oceanography and climatology, influencing various biogeochemical processes and marine ecosystems. For instance, **Bintoro *et al.* (2021)** and **Adivitasari *et al.* (2022**) highlighted that NOAA's Optimum Interpolation Sea Surface Temperature v2.0 dataset combines satellite and buoy observations to analyze SST, which is pivotal for understanding climate change effects. This dataset enables the identification and assessment of extreme conditions such as MHWs, which have been observed to increase in frequency and intensity across global regions, as shown in **Clinton *et al.* (2022)**. Furthermore, **Clinton *et al.* (2022)** provided a comprehensive global assessment of marine heatwaves, showing that the average properties of these events rely heavily on continuous data regarding SST over 34 years.

Urban areas are not the only regions impacted by rising SST; coastal environments show dramatic responses as well. **Gaol *et al.* (2010)** documented the gradual increase of SST along Australia's southwestern coast, predicting an escalation in temperature-related disturbances such as MHWs. Additionally, **Gustantia *et al.* (2021)** found that temperature gradients in the Mediterranean Sea, driven by Atlantic water inflow and North African winds, significantly influence local marine conditions, further affirming the need for targeted climate models to simulate future SST scenarios.

The repercussions of altered sea surface temperatures extend beyond physical measures, affecting marine biodiversity and ecosystem interactions. For example, **Jatisworo *et al.* (2022)** discussed the accelerated warming trend in the East China Sea, reporting instances of extreme SST anomalies that alter nekton communities. Meanwhile, high SSTs have been linked to detrimental effects on foundational species like seagrasses and kelp, leading to ecosystem disruption in some cases, as noted by **Puspasari *et al.* (2019a, b)**. This highlights the cascading effects that elevated temperatures can have, not just locally, but also at a larger scale across ecosystems, which may struggle to adapt to rapid environmental changes **(Puspasari *et al.*, 2016)**.

Moreover, climate models indicate that future SST seasonality will be influenced by enhanced ocean stratification, potentially leading to distinct seasonal temperature patterns that will affect marine life and ecosystem services **(Albo-Puigserver *et al.*, 2022)**. This coupling of higher average temperatures and altered seasonal dynamics is likely to exacerbate existing environmental stressors, pushing marine species beyond their adaptive limits **(Supraba *et al.*, 2016; Góes *et al.*, 2023)**. In the present study, the maximum density of phytoplankton was controlled by temperature with a relative increase in species number during hot seasons compared to cold ones **(Ali & El Shehawy, 2017)**.

The Bali Strait, located between Java and Bali in Indonesia, exhibits significant spatial-temporal variability in sea surface temperature (SST) and is influenced by various oceanographic phenomena, notably the El Niño-Southern Oscillation (ENSO) and the Indian Ocean Dipole (IOD). These factors play a crucial role in governing marine ecosystems, particularly for pelagic species such as *Sardinella lemuru* (*Lemuru* genus), which is vital for local fisheries.

SST in the Bali Strait varies considerably with seasonal changes, and these fluctuations have been studied extensively to understand their impacts on marine life. **Suniada and Susilo (2018)** stated that both ENSO and IOD significantly affect chlorophyll-a concentration along with SST, which directly influences the abundance of marine organisms in the strait. The interaction between these oceanographic phenomena can lead to altered marine productivity and fishing yields, as noted by **Suprianto *et al.* (2021a, b)**, who observed a marked correlation between SST changes and fish catch variability.

The study of upwelling dynamics in the Bali Strait adds another layer of complexity to understanding SST and its effects on marine ecosystems. **Susilo and Tito (2023)** investigated how the positive and negative phases of the IOD impact chlorophyll-a concentration, which is closely linked to primary productivity. This upwelling phenomenon enhances nutrient availability, thereby affecting local fisheries, particularly of *Sardinella lemuru*, which thrive in these enriched waters.

Remote sensing techniques have been pivotal for monitoring SST and chlorophyll-a in the Bali Strait. Several studies utilized data from the Moderate Resolution Imaging Spectroradiometer (MODIS) to analyze spatial patterns and temporal variations. For instance, **Syah *et al.* (2019)** reported that SST values experienced seasonal fluctuations ranging between 24.76 and 30.11°C over the period from 2009 to 2018, highlighting the strait's dynamic oceanographic conditions. Furthermore, **Syah *et al.* (2019)** conducted predictive assessments of potential fishing zones for mackerel tuna, reliant on SST and chlorophyll-a data collected via remote sensing.

The relationship between SST, chlorophyll-a, and marine biodiversity is crucial for sustainable fisheries management. **Satyawan *et al.* (2023)** emphasized that the dynamics of the lemuru fishery in the Bali Strait can fluctuate and are sensitive to changes in environmental conditions, including SST. The balance of these environmental factors is critical for maintaining the sustainable yield of fish populations, as indicated in studies by **Sastra *et al.* (2017)** and **Suardana *et al.* (2021)**, where the influence of SST on fish catch rates was examined across various seasons. *Lemuru* fish are one of the region's main fishery commodities and make seasonal movements influenced by oceanographic factors such as water temperature, ocean currents, and plankton availability **(Neka *et al.*, 2025)**.

SST in the Bali Strait is influenced by complex interactions between climatic phenomena such as ENSO and IOD, which have significant implications for marine ecology and fisheries. Monitoring these changes through advanced remote sensing techniques is essential for understanding the ongoing environmental adjustments in this vital marine corridor, thereby aiding sustainable fishery practices and ecological conservation.

The objective of this study was to utilize Geographic Information System (GIS)-based mapping to assess sardine productivity.

MATERIALS AND METHODS

This research was conducted in the Bali Strait from February to July 2025 using a remote sensing approach. The primary environmental data set comprised direct measurements of temperature, salinity, and chlorophyll-a. Secondary remote sensing data included satellite data on sea surface temperature (SST) and chlorophyll-a (Aqua-MODIS).

The creation of maps depicting sea surface temperature (SST) is a subject of considerable interest. The process can be delineated into five primary stages, as illustrated in the accompanying flowchart. This flowchart depicts the sequence of events from satellite measurement to the generation of a map that has undergone analysis.

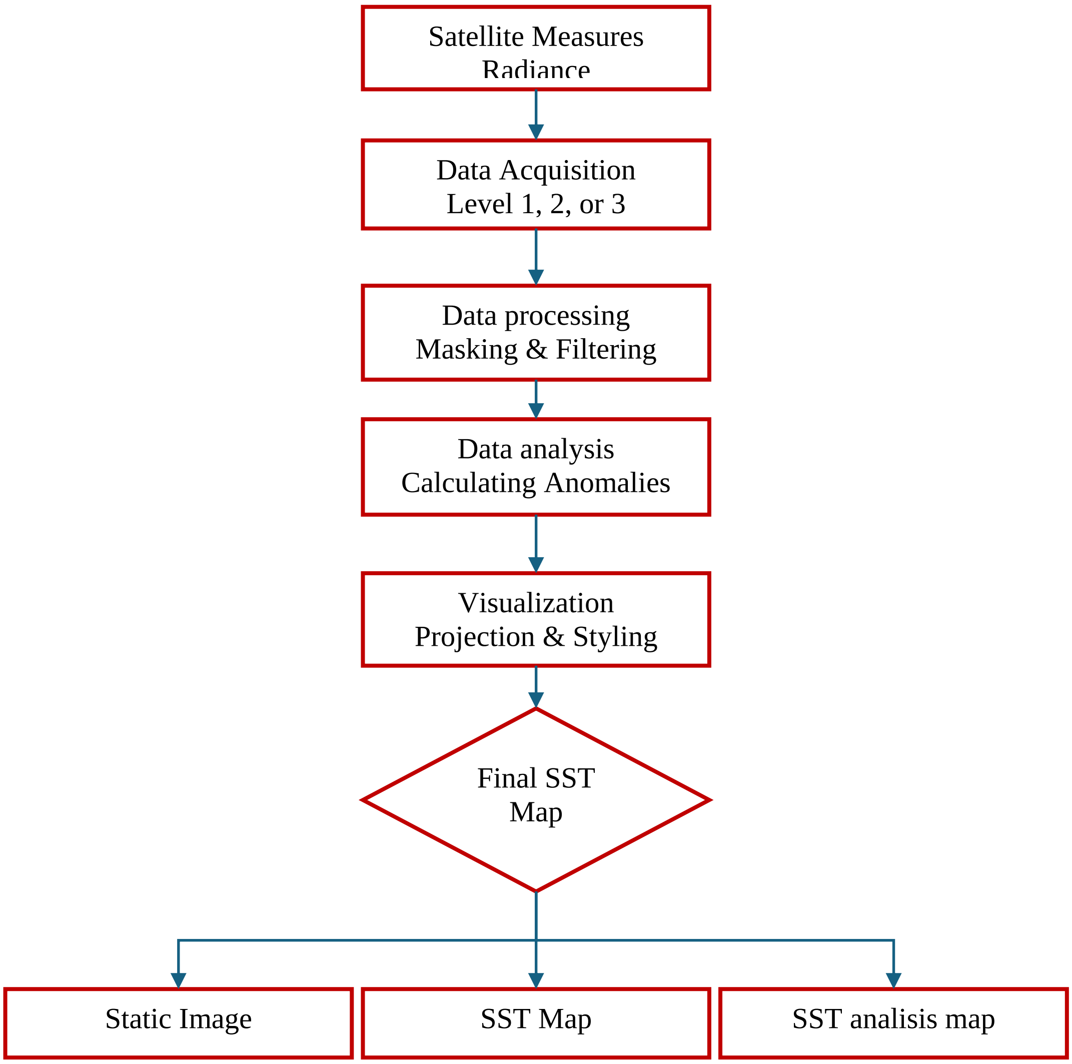

Fig. 1. Comprehensive methodology of sea surface temperature map

1. Data acquisition

This is the most critical step. Raw SST data need to be obtained. The primary sources were satellite data from various agencies.

1.1. Understanding data levels

- Level 1 (L1): Raw radiance data from the satellite sensor; this level requires significant processing and is not recommended for beginners.
- Level 2 (L2): Geophsical data (like SST) derived from L1 data, mapped to individual satellite swaths (the path the satellite took). It has a high resolution but with gaps.
- Level 3 (L3): Data that has been mapped to a regular grid. Gaps are often filled using interpolation. This is the most common and user-friendly type for creating maps.
- Level 4 (L4): Data that combines observations from multiple satellites using a sophisticated model to create a complete, gap-free, smoothed analysis. This is often the best for a final picture of the ocean's state.

1.2. Major Data Sources

NASA Earthdata (PO.DAAC): The primary source for satellite SST data.

- Datasets: MODIS Aqua/Terra, VIIRS-SNPP
- Access: Use the Earthdata search tool.

NOAA CoastWatch: Excellent for operational oceanography, with data tailored for regional use.

- Datasets: GOES-R Series (geostationary, high temporal resolution), JPSS series (VIIRS), and blended products.
- Access: Direct download or via APIs. NOAA CoastWatch Portal.

2. Data preprocessing and handling

Satellite data often comes in scientific data formats that require specific tools to read. Tools for Handling Data use ArcGIS software.

3. Data analysis (Adding value)

A simple SST map is good, but an analyzed one is better. This is represented by the Data Analysis step in the flowchart.

Calculating Anomalies: This is the most common analysis. It shows how much warmer or cooler the ocean is compared to a long-term average.

Get Climatology: Calculate the average SST for each time over a baseline period.

4. Visualization (Making the map)

This is where you create the actual visual product with ArcGIS software. For regional maps, an appropriate projection is used. The use of a perceptually uniform colormap is good for absolute SST. For anomalies, a divergent colormap like red for warm, blue for cool is used.

5. Interpretation and dissemination

Interpretation: Explaining what the map shows. Are there upwelling zones (cold water)? Are there warm eddies? How do the patterns relate to monsoon seasons? Output format maps PNG, JPEG.

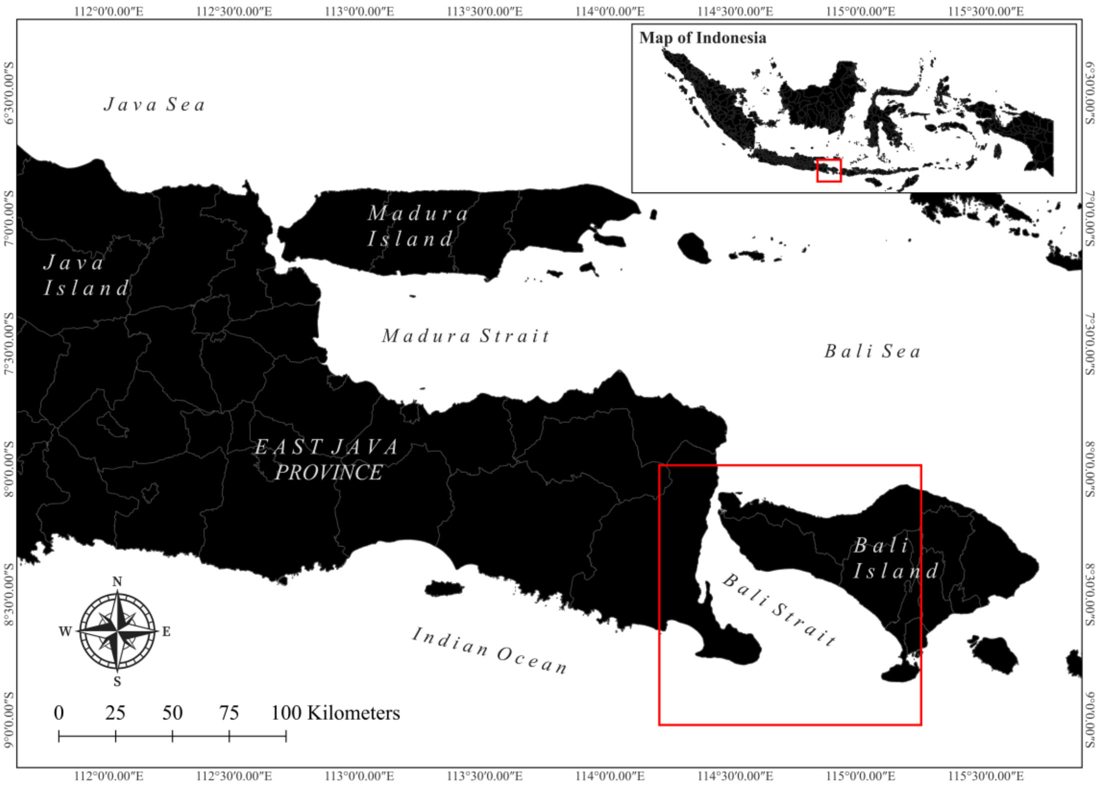

Fig. 2. Research location

RESULTS

Research on the sustainability of sardine fish

Research revealed the significant impact of sea surface temperature (SST) dynamics on pelagic fish populations, including lemuru, which depend heavily on environmental conditions for survival and reproduction **(Puspasari *et al.*, 2016; Puspasari *et al.*, 2019)**.

The Bali Strait, located between the islands of Bali and Java, is a critical marine environment significantly influenced by various oceanographic phenomena including upwelling, the El Niño Southern Oscillation (ENSO), and the Indian Ocean Dipole (IOD). Understanding the dynamics of sea surface temperature (SST) in this region is essential for ecological and fisheries management due to its impact on the distribution and catch of local fish species, particularly *Sardinella lemuru* (sardin fish).

Sea surface temperature (SST) dynamics

Research has shown that SST in the Bali Strait experiences significant seasonal and inter-annual variability, largely driven by climatic factors such as ENSO and IOD events. **Jatisworo *et al.* (2022)** reported that these events influence not only SST but also the concentration of chlorophyll-a (Chl-a), highlighting a relationship that affects marine biodiversity and productivity in the strait **(Jatisworo *et al.*, 2022)**. **Setyohadi *et al.* (2021)** similarly emphasized the impacts of ENSO and IOD variations on SST and Chl-a levels, observing that such fluctuations can shift the ecological balance and the availability of food sources for fish populations. A study by **Syah *et al.* (2019)**

identified that catch yields for *Sardinella lemuru* are optimized when SST values are within a specific range (26- 30°C).

Table 1. A synopsis of the spatial distribution and positioning of SSTs in February 2025

Location	Color	Temperature range (°C)	Characteristics
The south coast of Bali, in the vicinity of Jembrana, Tabanan, and Badung, is a region of significant cultural and historical significance.	The color is identified as yellow-orange. .	The range of values in question is from 30.32 to 34.49.	The phenomenon of elevated temperatures is influenced by solar radiation and the movement of warm water masses.
Bali Strait, located in proximity to Banyuwangi and Situbondo, is a body of water that merits consideration in this analysis.	The color green is associated with environmental sustainability and the natural world	The range of values in question is from 28.12 to 30.32	The presence of low temperatures is attributable to the influence of strong strait currents.

A thorough examination of sea surface temperature (SST) maps in the Bali Strait during February 2025 reveals a highly variable temperature distribution pattern. The map utilizes a color scale, with green (28.12- 30.32°C) denoting low temperatures and orange (32.52- 34.49°C) indicating high temperatures.

The present study focuses on the processing of sea surface temperature data for the Bali Strait. The following graph illustrates the sea surface temperature in the Bali Strait in February of 2025.

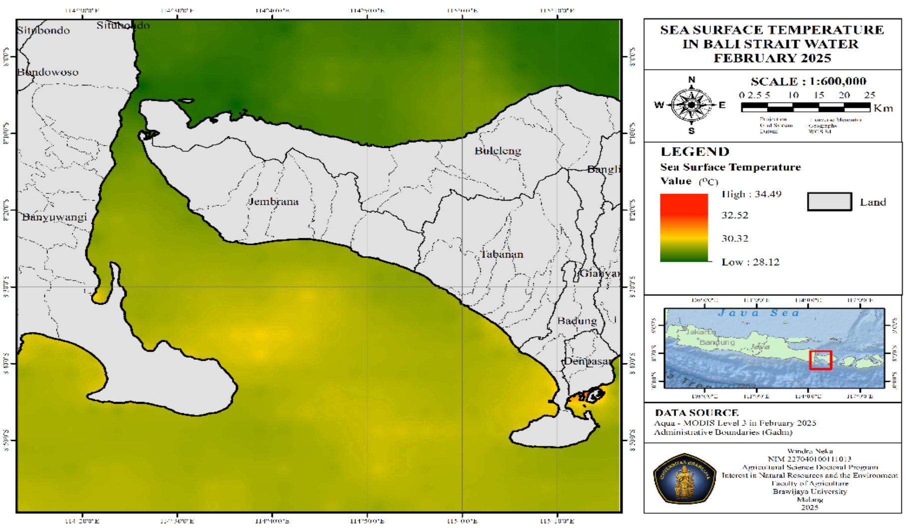

Fig. 3. A map of the sea surface temperature (SST) of the Bali Strait from February of 2025

The map indicates the prevalence of elevated temperatures in the majority of water bodies, particularly in the southern region of Bali. The waters along the southern coasts of Jembrana, Tabanan, and Badung have been observed to exhibit elevated temperatures, as indicated by yellow and orange hues. This phenomenon is believed to be attributable to two primary factors: the intense solar radiation experienced during this period and the calmer waters that characterize the dry season. These conditions, when combined, result in optimal surface heating. Furthermore, the presence of warm water masses from the Indian Ocean may also contribute to the observed increase in temperature in this region.

The primary impact of the persistent rises in sea water temperature in the Bali Strait waters is the potential for a number of grave ecological consequences, specifically coral bleaching. Rising temperatures have the potential to disrupt the balance of the marine food chain. Warmer waters characteristically exhibit diminished levels of dissolved oxygen. This condition can impede the ability of large marine life, including certain fish species, to engage in essential activities such as respiration. These alterations can precipitate shifts in species distribution, resulting in the predominance of species that are tolerant to elevated temperatures, while species with a need for cooler water will undergo migration or become locally extinct. This phenomenon portends a looming threat to the productivity of regional fisheries.

The natural phenomenon that engenders the sea's calmer state is the dry season. The presence of tranquil water bodies is an inherent feature of the dry season. The absence of storms and strong winds, which are more common during the rainy season, results in a decrease in wave activity. It is precisely these tranquil conditions, when amalgamated with the profound solar radiation, that engender the ideal heating of the sea surface.

In contrast to the southern region, the waters in the Bali Strait near Banyuwangi and Situbondo exhibit comparatively lower temperatures, as indicated in green. This phenomenon can be attributed to the presence of stronger currents in the strait, which facilitate water mixing and diminish surface warming. However, when contrasted with the lower temperatures typically exhibited by temperature maps in other months, the February 2025 temperatures are, on average, higher. The subsequent table offers a synopsis of the temperature distribution and its corresponding location.

Table 2. The following is a synopsis of the spatial distribution and positioning of SSTs in July 2025

Location	Color	Temperature range (°C)	Characteristics
Bali Strait is located in the vicinity of Banyuwangi and Jembrana.	The color green is associated with the environment and sustainability.	The range of values in question is from 26.00 - 27.20	The observed low temperatures are potentially attributable to upwelling and the strong currents resulting from the east monsoon winds.

The North Coast of Bali, encompassing the regions surrounding Buleleng and Situbondo, is a region of significant ecological and cultural importance.	The color is identified as yellow-orange.	The range of values in question is from 27.20 - 29.57	The phenomenon under consideration is characterized by elevated temperatures, a consequence of solar radiation and tranquil waters.

The following data set contains the sea surface temperature (SST) of the Bali Strait in July 2025.

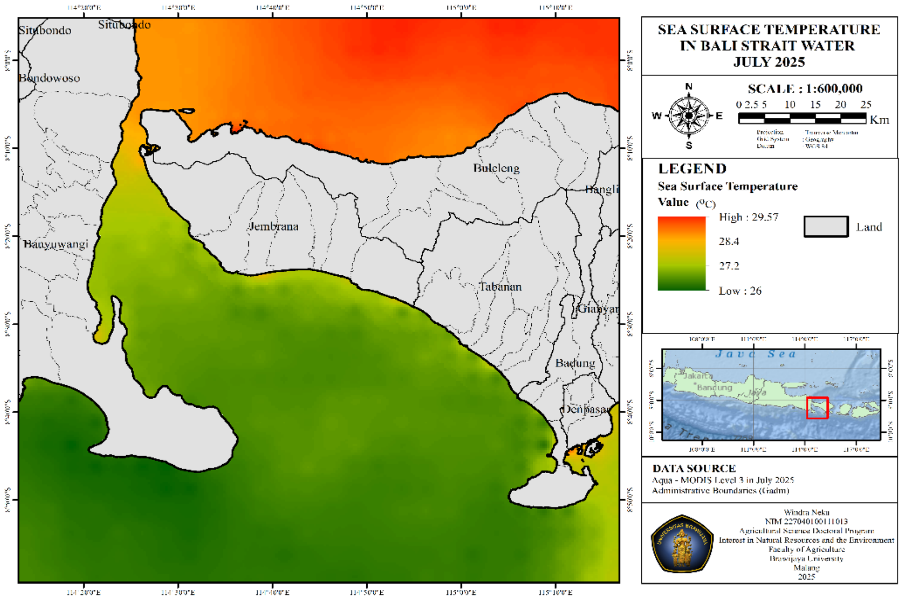

Fig. 4. A map of the sea surface temperature (SST) of the Bali Strait in July of 2025

A thorough examination of sea surface temperature (SST) maps in the Bali Strait during July of 2025 reveals a conspicuously variable temperature distribution pattern. The map utilizes a color scale, with green (26 - 27.2°C) denoting low temperatures and orange (28.4 - 29.57°C) indicating high temperatures. The temperature patterns in these waters are significantly influenced by geographical and hydrological conditions. The Bali Strait region, particularly the waters along the east coast of Banyuwangi and the south coast of Jembrana, exhibit low temperatures, as indicated by the presence of green colors. This phenomenon is most frequently observed in July, which corresponds to the dry season in Indonesia. The lower temperatures can be attributed to upwelling, a process in which cold, nutrient-rich water masses from the deep ocean rise to the surface due to the east monsoon winds. This condition is of particular significance to the marine ecosystem, as it supplies vital nutrients to phytoplankton the foundation of the marine food chain.

In this context, lower temperatures are indicative of lower values in both spatial and thermal domains. Specifically, lower temperatures manifest as lower values in comparison to other areas in the Bali Strait at the same time, as well as lower values in comparison to expected sea surface conditions devoid of upwelling processes. To enhance the comprehensibility of the spatial relationship between these phenomena, it is imperative to acknowledge the role of the east monsoon winds, which induce upwelling in the Bali Strait. These winds also contribute to the maintenance of calm conditions in the sheltered southern waters of Bali. Furthermore, the Jembrana region exemplifies intricate temperature variations, wherein the strait exhibits a cold temperature due to upwelling, while the southern coast experiences a warmer climate.

Conversely, the waters north of Bali, particularly in the regions of Buleleng and Situbondo, exhibit significantly higher temperatures, as evidenced by yellow to orange hues. The elevated temperatures in this region may be attributable to the presence of calmer and shallower waters, which permit solar radiation to heat the water surface more efficiently. Furthermore, the waters north of Bali experience reduced effects from the backwash and strong currents of the Bali Strait, leading to more stable and warmer temperatures.

The subsequent section delineates the temperature distribution and its corresponding location.

A study of sea surface temperature was conducted in 2025

A series of sea surface temperature (SST) maps in the Bali Strait were analyzed to draw conclusions about the temperature dynamics pattern in the region. The analysis was based on monthly data from February and July of 2025. The aforementioned pattern is significantly influenced by upwelling phenomena, water mass movements, and the prevailing season.

A study of annual and seasonal patterns is warranted

Southern Bali Strait Waters: The region encompassing the southern coast of Banyuwangi and Jembrana consistently exhibits comparatively lower temperatures, as indicated by the shaded green area in the map. The following map pattern is intended for July 2025. These low temperatures directly indicate the upwelling phenomenon, wherein the east monsoon winds displace surface water masses from the coast, thereby enabling the rise of nutrient-rich cold water from deeper layers to the surface. This condition results in a decrease in surface water temperature.

Northern Bali Waters: Conversely, the waters north of Bali, encompassing the regions of Buleleng and Situbondo, exhibit consistently elevated temperatures, as indicated by the yellow and orange shades in the map. The observed increase in temperature can be attributed to the presence of calmer and shallower waters, which facilitate optimal surface heating through solar radiation. Furthermore, this region exhibits a lesser degree of susceptibility to the return currents originating from the Bali Strait.

Seasonal differences: The monthly data for 2025 corroborates this seasonal pattern. The map from July 2025 reveals that the southern region experienced notably low temperatures, ranging from 26 to 27.2 degrees Celsius. This observation aligns with the period of peak aridity, known as the dry season, and the heightened intensity of upwelling, a process that involves the upward movement of cold, saline water. Conversely, the February 2025 map demonstrates a general increase in temperature (28.12- 34.49°C) across the majority of the water bodies, particularly in the southern region, attributable to the west monsoon winds, which diminish upwelling and augment surface warming.

Chlorophyll-a (Chl-a) dynamics

Table 31. A synopsis of the distribution of chlorophyll-a and its location in February of 2025

Location	Color	The following concentration range (mg/m^3)	The following characteristics are exhibited:
The North Coast of Situbondo	The color red is closely associated with the color orange.	The range of values in question is from 1.07 to 14.69.	Concentrations of these elements in the water column are indicative of intense upwelling and highly fertile waters.
The Central Bali Strait and the North Coast of Bali are the subjects of this study.	The color blue is associated with green.	The range of values in question is from 0.11 to 1.07.	Conversely, low concentrations are indicative of waters with reduced fertility.

A thorough examination of the chlorophyll-a maps from February 2025 in the Bali Strait is warranted.

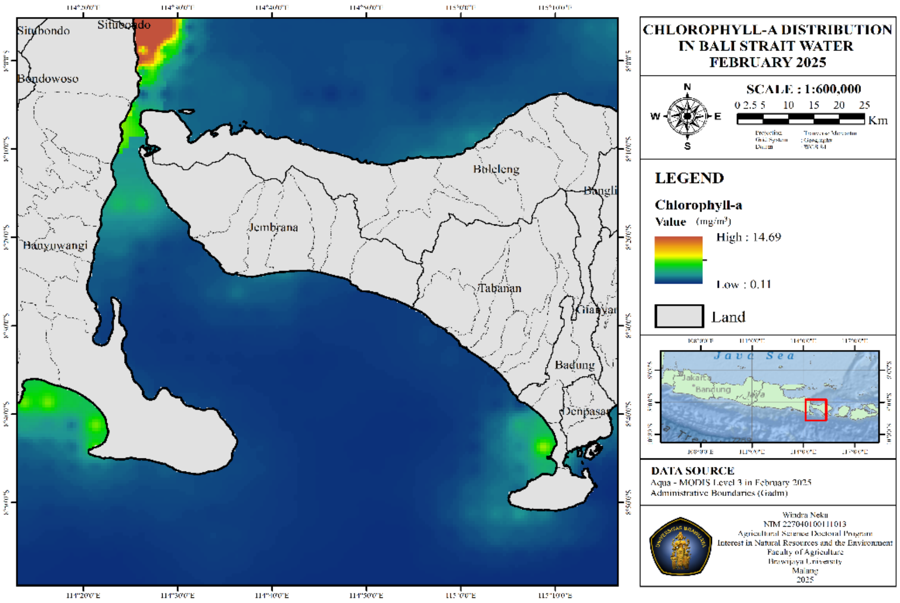

Fig. 5. A chlorophyll-a distribution map of the Bali Strait from February of 2024

An analysis of chlorophyll-a distribution maps in the waters of the Bali Strait for February 2025 reveals varied distribution patterns. Chlorophyll-a is a photosynthetic pigment that serves as a primary indicator of phytoplankton biomass. The map employs a color scale, with dark blue (0.11mg/ m3) denoting low concentrations and red (14.69 mg/m3) signifying very high concentrations.

The map indicates that elevated chlorophyll-a concentrations, indicated by red and orange hues, are predominantly present in the waters north of Situbondo. The remarkably elevated chlorophyll-a concentrations observed in this region are likely attributable to intense upwelling phenomena. Upwelling is defined as the process by which nutrient-rich cold water masses rise from the deep layers to the surface. These nutrients, including nitrates and phosphates, serve as the primary sustenance for phytoplankton growth, resulting in a substantial "bloom" of the phytoplankton population. These conditions render the waters highly fertile, thereby creating an optimal environment for fishing activities. High chlorophyll-a concentrations were also observed in several other coastal areas, such as south of Banyuwangi and Badung, although not to the same extent as in Situbondo.

Conversely, the waters in the central part of the Bali Strait and along the northern coast of Buleleng are characterized by a predominance of blue and green hues. This phenomenon is indicative of low chlorophyll-a concentrations. These areas are characterized by lower fertility levels, attributable to either a deficiency in nutrient supply or to water conditions that are not conducive to the growth of phytoplankton.

Table 42. A synopsis of the distribution of chlorophyll-a and its location in July of 2025

Location	Color	The following concentration range (mg/m^3)	The following characteristics are exhibited:
The south coast of Banyuwangi and Jembrana.	Exhibits a spectrum of red and yellow hues	concentrations ranging from 1.05 to 11.14	This phenomenon signifies a high degree of upwelling, indicative of robust oceanic processes. The presence of red and yellow hues in the water indicates the presence of fertile waters, a consequence of the east monsoon winds.
The Central Bali Strait and North Bali Coast	characterized by a blue-green hue	concentrations ranging from 0.18 to 1.05	This indicates that the waters in these regions are of low fertility.

A thorough examination of the chlorophyll-a maps from July 2025 in the Bali Strait is warranted.

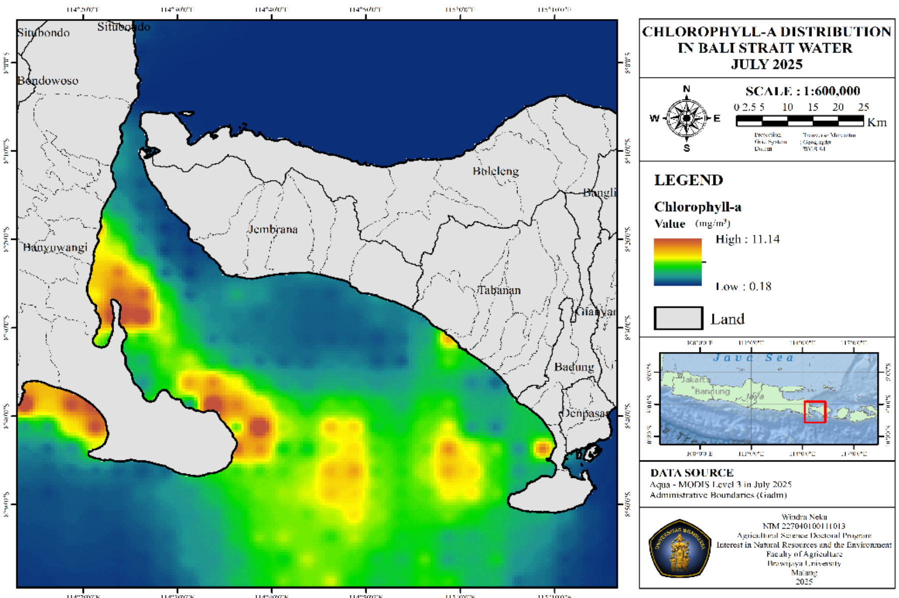

Fig. 6. A chlorophyll-a distribution map of the Bali Strait from July of 2024

An analysis of chlorophyll-a distribution maps in the waters of the Bali Strait for July 2025 reveals the presence of very high concentrations in several areas, indicating the presence of very fertile water conditions. Chlorophyll-a, a photosynthetic pigment found in phytoplankton, has been identified as a reliable indicator of phytoplankton biomass. The map employs a color scale, with dark blue (0.18mg/ m^3) denoting low concentrations and red (11.14mg/ m^3) signifying very high concentrations.

The map illustrates the elevated chlorophyll-a concentrations (denoted in yellow and red) that are predominantly concentrated in the waters south of Banyuwangi and the southwest coast of Jembrana, extending as far as the central region of the Bali Strait. The remarkably elevated chlorophyll-a concentrations observed in this region are attributable to the occurrence of intense upwelling phenomena. Upwelling is defined as the process by which cold, nutrient-rich water masses rise from the depths of the ocean to the surface. This phenomenon is prevalent in the southern waters of Indonesia during the east monsoon period, which occurs around July. These nutrients have been demonstrated to trigger substantial phytoplankton growth, which, in turn, has been shown to increase chlorophyll-a concentrations. The aforementioned conditions render the waters in this region highly productive, thus classifying it as a significant fishing area.

Conversely, the waters in northern Bali, particularly in the regions surrounding Buleleng and Situbondo, are characterized by a predominance of blue and green hues. This phenomenon is indicative of low chlorophyll-a concentrations. The area's suboptimal fertility is attributed to the absence of essential nutrients or to hydrographic conditions that are not conducive to the growth of phytoplankton. The subsequent table offers a synopsis of the distribution and location of chlorophyll-a, which is characterized by its notably elevated levels.

A study of chlorophyll-a conducted in 2025

A series of chlorophyll-a distribution maps of the waters of the Bali Strait were analyzed in February and July of 2025. This analysis allowed for the drawing of academic conclusions regarding the dynamics of phytoplankton in the region. Chlorophyll-a, an indicator of phytoplankton biomass, exhibits substantial spatial and temporal variability, which is significantly influenced by upwelling phenomena.

In general, high chlorophyll-a concentrations (marked by yellow to red colors) consistently appear in the coastal waters south of Banyuwangi and southwest of Jembrana. This phenomenon is indicative of the presence of a stable primary productivity zone within the area in question. This phenomenon is closely related to upwelling, where the east monsoon winds (from June to October) displace surface water masses from the coast, thereby allowing nutrient-rich cold water from the deep layers to ascend to the surface. These nutrients have been observed to trigger a phytoplankton population explosion (phytoplankton bloom), resulting in a marked increase in chlorophyll-a concentrations.

It has been determined that regions outside the upwelling zone, including the central part of the Bali Strait and the northern coasts of Buleleng and Situbondo, have been shown to consistently exhibit low chlorophyll-a concentrations (indicated in blue and green). These findings suggest that these areas are characterized by waters that tend to be less fertile.

The present study seeks to examine the relationship between sea surface temperature and chlorophyll-a

Table 5. A comparison of SST with chlorophyll-a is warranted

Map	Time	The range of surface temperature (°C) is low.	The maximum concentration of chlorophyll-a (in milligrams per cubic meter) is indicated here.	Description
SST Feb 2025	Rainy Season	28.12	14.69	Temperatures in the southern region are elevated, while the northern region is characterized by elevated levels of Chlor-a, indicative of a seasonal pattern.
SST July 2025	Dry Season	26.00	11.14	A significant decrease in temperature has been observed in the southern region, accompanied by a notable increase in Chlor-a levels, indicative of a seasonal pattern.

A robust inverse correlation has been observed between sea surface temperature and chlorophyll-a concentration. Conversely, areas exhibiting low temperatures (green) due to upwelling concurrently demonstrate high chlorophyll-a concentrations. This phenomenon occurs because the rising of cold water to the surface of the ocean brings nutrients, such as nitrates and phosphates, from the deeper layers of the ocean. These nutrients serve as the primary source of energy for the growth of phytoplankton, which, in turn, contributes to an increase in their biomass and, consequently, an increase in chlorophyll-a concentration.

The most evident illustration of this correlation is observable in the map published in July 2025. The SST map reveals the presence of low temperatures in the region south of Banyuwangi and Jembrana, while the chlorophyll-a map, covering the same time period, indicates notably elevated chlorophyll-a concentrations in the aforementioned area.

Seasonal variations and upwelling

The seasonal variations of SST are particularly pronounced during the Southeast Monsoon, a period characterized by significant upwelling events which cool the surface waters. Studies have indicated that upwelling can lower SST while simultaneously elevating Chl-a concentrations, creating nutrient-rich waters conducive to fish abundance **(Siwi & Priyono, 2020; Suprianto *et al.*, 2021a)**. For instance, **Setyohadi *et al.* (2021)** demonstrated that the positive phase of the IOD exacerbates upwelling effects, which are essential for sustaining fish stocks in the region. The frequency and intensity of these upwelling events are closely linked to the prevailing winds and global climate patterns, making them critical for understanding the marine ecosystem in the Bali Strait **(Siwi & Priyono, 2020; Suprianto *et al.*, 2021a)**.

This analysis, when viewed through a scientific lens, provides definitive evidence that upwelling serves as the predominant hydrological process, exerting a pivotal influence on the temperature and primary productivity of the waters within the Bali Strait. This phenomenon is most pronounced in the southern part of the strait during the dry season (east monsoon), which is characterized by low surface temperatures and high chlorophyll-a concentrations.

The Bali Strait, situated between Java and Bali, is a highly valued fishing area due to its abundant marine biodiversity and favorable oceanographic conditions. The strait functions as a migration route for pelagic species, including mackerel, tuna, and sardines, thus establishing it as a pivotal fishing area for local fishermen and the commercial fishing industry. The upwelling phenomenon in this region also brings nutrient-rich water to the surface, increasing primary productivity and supporting abundant fish stocks. The Bali Strait fishery, when managed effectively, has the potential to make a substantial contribution to food security and economic growth in the region.

Research has demonstrated the substantial impact of sea surface temperature (SST) dynamics on pelagic fish populations, including lemuru, which are highly dependent on environmental conditions for survival and reproduction. From a climatic perspective, fishing activities in the Bali Strait are strongly influenced by the seasons. A discernible seasonal pattern is evident, with the rainy and dry seasons exerting a marked influence on the period during which fishing activities occur. The rainy season, accompanied by prevailing northeast winds, persists from October to March and contributes to enhanced fishing productivity, including mackerel. It is imperative to comprehend this seasonal variability.

A correlation was identified between sea surface temperature and chlorophyll-a concentration, which in turn affects the distribution of small pelagics. The study concluded that sea surface temperature and food availability, influenced by chlorophyll-a, exhibit mutually influencing distribution patterns. The diet of these fish consists primarily of zooplankton and microalgae, suggesting their ecological significance within the marine food web. The availability of these species exhibits significant variations that are closely related to environmental and climatic factors, including sea surface temperature and seasonal changes in water productivity. The research underscores the significance of conducive environmental factors, including water temperature, chlorophyll-a concentration, and ocean currents, which exert a profound influence on the distribution of small pelagics.

A thorough review of the extant literature reveals several key findings. Initial research has identified a strong correlation between significant fluctuations in small pelagic populations and environmental variables, including sea surface temperature (SST) and chlorophyll-a concentration. This correlation is particularly pronounced during upwelling periods influenced by climate phenomena such as the Indian Ocean Dipole (IOD). For instance, during periods of favorable upwelling, higher chlorophyll-a levels have been found to be positively correlated with increased small pelagic catches. This underscores the necessity of environmental monitoring to facilitate the implementation of sustainable fishing practices.

In February 2025, chlorophyll-a analysis revealed a concentration of 5 milligrams per cubic meter in the waters surrounding the northern extremity of the Bali Strait, specifically between Gilimanuk and Ketapang, as well as in the vicinity of Kedonganan, Bali. This observation was evident from the striking intensity of the bright green color. In the central part of the strait, chlorophyll-a levels are typically lower, as indicated by the darker coloration.

During the data collection process in July 2025, chlorophyll-a analysis yielded the highest recorded value of 17mg/ m^3, with variations observed in the waters of Tanjung Sembulungan, located in front of Tanjung Blambangan, in the central region of the southern tip of the Bali Strait, and near the waters of Kedonganan Bay. This phenomenon is characterized by a distinctive cyan coloration in the water body.

A thorough examination of the carrying capacity of the Bali Strait environment in relation to *Sardinella lemuru* (sardine fish) reveals that contemporary purse seine fishing practices are rapidly approaching levels that are not sustainable in the long term. The study's findings suggest a decline in fish stock biomass and recruitment rates, attributable to overfishing and environmental pressures. These findings imply that the ecosystem's capacity to support current fishing levels has been surpassed. The discussion underscores the imperative for enhancing fisheries management, including the reduction of fishing effort, the implementation of seasonal closures, and the optimization of monitoring to avert the collapse of fish populations. Furthermore, climate variability and habitat degradation have been demonstrated to impose additional pressure on the ecosystem's carrying capacity, underscoring the necessity for ecosystem-based fisheries management. These findings underscore the importance of implementing sustainable practices to ensure the long-term viability of lemuru fisheries and the ecological balance of the Bali Strait.

A comprehensive analysis of sea surface temperature (SST) in relation to the carrying capacity of the Bali Strait waters for *Sardinella lemuru* offers significant insights into sustainable purse seine fishing practices. The study indicates that the optimal sea surface temperature for *Sardinella lemuru* fishing generally ranges between 25 and 26°C, which are crucial conditions for maximizing fishing yields. Within this temperature range, the presence of chlorophyll-a has been demonstrated to be beneficial, as it supplies vital nutrients that play a crucial role in maintaining the structural integrity of the food chain. Furthermore, the study demonstrates seasonal variations in SST and their correlation with the availability of *Sardinella lemuru*, indicating that higher catch rates occur during upwelling periods that enrich the waters with nutrients. This relationship underscores the significance of SST fluctuations, which are influenced by climatic factors such as the Indian Ocean Dipole (IOD), on biomass and, consequently, on the sustainability of fish stocks in the region. The utilization of remote sensing technology for the acquisition of SST data has been demonstrated to be of substantial value in the delineation of fishing zones and the alignment of fisheries management strategies with ecological realities. Consequently, these measures have contributed to the long-term sustainability of purse seine fishing targeting *Sardinella lemuru* in the Bali Strait. This study underscores the significance of incorporating oceanographic data analysis into fisheries management to ensure sustainable practices that safeguard ecological health and economic viability for local communities.

A thorough examination of sea surface temperature (SST) in the Bali Strait during February 2025 reveals substantial variation, with temperatures ranging from 28°C to 31°C, as depicted by the yellow to green gradation on the Bali Strait sea surface temperature map. This data is consistent with general seasonal warming trends in the region, but also shows local thermal anomalies, which are likely influenced by currents triggered by the rainy season and climate fluctuations such as the Indian Ocean Dipole (IOD). Higher sea surface temperatures (SST) were observed in coastal zones, likely associated with a decrease in upwelling intensity, which may affect nutrient availability and small pelagic distribution. These findings suggest that warmer surface waters may alter fish migration patterns and spawning behavior, posing additional challenges for fishing.

These temperature dynamics underscore the necessity of incorporating climate variability in the Bali Strait. A thorough analysis of sea surface temperatures (SST) in the Bali Strait in July 2025 reveals a temperature range between 26 and 29°C. These observations suggest a seasonal cooling phase in the region, a phenomenon associated with the influence of the northeast monsoon and increased upwelling processes.

The presence of cooler sea surface temperatures (SST) is particularly evident along the southern part of the strait, indicating a correlation with increased nutrient upwelling that supports primary productivity. This increased nutrient availability is a critical factor supporting the aggregation of small pelagics. However, local warming was detected in sheltered coastal areas, likely due to reduced current mixing. These temperature variations suggest a probable shift in fish distribution, with lemuru exhibiting a tendency to congregate in cooler, nutrient-rich zones. These findings underscore the pivotal function of the southwest monsoon in sustaining sufficient fishery productivity.

Impact on fisheries

The relationship between marine environmental conditions, including SST and Chl-a concentrations, directly affects the fishing zones for key species like *Sardinella lemuru*. **Adivitasari *et al.* (2022)** found that favorable fishing conditions correspond with optimal SST ranges. Furthermore, recent analyses report that fishers experience changes in catch rates correlating with SST deviations, providing evidence that long-term monitoring of SST can help predict fishing yields **(Gustantia *et al.*, 2021; Clinton *et al.*, 2022)**. The ecological interplay between SST and Chl-a is crucial for maintaining fish populations, emphasizing the importance of accurate marine monitoring **(Suardana *et al.*, 2021; Jatisworo *et al.*, 2022)**.

Primarily, the upwelling in the Bali Strait is greatly influenced by the seasonal monsoonal winds. During the southeast monsoon, occurring from May to September, the currents facilitate the rise of nutrient-rich waters from the thermocline layer to the surface. This phenomenon enhances the productivity of phytoplankton, which serves as the foundational food source for marine life **(Suprianto *et al.*, 2021a; Jatisworo *et al.*, 2022; Susilo & Tito, 2023)**. Studies indicate that during this period, chlorophyll-a concentrations increase significantly due to the nutrient enrichment brought by upwelling, subsequently boosting fish populations, particularly small pelagic species like *Sardinella lemuru* **(Gaol *et al.*, 2010; Bintoro *et al.*, 2021)**.

During the northwest monsoon, from November to March, upwelling activity tends to be weaker. Surface temperatures rise, leading to decreased nutrient availability as the warmer surface waters inhibit the upward movement of cold, nutrient-dense waters. Consequently, chlorophyll-a concentrations decline, which adversely affects phytoplankton populations, resulting in a reduced catch of pelagic fish as their food supply diminishes.

The interplay between the El Niño Southern Oscillation (ENSO) and the Indian Ocean Dipole (IOD) significantly impacts upwelling dynamics in the Bali Strait. El Niño events can alter the climate patterns and intensify certain oceanographic conditions that contribute to stronger upwelling in southern waters. Research demonstrates that during positive phases of the IOD, upwelling becomes more pronounced, leading to increased phytoplankton biomass and subsequently, higher catches of species such as *Sardinella lemuru*.

Hydrographic characteristics, including temperature gradients and the mixed layer's depth, also govern the strength and consistency of upwelling in this area. Variations in thermocline depth can dramatically affect nutrient dynamics within the strait, thus influencing biological productivity and fisheries outcomes **(Suniada & Susilo, 2018; Puspasari *et al.*, 2019a)**. The shallow bathymetry of the Bali Strait contributes to these seasonal fluctuations and can enhance biological productivity when upwelling conditions are optimal.

The seasonal variations in upwelling within the Bali Strait are intricately linked to monsoonal winds, ENSO and IOD phenomena, and local hydrographic features. During the southeast monsoon, upwelling is enhanced, providing a rich nutrient supply that stimulates primary production, whereas northwest monsoon conditions typically result in reduced upwelling and lower biological productivity. Understanding these dynamics is pivotal for effective fisheries management and conservation strategies in this ecologically and economically vital region.

CONCLUSION

The sea surface temperature (SST) and chlorophyll-a concentration in the Bali Strait exhibit intricate dynamics, heavily influenced by climatological phenomena such as El Niño Southern Oscillation (ENSO), Indian Ocean Dipole (IOD), and monsoons. A thorough examination of the data collected in February and July of 2025 reveals a robust inverse correlation between sea surface temperature (SST) and chlorophyll-a concentrations. This relationship indicates that lower SSTs, resulting from upwelling, facilitate the availability of nutrients that promote substantial phytoplankton proliferation, as evidenced by elevated chlorophyll-a levels. This phenomenon is seasonal, with the strongest upwelling occurring during the east monsoon (July) in the southern waters of Banyuwangi and Jembrana, thereby creating nutrient-rich zones of primary productivity.

The environmental conditions under consideration directly influence the abundance and distribution of pelagic fish, particularly *Sardinella lemuru*, with an optimal temperature range of 25- 30°C. However, the study also revealed that excessive fishing pressure and climate variability have pushed fish stocks close to sustainability limits, necessitating ecosystem-based fisheries management that considers oceanographic data to ensure resource sustainability and the welfare of local communities. The process of mapping sea surface temperature and chlorophyll-a for the purpose of sardine sustainability has evolved from the creation of static temperature maps to the development of a dynamic Decision Support System.

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