Sriwijaya Journal of Environment
Article
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Analysis of Upwelling Events and Potential Fishing Grounds for Frigate Tuna (*Auxis thazard*) in the Waters of West Sumatera

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Article history

Received	Received in revised form	Accepted	Available online
08 May 2025	20 June 2025	22 July 2025	11 August 2025

Abstract: West Sumatera has high fishery potential, particularly for Frigate tuna (*Auxis thazard*), whose presence is influenced by oceanographic factors such as sea surface temperature (SST), chlorophyll-a concentration, and ocean currents. This study aims to analyze the variability of SST, chlorophyll-a, and currents in West Sumatera waters, identify oceanographic indicators of upwelling events, and examine the relationship between upwelling and potential Frigate tuna fishing grounds. Using a quantitative survey approach and ArcGIS 10.8, spatial analysis was conducted to determine potential fishing zones. This study used oceanographic data from the Marine Copernicus database for two monsoonal periods: June 1 to August 31, 2022 (east monsoon) and December 1, 2022, to February 28, 2023 (west monsoon). Fish catch data were sourced from the fishing logbooks recorded at PPS Bungus (Oceanic Fishing Port Bungus). Results indicate SST fluctuated between 28.5°C (December 2022) and 30,4°C (July 2022), while chlorophyll-a showed monsoonal variation, peaking at 0.40 mg/m³ in June 2022. Current patterns are influenced by monsoonal winds and global atmospheric phenomena, with stronger currents during the East monsoon, promoting upwelling and marine productivity. Overlay analysis revealed weak to very weak upwelling occurring periodically. Despite the weak upwelling, West Sumatera remains a highly potential fishing area. Spatial correlation analysis indicates a positive relationship between SST and chlorophyll-a with the distribution of Frigate tuna fishing zones, suggesting that fishing areas tend to form in regions where both parameters are relatively elevated. However, regression analysis shows that increases in SST and chlorophyll-a are associated with a decrease in actual Frigate tuna catch volume, possibly due to ecological thresholds or time lag effects in fish response to environmental changes. In contrast, ocean currents exhibit a positive influence on Frigate tuna catches, likely aiding nutrient transport and fish aggregation. Overall, oceanographic variability significantly impacts fishing potential in West Sumatera.
Keywords: upwelling, fishing area, fishing monsoon

1. Introduction

The waters of West Sumatera, located along the West coast of Sumatera Island, hold significant potential in the fisheries sector. The region's Exclusive Economic Zone spans an area of 51,060.23 km², with a coastline stretching 570.55 km [1]. One of the key areas contributing to fishery production is Bungus District, which is home to the Bungus Oceanic Fishing Port. This port receives landings of various economically valuable fish species, including Frigate tuna (*Auxis thazard*) [2].

Frigate tuna is one of the dominant pelagic resources in this region, with a production volume reaching 27,184 tons in 2023 [3]. The distribution and abundance of this species are strongly influenced by oceanographic factors such as sea surface temperature (SST), chlorophyll-a concentration, and ocean currents. [4]. These parameters are crucial in predicting fish presence and determining potential fishing grounds. One of the key oceanographic phenomena related to marine productivity is upwelling, a process where nutrient-rich deep water rises to the surface, stimulating phytoplankton growth and enhancing the fertility of the waters [5].

Upwelling can be identified through spatial and temporal variations in SST, chlorophyll-a levels, and current patterns. [6]. Therefore, analyzing these parameters is essential in locating productive fishing grounds and determining optimal fishing monsoons, particularly during the east monsoon (June-August), which is associated with coastal upwelling along the West Sumatera coast [7]. Previous studies have indicated that the Frigate tuna fishing monsoon in the region extends from July to December, peaking in October, while January to June is considered the off monsoon[8]. Sea surface temperature data from the Mentawai waters, ranging from 23.1°C to 30.1°C [9], suggest the potential occurrence of upwelling events across different monsoons, although detailed current distribution data remains limited. Hence, research on the analysis of upwelling events and the identification of potential Frigate tuna fishing grounds in the waters of West Sumatera is essential to support sustainable fisheries management and enhance fishermen's catch productivity.

2. Materials and Methods

2.1. Materials

This study utilized oceanographic parameter data obtained from the Copernicus Marine Environment Service (CMES), accessible at http://marine.copernicus.eu/. The data used in this research included sea surface temperature, chlorophyll-a concentration, and ocean currents, covering the periods from June 1, 2022, to August 31, 2022, and from December 1, 2022, to February 28, 2023, these timeframes were selected to capture the monsoonal variations occurring in the waters of West Sumatera. Logbook Fish catch data were obtained from the fishing logbooks archived at PPS Bungus (Pelabuhan Perikanan Samudera Bungus), Padang, West Sumatra.

2.2. Methods

This study is qualitative research employing a survey approach. According to [10] the survey method is defined as an investigation conducted to obtain data and facts regarding existing phenomena by seeking factual information.

2.2.1. Data collection methods

This study uses a survey method to collect data related to fishing activities and oceanographic parameters. Catch data were obtained from fishing logbooks at PPS Bungus, while oceanographic data (SST, chlorophyll-a, and currents) were sourced from the Copernicus Marine Environment Monitoring Service (CMEMS) for the periods of June–August 2022 and December–February 2023.

2.2.2. Data processing methods

The collected data were then processed using ArcGIS 10.8 for spatial analysis and mapping of fishing grounds and oceanographic variables. In addition, statistical analyses such as correlation and regression were conducted using Microsoft Excel to examine the relationship between environmental parameters and Frigate tuna catch distribution.

2.2.3. Estimation of Potential Fishing Ground

The determination of the strength of potential fishing grounds is carried out through the following steps:

1. Determining the monthly maximum and minimum values of sea surface temperature, chlorophyll-a, and currents, followed by calculating the mean values.
2. After obtaining the mean values of each parameter (SST, chlorophyll-a, and current speed), the standard deviation was calculated to assess the variability of environmental conditions across the study area. The analysis covered the coastal waters of West Sumatera, including the region between the mainland and the Mentawai Islands, during two monsoonal periods: June–August 2022 and December–February 2023.
3. Calculating threshold values using the following formulas [11]:
   Sea Surface Temperature (°C):
   A = (Average) – (0.5 × standard deviation)
   B = (Average) + (0.5 × standard deviation)
   C = B + standard deviation
   Chlorophyll-a (mg/m³):
   A = (Average) – (0.5 × standard deviation)
   B = (Average) + (0.5 × standard deviation)
   C = B + standard deviation
   Current Speed (m/s):
   A = (Average) – (0.5 × standard deviation)
   B = (Average) + (0.5 × standard deviation)
   C = B + standard deviation

The values of A, B, and C are used to classify the parameter into three categories: low (≤ A), medium (between A and C), and high (≥ C). This classification helps identify the distribution patterns of the parameter in relation to potential fishing zones.

4. Once the threshold values are determined, the raster calculator tool in ArcGIS is used to perform conditional classification based on sea surface temperature and chlorophyll-a values. For example, areas with SST ≥ 28°C and Chl-a ≥ 0.3 mg/m³ are categorized as "very strong" fishing grounds. The specific logical expressions used are detailed in Table 1.

Table 1. Categories of Potential Fishing Ground

	VS	S	W	VW
SST	X≤ A	(B≥X)& (X>A)	(C≥X)& (X>B)	X>C
CHL	Y≥C	(B≤Y)& (Y<C)	(A≤Y)& (Y<B)	Y<A
Curent	Z≤ A	(B≥Z)& (X>Z)	(C≥Z)& (Z>B)	Z>C

Description:
X = Sea Surface Temperature
Y = Chlorophyll-a
Z = Current Speed
VS = Very Strong
S = Strong
W = Weak
VW = Very Weak

2.3. Data Analysis

2.3.1. Determination of Upwelling Areas

The identification of upwelling areas was conducted by overlaying chlorophyll-a data with sea surface temperature (SST) data. The intensity of upwelling was then classified based on calculations using a raster calculator. The upwelling criteria used in this study follow those outlined[12], as presented in Table 2.

Table 2. Upwelling Categories

Category	Sea Surface Temperature (ºC)	Chlorophyll-a (mg/m³)
Very Weak Upwelling (VWU)	>29.008	< 0.147
Weak Upwelling (WU)	≤ 28.033 - ≤ 29.008	≤ 0.147 - ≤ 0.353
Strong Upwelling (SU)	≤ 27.058 - ≤ 28.033	≤ 0.353 – ≤ 0.560
Very Strong Upwelling (VSU)	< 27.058	> 0.560

2.3.2. Multiple Linear Regression

The influence of oceanographic parameters (sea surface temperature, chlorophyll-a, and currents) can contribute to the formation of upwelling phenomena, which in turn affect potential fishing grounds. Therefore, multiple linear regression analysis was conducted to examine the influence of these parameters on the distribution of potential fishing grounds. Multiple linear regression analysis was conducted to measure the direct impact of sea surface temperature, chlorophyll-a, and currents on the distribution of potential fishing grounds, while descriptive analysis using maps was used to visualize the spatial patterns. According to [13]Multiple linear regression is used to determine the effect of one or more independent variables on a dependent variable. The regression formula used is as follows:

$$Y = a + b_1X_1 + b_2X_2 + b_3X_3$$

Description:
Y : Frigate tuna catch
a : Constant
X_1: Sea surface temperature
X_2: Chlorophyll-a
X_3: Ocean current
b_1: Regression coefficient of sea surface temperature
b_2: Regression coefficient of chlorophyll-a
b_3: Regression coefficient of ocean current

Table 3. Categories of regression values

No.	Category	Value Range
1.	Strong	0,67-1.00
2.	Moderate	0,33-0,66
3	Weak	0,19-0,32

Source:[14]

2.3.3. Correlation

The next step is to conduct a correlation analysis to determine the relationship between Potential Fishing Ground (PFG) and the upwelling phenomenon, which is influenced by sea surface temperature and chlorophyll-a. The Spearman correlation can be calculated using the formula as stated [15].

$$r = \frac{N(\sum XY) - (\sum X \sum XY)}{\sqrt{(N(\sum X^2 - (\sum X)^2) - (N(\sum Y^2) - (\sum Y)^2)}}$$

Description:
r : Correlation coefficient (representing the relationship with PFG)
x : Sea surface temperature values
y : Chlorophyll-a values
N : Number of data points

3. Results and Discussion

Based on statistical data from the Bungus Oceanic Fishing Port in 2020, five fish species recorded the highest production yields, namely yellowfin tuna (*Thunnus albacares*), frigate tuna (*Auxis thazard*), anchovies (*Stolephorus* sp.), longtail tuna (*Thunnus tonggol*), and skipjack tuna (*Katsuwonus pelamis*) [16]. This finding is supported by [17], who reported that three major fish species were primarily caught by lift-net fishing boats and landed at PPS Bungus, specifically Frigate tuna (*Auxis thazard*), yellowfin tuna (*Thunnus albacares*), and mackerel scad (*Decapterus macrosoma*). These species are known to inhabit waters influenced by upwelling and rich in chlorophyll-a, indicating that the oceanographic conditions in the study area play a significant role in shaping potential fishing grounds.

3.1 Spatial Temporal Distribution of Sea Surface Temperature, Chlorophyll-a, and Currents

The spatio-temporal distribution of sea surface temperature, chlorophyll-a, and ocean currents is a crucial aspect in assessing marine productivity and determining potential fishing grounds. Spatio-temporal analysis provides an overview of the variations and distribution patterns of each parameter, as well as the interactions among them. The occurrence of upwelling in a marine area can be indicated by the spatial and temporal distribution of sea surface temperature [18].

Sea surface temperature patterns are useful indicators of upwelling events, which increase nutrient availability and promote phytoplankton growth, reflected in high chlorophyll-a concentrations. This relationship was evident in our study, where areas with lower SST and higher chlorophyll-a values corresponded to identified potential fishing grounds. Chlorophyll-a is a critical pigment in the photosynthesis process of marine phytoplankton [19].

3.1.1 Sea Surface Temperature

Based on the data analysis conducted, monthly SST in West Sumatra waters exhibited monsoonal variability between June–August 2022 and December 2022–February 2023. The highest temperature was recorded in July 2022 at 30.4°C, which corresponds to the East monsoon, while the lowest SST was observed in February 2023 during the West monsoon, with a value of 28.1°C.

As shown in the figure 1, SST during the east monsoon exhibited noticeable temporal fluctuations. In July 2022 (figure 1 B), daily SST values ranged between 29.6°C and 30.4°C, while in August (figure 1 C), the range was between 28.5°C and 29.4°C. The warmer SST observed in early East Monsoon or June (figure 1 A) is attributed to increased solar radiation in the Northern Hemisphere, which causes sea surface temperatures to rise in the northeastern part of the eastern Indian Ocean [20].

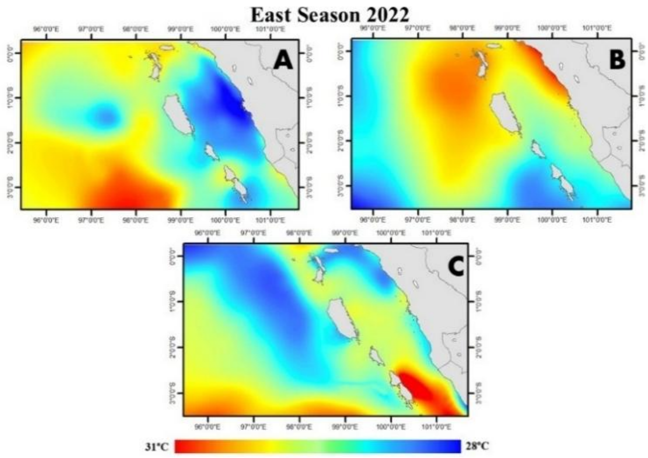

Figure 1. Sea Surface Temperature East Monsoon 2022.
A. June B. July C. August

During the East Monsoon on July and August (Figure 1 B & C), sea surface temperatures tend to be warmer compared to those during the West Monsoon December to February (Figure 2). The highest monthly average sea surface temperature was recorded in February (Figure 2 F), reaching approximately 29.9°C, while the lowest was observed in December (Figure 2 D) at around 28.5°C. In December (Figure 2 D), temperatures range between 28.5°C and 29.1°C, while in January (Figure 2 E), they range between 28.4°C and 29.5°C.

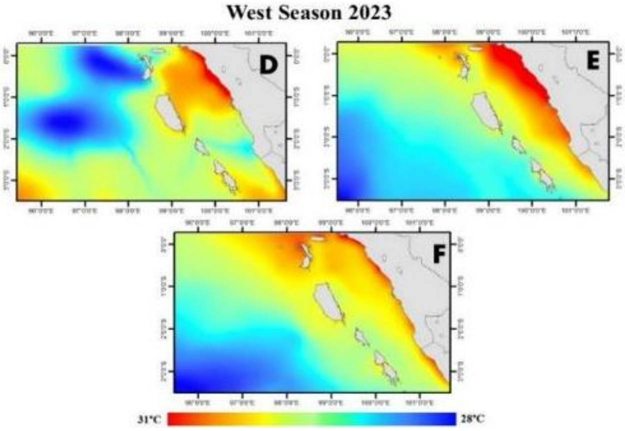

Figure 2. Sea Surface Temperature West Monsoon 2023.
D. December E. January F. February

High rainfall intensity during this period, accompanied by strong winds, contributes to the lower sea surface temperatures. Elevated precipitation levels indicate overcast sky conditions, which reduce the effectiveness of solar radiation in heating the sea surface directly. Consequently, the sea surface temperature decreases [21].

3.1.2 Chlorophyll-a

The highest distribution of chlorophyll-a concentration was recorded in June 2022 (Figure 3 A), during the East Monsoon, with a concentration of 0.40 mg/m³. In contrast, the lowest concentrations, 0.10 mg/m³, were observed in August 2022 (Figure 3 C) East Monsoon and in February (Figure 4 F). These findings are consistent with the study conducted by [22], which reported that the lowest average chlorophyll-a concentration occurred during the East Monsoon at 0.13 mg/m³, while during the West Monsoon, the average concentration was slightly higher at 0.14 mg/m³. Based on these values, the waters off West Sumatera fall within the optimum range for the habitat suitability of Frigate tuna, *Auxis thazard*, as defined by [23], which is between 0.2 mg/m³ and 0.5 mg/m³.

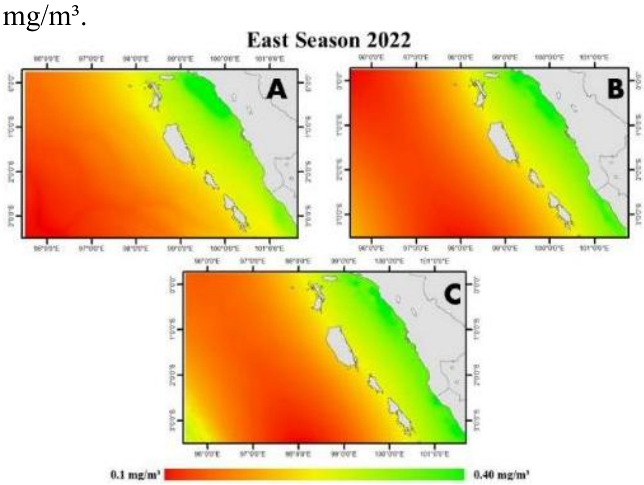

Figure 3. chlorophyll-a East Monsoon 2022.
A. June B. July C. August

During the East monsoon (Figure 3), chlorophyll-a exhibited monthly variations, based on contour data retrieved from the Marine Copernicus platform, representing spatially distributed measurements across the study area. In June 2022(Figure 3 A), chlorophyll-a concentrations ranged from 0.1 mg/m³ to 0.4 mg/m³. In July 2022(Figure 3 B), the concentration slightly decreased, ranging between 0.11 mg/m³ and 0.3 mg/m³. Meanwhile, in August 2022 (Figure 3 C), the chlorophyll-a concentration ranged from 0.1 mg/m³ to 0.27 mg/m³. These values are supported by the findings of [24], who reported that the average chlorophyll-a concentration in the waters of West Sumatera ranged from 0.08 mg/m³ to 0.13 mg/m³.

The concentration of chlorophyll-a during the West monsoon (Figure 4) exhibited variation. In December 2022 (Figure 4 D), chlorophyll-a concentrations ranged from 0.12 mg/m³ to 0.35 mg/m³. In January 2023 (Figure 4 E), the concentrations ranged from 0.12 mg/m³ to 0.29 mg/m³. Subsequently, in February 2023 (Figure 4 F), the range of chlorophyll-a concentrations decreased to 0.10 mg/m³ to 0.25 mg/m³.

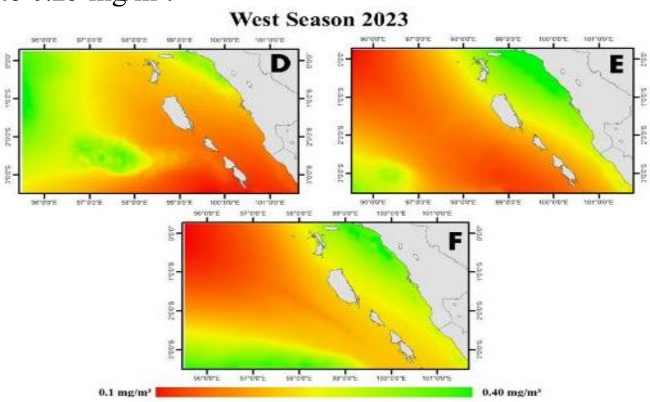

Figure 4. Chlorophyll-a West Monsoon 2023.
D. December E. January F. February

During the West monsoon (Figure 4), according to [25]The distribution of chlorophyll-a tends to be most concentrated in areas near the coastline. This phenomenon occurs due to river flows that carry nutrients from the land and discharge them into coastal waters, thereby increasing chlorophyll-a concentrations. Intensive rainfall during this monsoon also influences the distribution of chlorophyll-a. The chlorophyll-a content is closely related to the nutrient supply originating from terrestrial sources, particularly through river discharges into the marine environment.

According to [26] and [27] The distribution of chlorophyll concentration indicates that the classification of chlorophyll-a concentration based on the trophic status of West Sumatera waters falls into the oligotrophic category, with chlorophyll-a concentrations ranging from 0-2 mg/m³. On the chlorophyll-a distribution map, green coloration is visible along the coastline of West Sumatera. The presence of green coloration, indicating higher chlorophyll-a concentrations along the coast, is supported by the study[28], which found that spatially, chlorophyll-a concentrations are higher in coastal areas and gradually decrease towards offshore areas [29] stated that the high concentration of chlorophyll-a along the coast may be attributed to the accumulation of nutrients transported from land and human activities, which can stimulate phytoplankton growth through increased nutrient availability.

3.1.3 Current

The patterns and characteristics of ocean currents, including the dominant current type, velocity, direction, and movement patterns, contribute to making a marine area more dynamic. Understanding the distribution of current movements is essential as it provides valuable information for fishing activities[19]. Surface currents are influenced by climate and weather, where these currents play a role in transferring heat from tropical regions to mid and high latitudes, distributing nutrients and marine organisms, as well as supporting marine transportation [30].

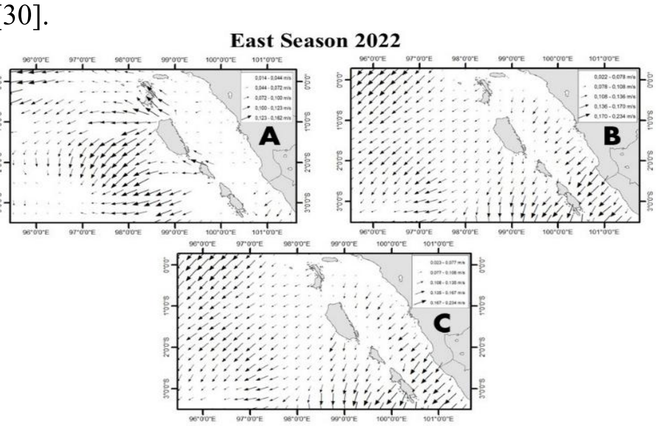

Figure 5. Current East Monsoon 2022.
A. June B. July C. August

The results obtained show that the current speed in West Sumatera during the East Monsoon (Figure 5) ranges from 0.00 to 0.28 m/s, while during the West Monsoon (Figure 6), it ranges from 0.00 to 0.54 m/s. According to the current speed classification stated by [31], The West Monsoon (Figure 6) is categorized as a moderate current with a range of 0.20–0.39 m/s, while the East Monsoon (Figure 5) also falls within the moderate current category with a range of ≥0.40 m/s, based on the current classification.

This is supported by [32], who reported that the surface current speed during the West Monsoon ranges from 0.9 - 1.5 m/s. This considerably higher current velocity may be attributed to the intensified northwest monsoonal winds, which drive stronger surface circulation across the region. The strong current may enhance water mass transport, nutrient mixing, and influence the distribution of marine organisms during this monsoon. The waters of the northeastern Indian Ocean, to the west of Sumatera, possess unique and complex characteristics because their dynamics are significantly influenced by the monsoon wind system, the trade wind system, and geostrophic currents. Furthermore, [33] revealed that higher current speeds may occur due to high rainfall intensity, which causes significant changes in current speed.

In the figure 5 (A), the ocean current flows from the southeast towards the northwest with speeds ranging from 0.014 to 0.162 m/s. The current's direction, moving away from the West coast of Sumatera, indicates a divergence process that has the potential to trigger upwelling. This upwelling brings nutrient-rich water from the deeper layers to the surface, thereby enhancing primary productivity [34]. In figure 5 (B), the current pattern tends to align parallel to the West coast of Sumatera, with a dominant flow direction from south to north. The current speed during this period ranges from 0.022 to 0.234 m/s. The steady northward flow is part of the Eastern Monsoon current system, driven by the southeast trade winds.

Figure 5 (C) shows a more intense and focused flow pattern, with the dominant direction from the south to the northeast, and current speeds ranging from 0.022 to 0.234 m/s. This current indicates an intensification of the monsoonal flow, most likely influenced by the strengthening of the East Monsoon winds during that period [35]. Overall, the three panels demonstrate that during the 2022 East monsoon (Figure 5), surface currents in the waters of West Sumatera flowed in a relatively consistent direction toward the north or northwest. Current speeds varied from 0.002 to 0.234 m/s, with a tendency to increase during specific periods in response to the influence of the monsoon winds.

In general, the flow pattern observed during the West Monsoon (Figure 6) is dominated by currents flowing towards the southeast and south, parallel to the west coast of Sumatera. This indicates the strong influence of the monsoonal winds blowing from the northwest during the West Monsoon [32]. The surface currents tend to move away from the west coast of Sumatera, particularly in figures 6 (D and E), indicating a divergence process along the coastal zone. This process has the potential to induce upwelling. In terms of velocity, the surface currents exhibit significant variation. In figure 6 (D), the current speeds range from 0.060 to 0.380 m/s, with the majority of the coastal area showing relatively strong currents, especially in the southern part.

Figure 6 (E) illustrates even higher speeds in some areas, reaching 0.546 m/s, particularly from Siberut Island towards Sipora Island and Pagai Island. Meanwhile, in Figure 6 (F), although the current direction still exhibits a dominant southern pattern, the current speed remains relatively consistent, ranging from 0.022-0.312 m/s. This current pattern aligns with the conditions of the north-west monsoon winds blowing from Asia towards Australia during the West Monsoon, pushing surface seawater masses southeastward and strengthening the circulation of currents in the West region of Sumatera [36].

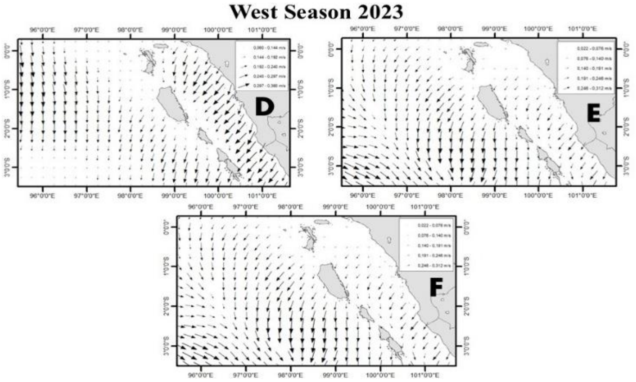

Figure 6. Current West Monsoon 2023.
D. December E. January F. February

3.2 Upwelling

The distribution of upwelling is categorized into four types, with weak and very weak categories dominating in this study. The upwelling phenomenon occurring in the waters of West Sumatera is initially classified as weak to very weak based on the sea surface temperature (28.1°C), which falls within the threshold range of ≤ 28.033°C to ≤ 29.008°C [12] However, the observed chlorophyll-a concentration of 0.47 mg/m³ exceeds the threshold for weak upwelling (≤ 0.353 mg/m³), suggesting either a localized nutrient input or a stronger upwelling event than initially categorized. The conclusion drawn from Figure 7 is that upwelling is more dominant and intense during June and July in the East Monsoon (Figure 7 A and B), as indicated by the extensive areas with medium to dark blue color along the west coast of Sumatera. In August (Figure 7 C), upwelling activity tends to decrease, as shown by the predominance of white and very light blue, which symbolize the weakening of this phenomenon.

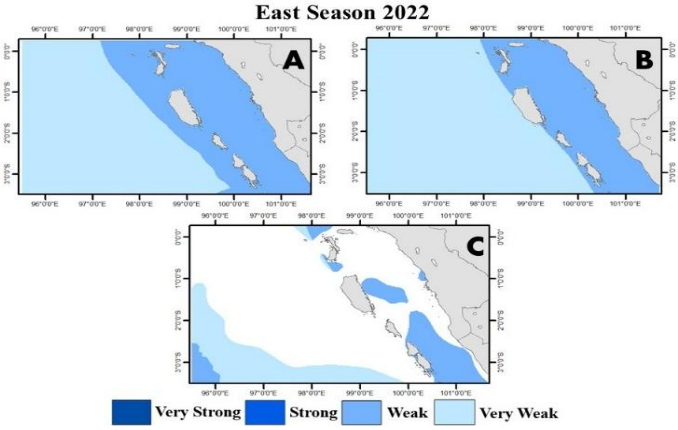

Figure 7. Upwelling East Monsoon 2022.
A. June B. July C. August

The occurrence of upwelling during the East Monsoon (Figure 7), according to [37], is caused by cold seawater resulting from strong southeast Monsoon winds (with speeds ranging from 0.90 to 6.61 m/s in West Sumatera), significantly higher than the wind speeds during the Transition and West Monsoons. This increased wind intensity enhances vertical mixing, leading to a rise in nutrient-rich water to the surface, which in turn supports higher chlorophyll-a concentrations and promotes biological productivity in the region. In the positive phase of the Indian Ocean Dipole (IODM), stronger than usual East Monsoon winds blow for a longer period, and if their intensity is much higher, the upwelling location shifts to West Sumatera.

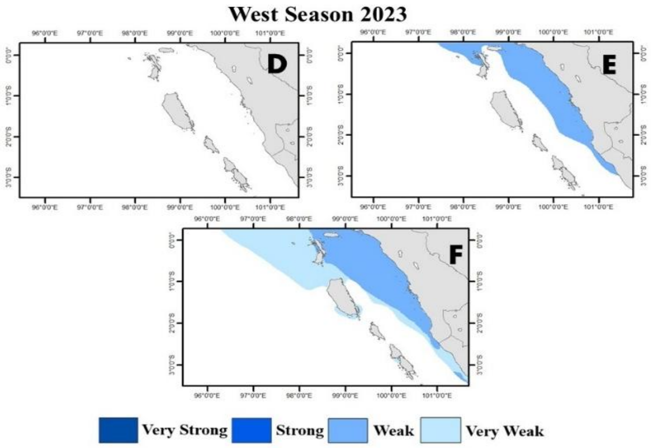

Figure 8. Upwelling West Monsoon 2023
D. December E. January F. February

During the West Monsoon in December (Figure 8 D), it is observed that there is no upwelling activity occurring in the waters off the coast of West Sumatera, as indicated by the entire area being marked in white. As January (Figure 8 E) arrives, upwelling activity begins to emerge with weak to strong intensity, particularly along the central to southern coastline of West Sumatera, marked by a combination of light blue and bright blue colors. By February (Figure 8 F), upwelling activity expands and increases in intensity across a broader region, ranging from the northern to southern parts of the West Sumatera coast, although the dominant intensity still falls within the weak to very weak categories. The figure 8 illustrates that upwelling activity in the West Sumatera region during the 2023 West Monsoon tends to emerge starting in January (Figure 8 E), with an increase in spatial coverage until February (Figure 8 F), although its intensity remains relatively low. According to [37]The decrease in upwelling intensity during the West Monsoon is due to the southwesterly monsoon winds, which bring warm water masses from the Indian Ocean to the Indonesian waters. This results in an increase in sea surface temperature (SST) and a reduction in upwelling intensity.

During the East Monsoon (Figure 7) of 2022, upwelling activity in West Sumatera, particularly in the southern part, was very strong and showed a consistent pattern with the national upwelling distribution map of Indonesia (Figure 8). In other monsoons, such as the First and Second Transition Monsoons, as well as the West Monsoon, upwelling in this region was weakened or was even undetectable, reflecting the monsoonal dynamics that are also represented in the national map. This pattern similarity supports

In other monsoons, such as the First and Second Transition Monsoons, as well as the West Monsoon, upwelling in this region was weakened or was even undetectable, reflecting the monsoonal dynamics that are also represented in the national map. This pattern similarity supports the notion that the western region of Sumatera is an important part of the Indonesian upwelling zone, as also identified in studies such as [38]. The upwelling in this region is highly dependent on monsoonal factors, particularly during the East Wind Monsoon, which supports the process of uplifting nutrient-rich water to the surface. The upwelling occurring in the waters of West Sumatera, which does not happen at all times, according to [8], is classified as a periodic type that occurs only during one monsoon. The location of upwelling in West Sumatera, which takes place in the open sea, can occur, as stated by [39], because upwelling in the open sea can be influenced by strong ocean currents and the trade winds in the equatorial region that push surface waters to the north and south, allowing deeper waters to rise.

3.3 Potential Fishing Ground

The potential Frigate tuna fishing areas in West Sumatera cover a wide region, ranging from the coastal areas to the offshore zone around the Mentawai Islands. Generally, Potential Fishing Ground are not fixed; they constantly change and shift in response to environmental conditions, as fish naturally choose habitats that are more suitable. These habitats are greatly influenced by oceanographic parameters such as sea surface temperature and chlorophyll-a [40].

Compared to the study by[41], potential fishing ground areas can be classified into three categories. The waters of West Sumatera fall into the moderately potential category, characterized by sea surface temperatures ranging from 27–32°C and chlorophyll-a concentrations between 0.07–0.2 mg/m³. These ranges indicate favorable environmental conditions, where SST influences the physiological comfort and migratory behavior of pelagic fish species, while chlorophyll-a reflects phytoplankton abundance, which serves as a primary food source at the base of the marine food web. Therefore, the combination of optimal SST and sufficient chlorophyll-a supports the presence of target fish species, making the region a moderately suitable fishing ground. Thus, even though the fishing locations are not within upwelling areas, abundant catches of Frigate tuna are still found, as the waters of West Sumatera are categorized as very strong potential fishing zones**.** This is also supported by [8], who stated that Frigate tuna are generally caught in waters with sea surface temperatures ranging from 27°C to 29°C. Fishing efforts are conducted far from upwelling areas due to the considerable distance from the fishing base.

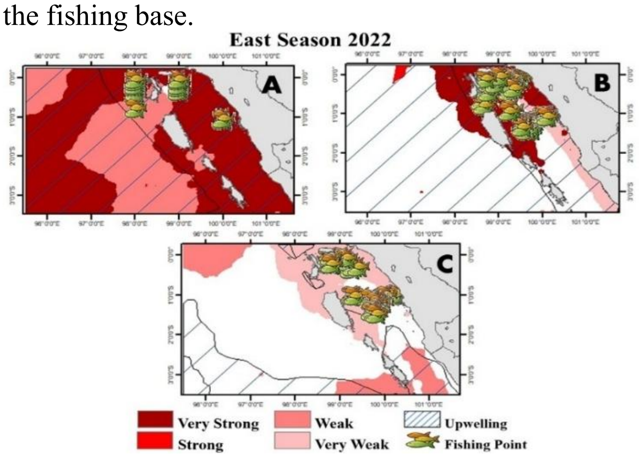

Figure 9. Potential Fishing Ground East Monsoon 2022.
A. June B. July C. August

Figure 9 (A) shows the West Sumatera region, where the area is dominated by zones with strong to very strong PFG potential, indicating that it is a highly potential area for fishing activities. Fishing points are also seen scattered along these waters, with upwelling occurring throughout the entire region. Figure 9 in (B) illustrates that the water area is also dominated by zones with very strong PFG, especially in the northern coastal area. More fishing points are observed compared to area (Figure 9 A), indicating a relatively high level of fishing activity in this region. Figure 9 (C) illustrates a range of potential fishing categories, from Very Weak to Very Strong. Areas with upwelling are particularly important, as they typically increase nutrient availability, which in turn elevates chlorophyll-a concentrations and attracts fish. These areas also tend to have optimal sea surface temperatures, creating favorable conditions for target species. Accordingly, fishing points are densely concentrated in regions categorized as high potential due to the presence of these key oceanographic parameters.

Figure 10 (D) shows the Potential Fishing Ground in December, where the water body is predominantly dominated by the Strong PFG zone, particularly along the coastline extending to the offshore areas of the Mentawai Islands. The fishing catch points appear to be relatively dense in the northern to central coastal regions, indicating that this area has high fisheries productivity during the West monsoon. Figure 10 (E) displays a region with a wide distribution of the Strong PFG zone and a small portion of the Very Strong PFG zone from Pini Island to Siberut Island. The concentration of fishing catch points is dense in this area, particularly in regions showing high potential. This suggests that the area is one of the strategic zones for. fishing activities during the West monsoon.

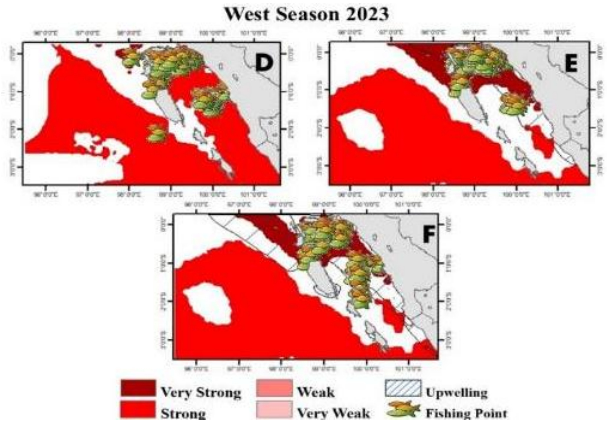

Figure 10. Potential Fishing Ground West monsoon 2023.
D. December E. January F. February

Figure 10 (F) illustrates a region where most of the water body falls under the Strong PFG category, with the presence of Very Strong PFG at certain points. The number of fishing catch points is also relatively high and evenly distributed, especially in areas adjacent to the Strong PFG zones.

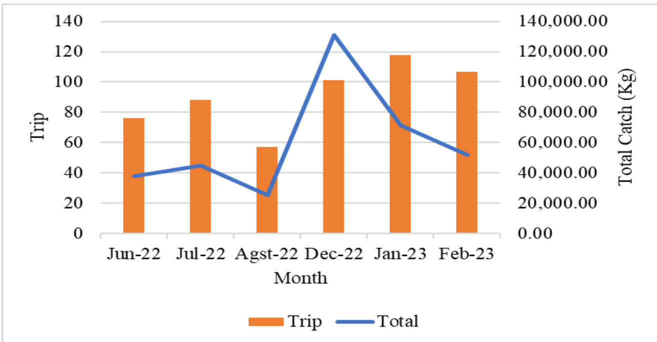

Figure 11. Frigate tuna catch results.

Based on the graph, it can be observed that the total catch fluctuates from month to month. During the East Monsoon (June-August), the total catch ranges from 25,175 to 44,622 kg. When related to Figure 25 (A-C), which illustrates the East Monsoon (Figure 9), it is evident that the waters of West Sumatera during these months are dominated by the PFG zones ranging from Strong to Very Strong. However, the data from the graph shows that despite an increase in trips, the total catch does not exhibit a proportional increase. This may be attributed to the migration of fish following oceanographic parameters. Furthermore, Figure 9 (C) shows the presence of categories ranging from Weak to Very Strong, which likely contributes to the uneven distribution of the collected catch.

During the West Monsoon (Figure 10) (December–February), a significant increase is observed, particularly in December, which recorded 130,972 kg, making it the month with the highest yield throughout the period. The abundant catch during the West Monsoon can be attributed to the water conditions prevailing during this period, as shown in Figure 10 (D-E), where the West Sumatera region is dominated by the PFG (Sea Surface Temperature) Zone, ranging from Strong to Very Strong. Additionally, the large number of fishing points during these months supports the notion that Frigate tuna migrates to regions with optimal oceanographic conditions, such as sea surface temperatures between 27–29°C and chlorophyll-a concentrations that promote primary productivity, as found by [41] and [8].

3.4 Relationship Analysis

The multiple linear regression analysis revealed that among the three predictors, sea surface temperature and chlorophyll-a significantly influenced catch yield, whereas current velocity did not The regression results explain approximately 37.3% of the variation in the dependent variable, as indicated by the coefficient of determination ($R^2 = 0.373$). This means that the independent variables sea surface temperature, chlorophyll-a concentration, and current velocity collectively account for 37.3% of the variability in fish catch yields. The remaining 62.7% of variation in catch yield may be attributed to other factors such as vessel gross tonnage, crew size, fishing trips, and gear type, as reported by [42]. The analysis of variance (ANOVA) indicates that this regression model is statistically significant ($p < 0.05$).

Table 4. Results of the analysis of factors influencing catch results.

Variable	Coefficient	t Stat	Pvalue
Constant	1.455,776	3,522	0.002
SST	-263,297	- 3,449	0.002*
CHL	-59,590	-2,937	0.007*
Current	71,909	0,806	0.002*
R Square : 0,373			
Adjusted R Square : 0,301			
F statistics : 5,153			

Note : * Significant at test level α 5%

When compared to the study by [4] the results of the linear regression test between sea surface temperature and chlorophyll on catch yields indicate that 37% of the sea surface temperature and chlorophyll-a factors influence the catch of Frigate tuna in Lampu Bay. Both results demonstrate consistency, showing that oceanographic variables such as sea surface temperature, chlorophyll-a, and currents have a significant effect on frigate tuna catch yields, although a majority of the variation in catch results is still influenced by other factors.

The regression coefficients indicate that sea surface temperature (X1) has a significant negative effect on the dependent variable ($p < 0.05$), with each one-unit increase in sea surface temperature (X1) resulting in a decrease of 263.297 units in the dependent variable. In contrast, chlorophyll-a (X2) also shows a significant negative effect on the dependent variable ($p < 0.05$), with each one-unit increase in chlorophyll-a (X2) leading to a decrease of 59.590 units in the dependent variable.

However, currents (X3) exhibit a significant positive effect on the dependent variable ($p < 0.05$), with each one-unit increase in currents (X3) resulting in an increase of 71.909 units in the dependent variable. Overall, this regression analysis demonstrates that sea surface temperature (X1), chlorophyll-a (X2), and currents (X3) are significant predictors for the dependent variable or catch yields.

3.5 Correlation Analysis

The correlation analysis revealed that sea surface temperature (SST) and chlorophyll-a concentration are strongly correlated ($r = 0.642$), which may jointly influence the spatial distribution of potential fish catch areas. Referring to the interpretation of correlation coefficients by [15] this value falls within the strong correlation category, indicating a meaningful statistical relationship. This suggests that changes in SST are often accompanied by changes in chlorophyll-a concentrations in the observed area.

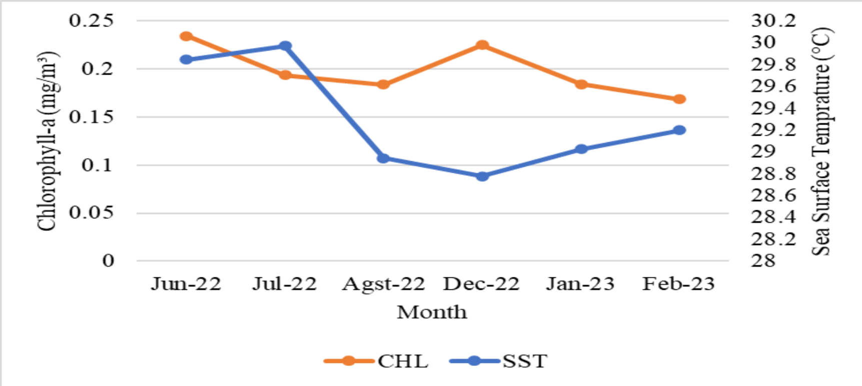

Figure 12. Correlation Graph of Sea Surface Temperature and Chlorophyll-a.

Chlorophyll-a is a key pigment used in photosynthesis by phytoplankton, which serve as primary producers in marine ecosystems [43]. Higher concentrations of chlorophyll-a are typically associated with greater phytoplankton biomass and primary productivity. Since phytoplankton form the base of the aquatic food web, areas with high chlorophyll-a levels can attract zooplankton, small pelagic fish, and eventually larger predators such as Frigate tuna [44]. The observed positive relationship between SST and chlorophyll-a may indicate favorable environmental conditions for phytoplankton growth in warmer waters.

Despite the positive correlation, it is important to emphasize that correlation does not imply causation. An increase in SST does not necessarily cause an increase in chlorophyll-a, as other factors such as nutrient availability, sunlight intensity, and ocean current patterns also strongly influence phytoplankton dynamics. Moreover, the moderate strength of the correlation suggests that SST alone cannot fully explain variations in chlorophyll-a concentration, indicating that a multivariate approach is needed to better understand the factors influencing fish catch potential.

4. Conclusion

Based on these findings, it is recommended that fisheries management in West Sumatera prioritize the utilization of areas classified as having strong to very strong fishing potential, especially those that are currently underutilized. The use of oceanographic data such as SST and chlorophyll-a concentration can be integrated into early warning systems or dynamic fishing maps to assist local fishers in locating productive fishing grounds. In addition, decision-makers should consider promoting the use of satellite-based environmental monitoring tools and providing training for fishers on how to interpret such data for sustainable fishing practices. This integrative approach can optimize catch yields while reducing pressure on overfished areas, thereby supporting long-term fisheries sustainability in the region.

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