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Corresponding Author:
Domu Simbolon
Department of Fisheries Resources Utilization
IPB University
E-mail: domu@apps.ipb.ac.id

Prediction of Potential Fishing Zones Based on Upwelling in The Southern Part of Palabuhanratu Bay

Rivaldi Abdul Rasyid[1], Domu Simbolon[1]*, Am Azbas Taurusman[1]

[1]Department of Fisheries Resources Utilization, Faculty of Fisheries and Marine Sciences, IPB University, Agatis Street, IPB Dramaga Campus, Bogor, West Java 16680, Indonesia

Abstract

Fishing-ground estimation is commonly conducted using catch-based analysis. However, this approach has not consistently produced accurate estimates. Upwelling offers an alternative approach because it influences the variability of oceanographic parameters, which, in turn, affect fish distribution and the dynamics of fishing grounds. This study aimed to (1) identify upwelling-favorable conditions based on the combined variability of SST, chlorophyll a, salinity, and SLH, and (2) predict potential fishing zones associated with upwelling in the southern waters of Palabuhanratu Bay. Satellite derived SST, chlorophyll a, salinity, and SLH data were integrated to estimate the location and timing of upwelling, while catch and fishing effort data from trolling line fleets were used to calculate fishing productivity. The results showed that upwelling occurred predominantly from July to November and was characterized by decreased SST (24.21–29.56°C), increased chlorophyll-a concentration (0.07–0.76 mg/m^3), elevated surface salinity (32.91–34.49‰), and persistent negative SLH anomalies (0.19–0.67 m). Upwelling events were more frequent and intense in coastal waters than in offshore areas. Locations and periods with higher upwelling frequency consistently exhibited higher catch per unit effort (CPUE). Statistical analysis revealed a significant relationship between upwelling and catch productivity ($r = 0.570$; $F = 3.854$; $p < 0.05$). During the upwelling period, CPUE in potential fishing zones reached 759–1,067 kg/trip, while CPUE in coastal upwelling areas reached 658–749 kg/trip, exceeding the cumulative CPUE of 643 kg/trip. Integrating oceanographic indicators with fisheries data enhances fishing-ground prediction and ecosystem-based fisheries management.

Keywords: fisheries productivity, oceanographic variability, Palabuhanratu Bay, potential fishing zone, upwelling

1. Introduction

Accurate identification of potential fishing zones is a fundamental requirement for improving fishing efficiency, reducing operational costs, and supporting sustainable fisheries management in tropical marine ecosystems. In many developing coastal regions, including Indonesian waters, fishing activities remain largely dependent on experiential knowledge and traditional indicators such as surface water color, seabird aggregation, and surface foam (Simbolon et al., 2025). While these methods are culturally embedded and locally adaptive, they are inherently subjective and increasingly inadequate in the face of environmental variability and climate-driven oceanographic changes.

Upwelling is widely recognized as one of the most influential oceanographic processes governing fish aggregation and fishing ground formation. By transporting cold, nutrient-rich subsurface waters into the euphotic zone, upwelling enhances primary productivity and initiates trophic amplification that supports pelagic fish populations. Consequently, upwelling-prone regions often coincide with productive fishing grounds, particularly for pelagic predators such as tuna. Numerous studies have demonstrated the utility of individual oceanographic parameters, such as sea surface temperature (SST), chlorophyll-a concentration, or wind stress as indicators for identifying upwelling events. Fish distribution in marine waters is strongly influenced by environmental conditions and oceanographic phenomena, such as upwelling. Upwelling refers to the vertical movement of cold, nutrient-rich water from deeper layers to the sea surface (Hanifah et al., 2026). The nutrients transported to the surface enhance water fertility, leading to increased phytoplankton abundance and consequently higher chlorophyll-a concentrations. Chlorophyll-a is widely used as an indicator of water productivity and the formation of potential fishing zones (Mursyidin et al., 2015; Simbolon 2019).

Many studies on the estimation of potential fishing zones rely only on descriptive analyses of catch data, which cannot fully explain the processes that lead to the formation of potential fishing zones. On the other hand, the use of big data from oceanographic parameters tends to focus more on analyzing variability without connecting it to the spatial distribution of fishing grounds. In this context, empirical validation using fish catch data has not been carried out because fish catch data is limited or absence of catch data. The approach used in this study is expected to bridge the gap between the analysis of oceanographic phenomena, particularly upwelling, and fish catch data in predicting the spatial and temporal distribution of fishing grounds. This approach is expected to generate more accurate information on potential fishing zones, thereby improving fishing efficiency.

Previous studies have documented the occurrence of upwelling along the southern coast of Java (Atmadipoera et al., 2020). Xu et al. (2021) and Swara et al. (2021) also reported that Palabuhanratu Bay, located on the southern coast of Java, represents a dynamic coastal system influenced by monsoon forcing, large-scale climate variability, and intermittent upwelling events associated with the circulation of the Indian Ocean. However, systematic assessments of upwelling characteristics in relation to fisheries productivity remain limited, making it difficult to verify the presence of upwelling as a practical indicator of potential fishing zones at the local operational scale.

Previous studies have generally used oceanographic parameters in a partial or single-parameter approach to detect upwelling. In contrast, this study develops a multi-parameter framework by integrating sea surface temperature (SST), chlorophyll-a concentration, salinity, and SLH to identify the spatial and temporal occurrence of upwelling. Furthermore, the fishing zones estimated based on upwelling are empirically validated using fishing productivity data, namely catch per unit effort (CPUE) from handline fleets operating in the study area. This integrated approach offers a novelty in the form of a more comprehensive and operational method that is directly relevant to capture fisheries to increase the accuracy of information about potential fishing zones and ultimately increase the efficiency of fishing operations.

This study aims to (1) identify upwelling-favorable conditions based on the combined variability of sea surface temperature (SST), chlorophyll-a concentration, salinity, and sea level height (SLH), and (2) predict potential fishing zones based on upwelling through empirical verification using catch per unit effort (CPUE) data from trolling line fisheries in the southern waters of Palabuhanratu Bay.

2. Materials and Methods

2.1. Study Area and Data

This study began with an exploration of fishing fleet data based at PPN Palabuhanratu. The data collected included the kind of species and amount of catch, time and fishing spots. Fishing spots were required to be within waters previously identified as upwelling areas (Purba and Khan 2019; Atmadipoera et al., 2020). The preliminary assessment showed that only the troll line fleet consistently recorded detailed fishing information, including the kind of species, amount of catch, time and fishing spots, making it suitable for this study. From a total of 15 troll line vessels operating from PPN Palabuhanratu, 10 vessels were selected as samples based on the availability and completeness of fishing logbook records. These vessels routinely documented the kind of species, amount of catch, time and fishing spots throughout January–December 2023. The selected sample size represents the majority of the active troll line fleet operating from the port and was therefore considered adequate to describe fishing activities in the study area. In addition, the captains of all sampled vessels agreed to participate as respondents, allowing the verification and validation of fishing activity data recorded in the logbooks. Observation stations **(Figure 1)** were determined based on the spatial distribution of fishing spots recorded in the logbooks of the sampled vessels. These stations were further verified through interviews with vessel captains to ensure the accuracy of data/information. Fishing operations may occur at multiple spots during a single fishing trip, as fishing trips typically last 10–18 days.

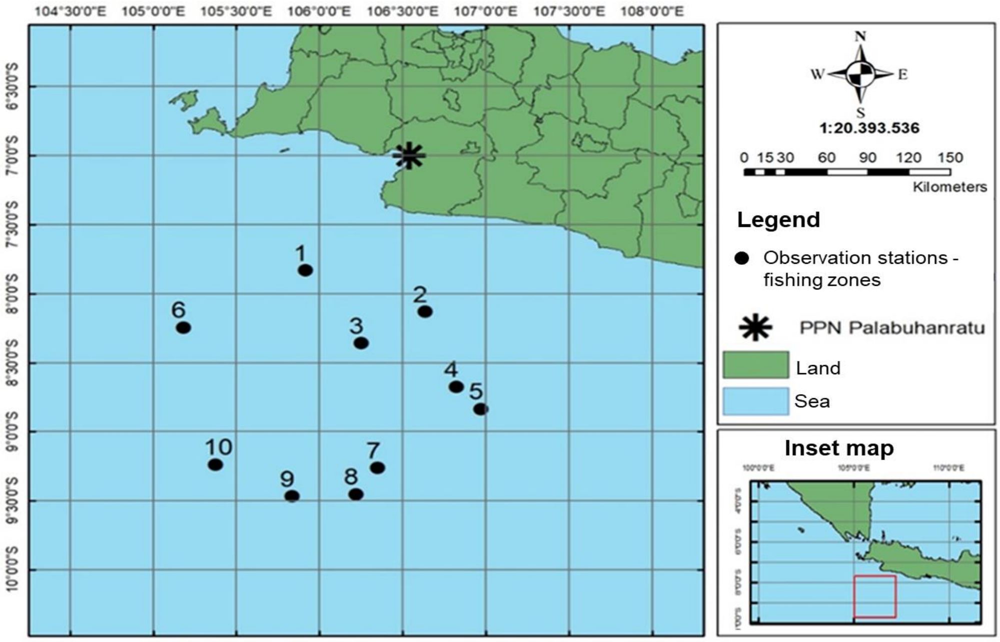

Figure 1. Study area showing the distribution of observation stations and the location of Palabuhanratu Fishing Port in the southern waters of West Java, Indonesia.

2.2. Data Analysis

Oceanographic data, including sea surface temperature (SST), chlorophyll-a concentration, salinity, and SLH were obtained from the Copernicus Marine Service (https://marine.copernicus.eu/) for the period January–December 2023. The datasets were derived from level-4 global ocean analysis and satellite-based products provided by Copernicus Marine. The oceanographic variables were available at a daily temporal resolution with a horizontal spatial resolution ranging from approximately 0.04°–0.25° depending on the product. For example, global ocean colour chlorophyll-a products are typically distributed at 4 km spatial resolution with daily or monthly composites, enabling continuous spatial coverage of marine productivity. All datasets were downloaded in NetCDF format and processed using spatial mapping software to generate monthly composites and spatial distributions of oceanographic parameters in the study area. The criteria used to determine the timing and location of upwelling are based on previous research (Simbolon et al., 2024; Fadlan et al., 2017; Mursyidin et al., 2015). These criteria include: (1) lower SST due to the upward movement of cooler subsurface waters, (2) increased chlorophyll-a concentrations resulting from nutrient enrichment in the euphotic layer, (3) increased salinity associated with deeper water intrusion, and (4) a depression of SLH (negative anomaly) caused by surface water divergence**.** An upwelling event was considered to occur when at least three of the four predefined criteria were simultaneously met (Simbolon et al., 2024). To minimize potential misidentification arising from variability in a single parameter, an upwelling event was considered to occur only when at least three of the four indicators were simultaneously satisfied**.** This rule ensures that the detected signal reflects a consistent oceanographic response across multiple variables, rather than fluctuations in an individual parameter that may be driven by other processes such as surface heating, river discharge, or mesoscale circulation. The criteria used in this study follow the approach proposed by Simbolon et al. (2024), which was developed for detecting upwelling signals in tropical areas.

The use of SST, chlorophyll-a concentration, salinity, and SLH as indicators of potential fishing zones is based on their ecological relevance to pelagic fish distribution. Lower SST and negative SLH anomalies indicate the upward movement of subsurface waters, while increased chlorophyll-a reflects enhanced primary productivity that may support the aggregation of forage organisms and higher trophic-level predators such as tuna. Increased salinity further indicates the intrusion of deeper water masses associated with upwelling processes. Therefore, the combined variability of these oceanographic parameters was assumed to represent favorable environmental conditions for pelagic fish aggregation and fishing activity.

Verification and validation of upwelling locations as potential fishing zones were conducted descriptively by overlaying upwelling events with catch productivity in each observation zone. Catch per unit effort (CPUE) was calculated as (Gulland, 1983):

$$CPUE = \frac{C}{E} \tag{1}$$

where C is catch (kg) and E is fishing effort (trip). CPUE values obtained from each location/zone were compared with the annual cumulative averages. Based on this comparison, the productivity level of each location was determined.

Although CPUE was used to evaluate fishing productivity, this metric may be influenced by factors other than fish abundance, including skill of fishers, weather conditions, accessibility of fishing grounds, and fishing methods. Therefore, CPUE in this study was interpreted as a relative indicator of fishing productivity rather than as a direct estimate of fish biomass. In addition, the analysis did not include independent biological observations such as acoustic biomass estimates or species-specific abundance data. Consequently, the relationship between upwelling and fish aggregation was inferred indirectly through catch productivity patterns.

The intensity of upwelling events was quantified using a multi-indicator consistency approach**.** Upwelling was identified when at least three of the four oceanographic indicators were satisfied. Events meeting three indicators were classified as moderate upwelling, whereas those meeting all four indicators were classified as strong upwelling, reflecting a stronger and more coherent physical–biogeochemical response associated with upwelling processes.

The levels or categories of fishing ground (potential or non-potential) for each observation zone were analyzed using research by Simbolon et al. (2024). Spatial distribution was analyzed descriptively by comparing different observation zones/stations. In this case, the observation zones were divided into two groups: (1) the zone leading to the coast (stations 1 to 5), and (2) the zone leading to the open sea (stations 6 to 10). The temporal distribution of upwelling and fishing grounds was analyzed descriptively by comparing them across different seasons (west, transition-1, east, and transition-2).

The relationship between upwelling and productivity (CPUE) was tested using the multiple correlation test method because upwelling is represented by SST (x1), chlorophyll-a (x2), SLH (x3), and salinity (x4). Catch production (CPUE) was treated as the dependent variable, while upwelling was represented by four oceanographic parameters (SST, chlorophyll-a concentration, SHL, and salinity. The analysis involved three main steps (Yuniar et al., 2026). First, hypotheses were defined: the null hypothesis (H_0) stated that upwelling-related variables have no significant relationship with CPUE, while the alternative hypothesis (H_1) stated that a significant relationship exists. Second, correlation coefficients (r) were computed to evaluate the strength and direction of the relationships among variables. Finally, an overall significance test (F-test) was applied to assess whether the combined effect of the upwelling variables significantly influences CPUE. The calculated F-value was compared with the critical F-value at a 5% significance level (α = 0.05). A result of F_calculated > F_table indicates a statistically significant relationship, leading to rejection of H_0.

3. Results and Discussion

3.1. Sea Surface Temperature, Chlorophyll-a, Salinity and Sea Level Height

Sea surface temperature during the west monsoon ranged from 28.23–29.11 °C (mean 28.71 °C), and increased during transition-1 to 29.07–29.56 °C (mean 29.32 °C). In contrast, SST decreased substantially during the east monsoon and transition-2 seasons. This cooling pattern is consistent with the development of seasonal upwelling along the southern coast of Java, which is driven by southeasterly monsoon winds that induce offshore Ekman transport and the upward movement of cooler subsurface waters (**Figure 2**). Spatial SST distribution showed relatively uniform warm temperatures during the west and transition-1 seasons. During the east and transition-2 seasons, cooler waters were observed in coastal-oriented areas (station 1–5), while offshore-oriented areas (station 6–10) exhibited warmer temperatures (**Figure 3**). The tendency for cooler temperatures near the coast during the east and transition-2 seasons indicates the presence of an upwelling phenomenon.

Chlorophyll-a concentrations ranged from 0.09–0.47 mg/m³ (mean 0.19 mg/m³). Low concentrations were observed during the west and transition-1 seasons, while significant increases occurred from late east monsoon (August) through transition-2 (November) (**Figure 4**). During the west and transition-1 seasons, chlorophyll concentrations were generally low (below the cumulative mean) and relatively uniform across all observation stations. During the east monsoon, chlorophyll-a concentrations increased at several stations. The highest chlorophyll-a levels during this season were observed at stations 1 and 2, which are located in coastal-oriented zones. Chlorophyll concentrations increased markedly during the transition-2 season at all observation stations, including both coastal and offshore-oriented stations. The higher chlorophyll-a concentrations observed in the coastal zone during the east and transition-2 seasons are likely closely associated with indications of upwelling occurring at the same time and location (**Figure 5**).

Salinity during the west and transition-1 seasons was lower than during the east and transition-2 seasons (**Figure 6**). The spatial distribution of salinity (**Figure 7**) indicates that salinity increased toward offshore waters during the west and transition-1 seasons. This offshore-increasing salinity trend was not observed during the east and transition-2 seasons. During these latter periods, the highest salinity values were instead recorded at stations 1 and 2, which are located in coastal-oriented waters. The increase in salinity in nearshore areas is closely associated with upwelling processes, whereby high-salinity subsurface water masses are transported upward to the surface layer.

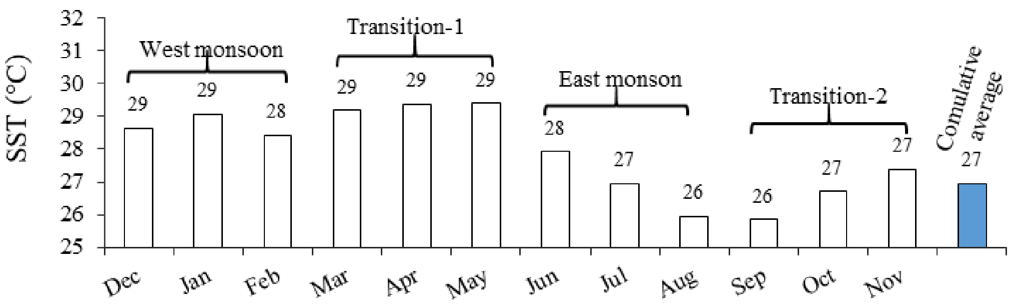

Figure 2. Monthly variation of sea surface temperature (SST) across monsoon and transition seasons in the southern waters of Palabuhanratu Bay.

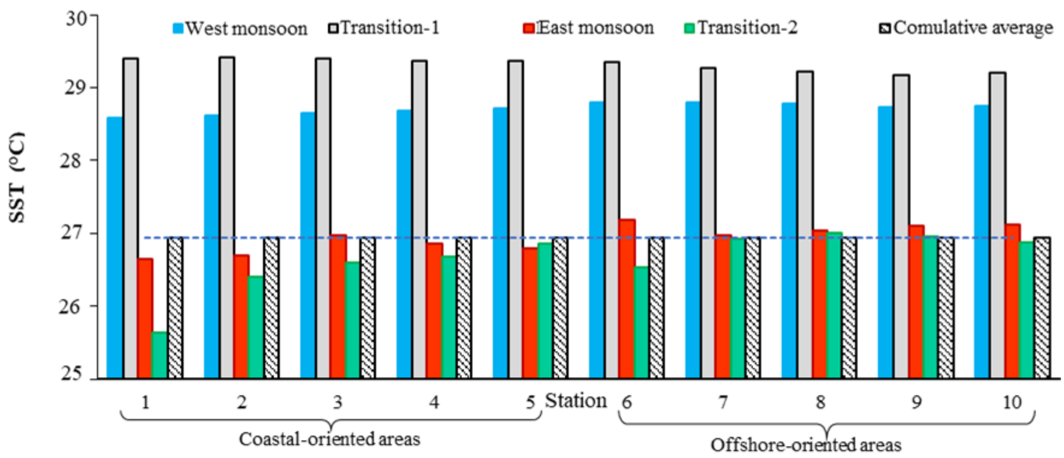

Figure 3. Spatial and seasonal variations of sea surface temperature (SST) across coastal-oriented and offshore-oriented observation stations in the southern waters of Palabuhanratu Bay.

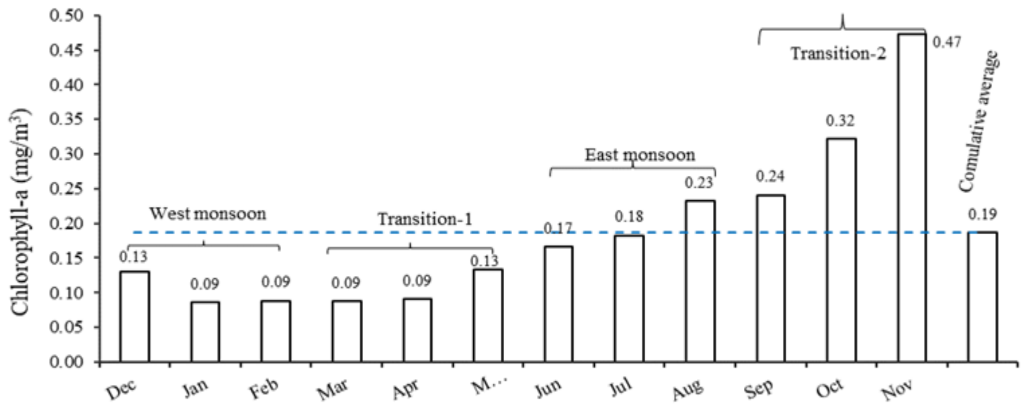

Figure 4. Monthly variation of chlorophyll-a concentration across monsoon and transition seasons in the southern waters of Palabuhanratu Bay.

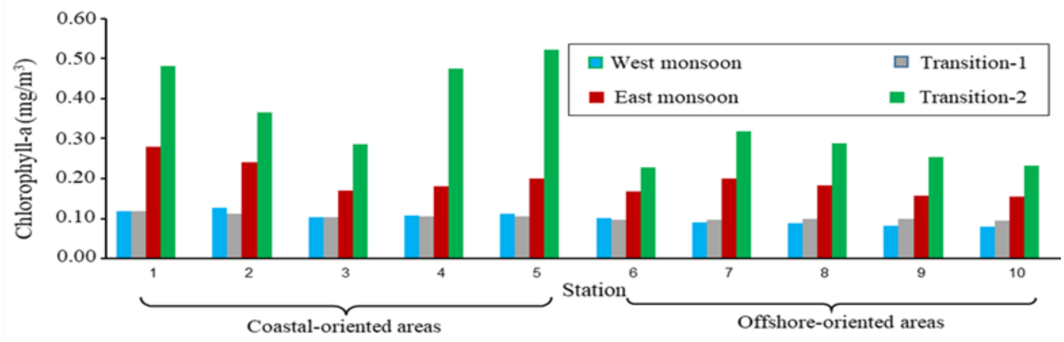

Figure 5. Spatiotemporal Variations of Chlorophyll-a Concentration across Coastal and Offshore Zones in Palabuhanratu Bay.

Mean sea level height (SLH) during the study period was 0.42 m. Negative SLH anomalies occurred in December and consistently during transition-2 (**Figure 8**). The spatial distribution of SLH during the west monsoon (**Figure 9**) was generally higher than the mean sea level (MSL), indicating positive anomalies across all observation stations, both in coastal-oriented and offshore-oriented zones. During the east monsoon, negative anomalies were observed at all coastal-oriented stations, whereas offshore-oriented stations exhibited positive anomalies. Negative sea level anomalies were recorded across all observation stations during the transition-2 season, in both coastal and offshore zones. The sea level analysis indicates that the negative anomalies observed during the transition-2 season may serve as an indicator of upwelling occurrence.

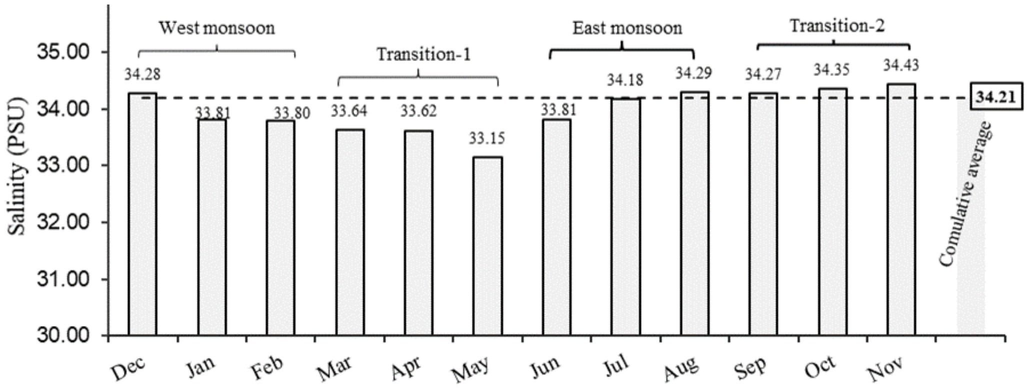

Figure 6. Monthly mean surface water salinity (PSU) in Palabuhanratu Bay during the west monsoon, first transitional season, east monsoon, and second transitional season.

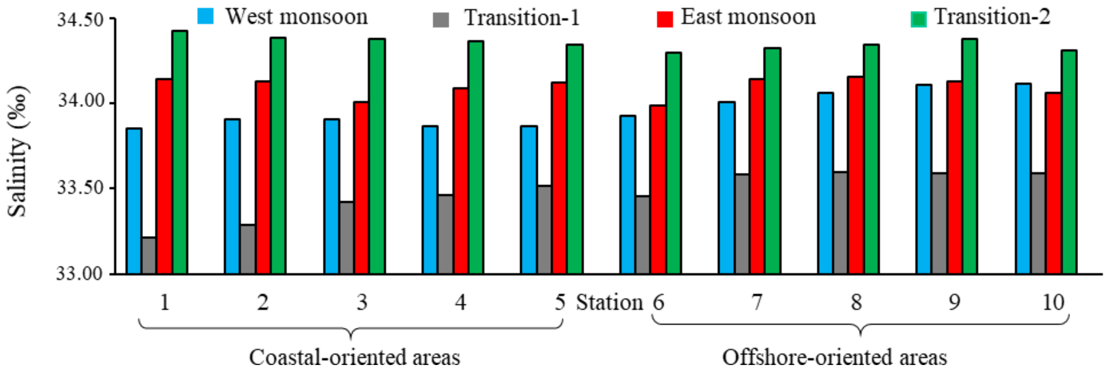

Figure 7. patial variation of surface water salinity (PSU) at coastal- and offshore-oriented stations in Palabuhanratu Bay, during the west monsoon, Transition-1, east monsoon, and Transition-2 periods.

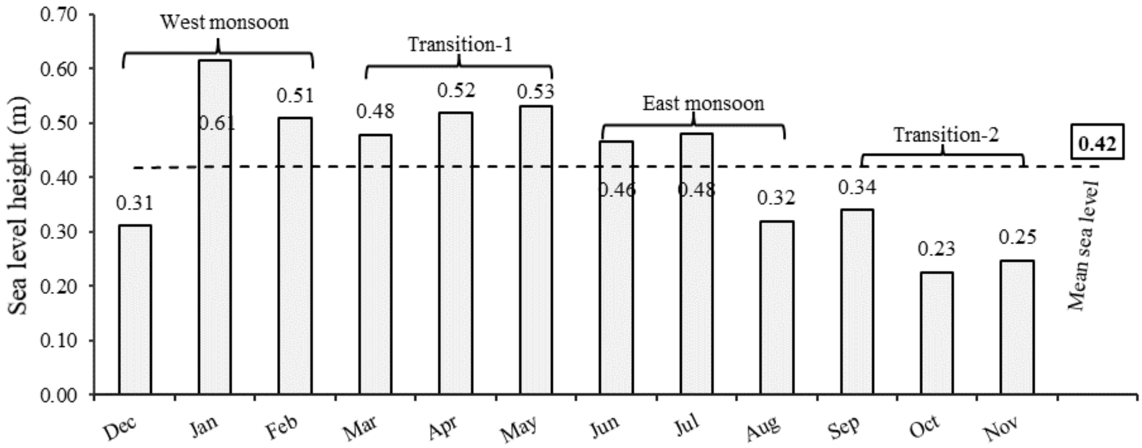

Figure 8. Monthly mean sea level height in Palabuhanratu Bay, during the west monsoon, Transition-1, east monsoon, and Transition-2 periods.

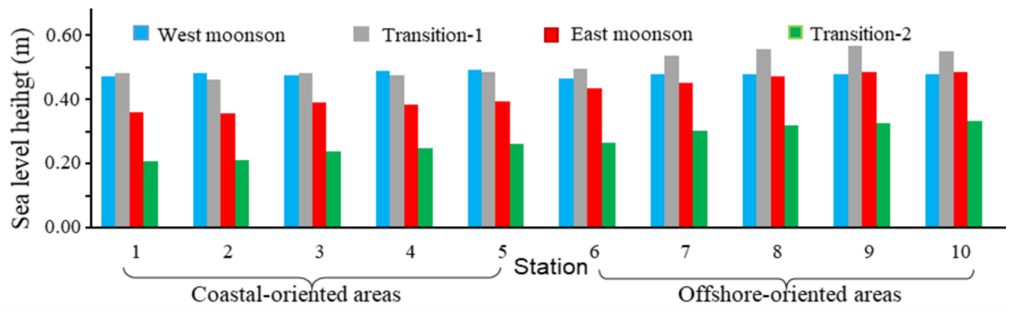

Figure 9. Spatial variation of sea level height (m) at coastal and offshore-oriented stations in Palabuhanratu Bay, during the west monsoon, Transition-1, east monsoon, and Transition-2 periods.

3.2. Upwelling

Evaluation of SST, salinity, chlorophyll-a, and SLH revealed both temporal and spatial upwelling patterns (**Figure 10** and **11**). Upwelling events occurred from July to November, with increasing frequency from late east monsoon through transition-2. During the east monsoon, the frequency of upwelling events remained low, with only two occurrences recorded. The frequency of upwelling increased markedly toward the end of the east monsoon and throughout the transition-2 season (August–November). During this period, the majority of observation stations experienced upwelling events, with frequencies ranging from 6 to 10 occurrences.

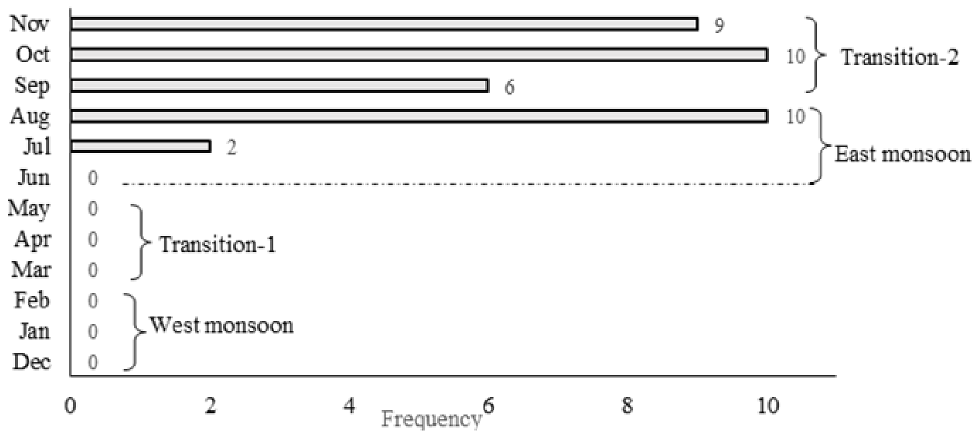

Figure 10. Monthly frequency of upwelling occurrence in Palabuhanratu Bay, during the west monsoon, Transition-1, east monsoon, and Transition-2 periods.

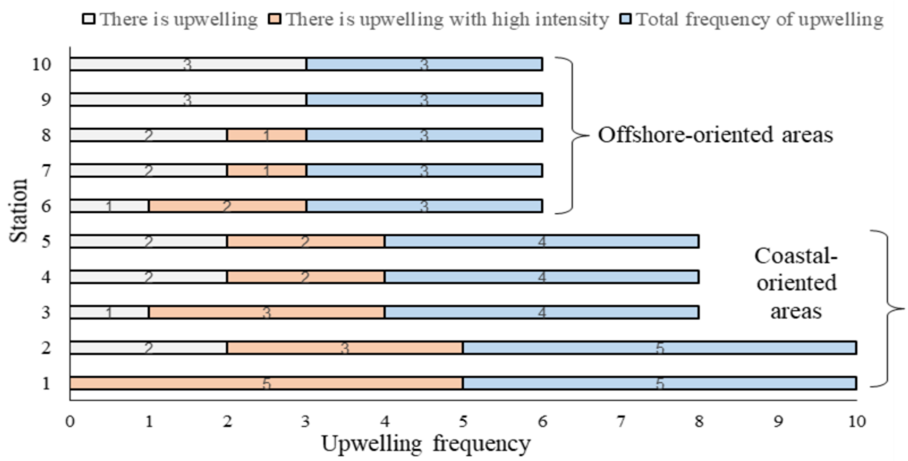

Figure 11. Spatial frequency of upwelling occurrence in Palabuhanratu Bay at coastal and offshore-oriented stations.

Upwelling events were more frequently observed in coastal-oriented areas than at offshore-oriented areas (**Figure 11**). The highest upwelling frequency was recorded at Stations 1 and 2 (the coastal-leading zone), whereas the lowest frequencies were observed at stations progressively farther offshore (Stations 6–10). This spatial pattern suggests that the upwelling signal is more pronounced in coastal-oriented areas than in offshore-oriented areas, which is consistent with the typical characteristics of coastal upwelling systems where wind-driven offshore Ekman transport promotes the upward movement of subsurface waters near the coast. Consequently, the likelihood of upwelling occurrence in the study area is greater in coastal compared to offshore zones.

3.3. Prediction of Potential Fishing Zones Based on Upwelling

Monthly productivity (CPUE) derived from 10 trolling line samples from January to December 2023 ranged from 414 to 1,067 kg per trip, with a cumulative mean productivity of 643 kg per trip (**Figure 12**). Productivity values exceeding the cumulative CPUE can be categorized as high productivity and were observed from July to November. During this period, the frequency of upwelling events was also high. These finding indicates that upwelling plays an important role in the formation of potential fishing zones and significantly increases CPUE (759–1,067 kg per trip) compared to the cumulative CPUE.

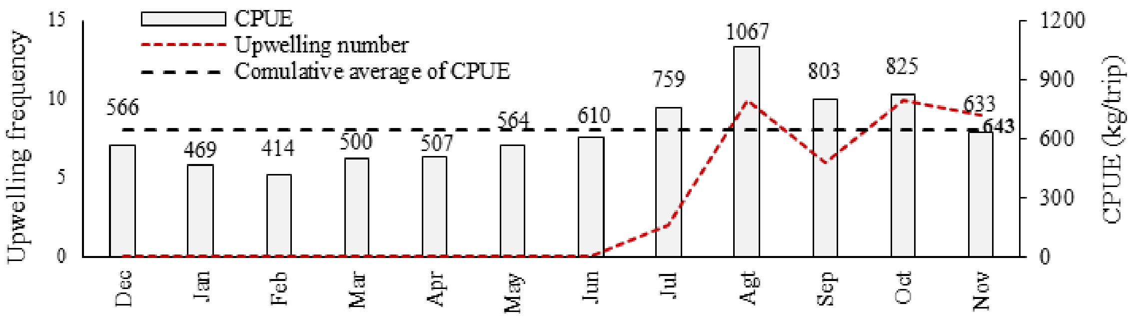

Figure 12. Temporal distribution of upwelling frequency and catch productivity in South Palabuhanratu Bay.

The results of the regression test between the independent (upwelling) and dependent (catch productivity) variables are presented in **Table 1**. The statistical analysis revealed that upwelling has a significant effect on fishing productivity, with a moderate positive correlation ($r = 0.570$). Furthermore, the overall model was statistically significant ($F = 3.854$, $p < 0.05$), indicating that upwelling-related variables jointly influence CPUE. This finding confirms that upwelling-driven oceanographic changes (e.g., nutrient enrichment and primary productivity) contribute to increased fish aggregation and fishing productivity.

Table 1. Results of the regression test between upwelling and catch productivity

No	Coefficient	Value
1	r	0.570
2	R^2	0.525
3	Calculated F-value	3.854
4	Critical F-value	2.670

Upwelling was detected at all observation stations; however, its frequency varied spatially. The spatial pattern indicates that upwelling occurred more frequently in nearshore (coastal-oriented) waters (stations 1–5) than in offshore-oriented waters (stations 6–10). Catch productivity and CPUE were consistently higher in areas characterized by a higher frequency of upwelling events (**Figure 13**). These results suggest that upwelling exerts a significant influence on fishing performance. Accordingly, upwelling can be considered a reliable oceanographic indicator for the formation of potential fishing zones (PFZs) for trolling line fisheries in the southern waters of Palabuhanratu Bay.

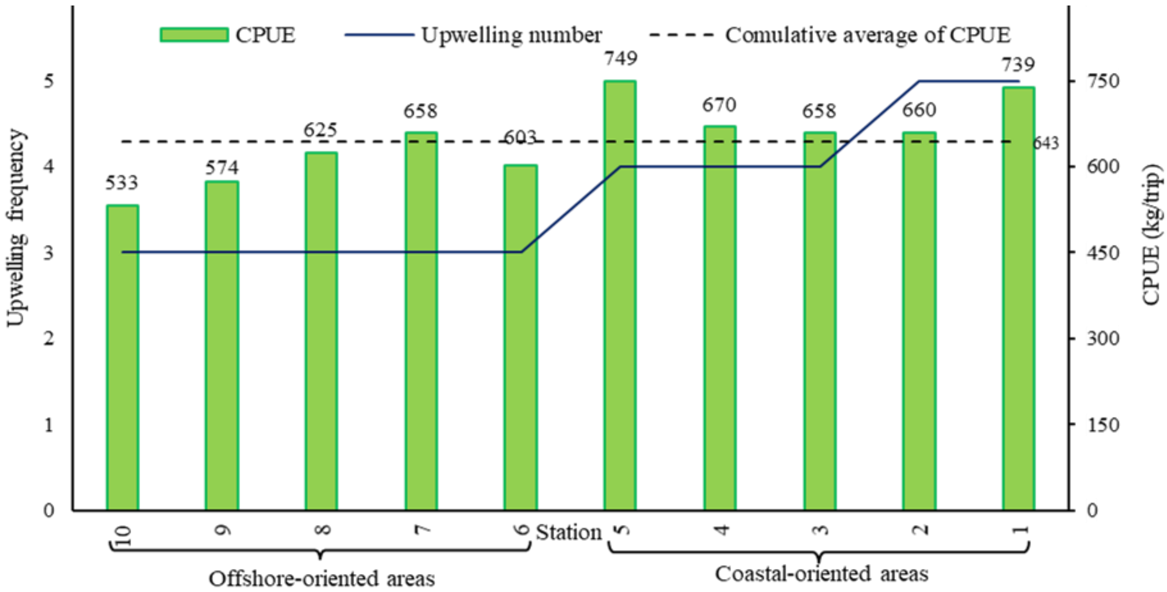

Figure 13. Spatial distribution of upwelling and catch productivity at offshore-oriented areas and coastal-oriented areas in South Palabuhanratu Bay.

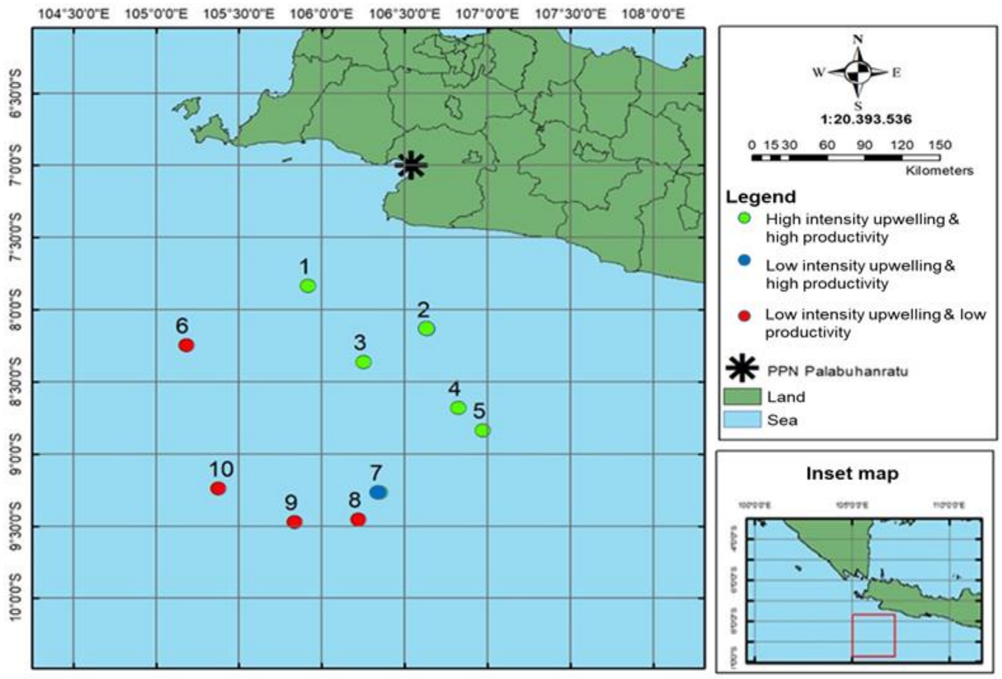

Figure 14. Spatial distribution of potential fishing zone based on upwelling and CPUE during 2023 in South Palabuhanratu Bay.

Stations classified as potential fishing zones were those exhibiting high-category productivity in coastal-oriented areas, namely zones 1, 2, 3, 4, and 5. In offshore-oriented waters, high-productivity potential zones were identified only in zone 7. The spatial distribution of potential fishing zones based on upwelling occurrences during the study period is presented in **Figure 14**.

3.4. Discussion

The occurrence of upwelling in the southern waters of Palabuhanratu Bay is strongly associated with distinct variations in sea surface temperature (SST), chlorophyll-a concentration, salinity, and sea level height (SLH). These parameters collectively reflect the vertical displacement of subsurface water masses that are colder, more saline, and nutrient-rich compared to surface waters. The present study confirms that the simultaneous response of these oceanographic variables provides a robust basis for identifying upwelling-favorable conditions and their role in the formation of potential fishing zones.

The decrease in SST during the east monsoon is consistent with the development of seasonal upwelling along the southern coast of Java. During this period, southeasterly monsoon winds drive offshore Ekman transport, causing surface waters to move away from the coast and allowing cooler, nutrient-rich subsurface waters to rise to the surface (Sprintall et al., 2014).

An increase in chlorophyll-a concentration was consistently observed during periods identified as upwelling events. This response represents enhanced primary productivity driven by nutrient enrichment in surface waters, a well-documented consequence of upwelling processes (Mursyidin et al., 2015). Phytoplankton blooms triggered by upwelling form the foundation of pelagic food webs and create favorable feeding habitats for higher trophic levels, including small pelagic fishes and their predators such as tuna. Consequently, chlorophyll-a serves not merely as a proxy for productivity, but as an ecological linkage between physical oceanographic processes and fish aggregation.

In contrast to chlorophyll-a, SST and salinity exhibited inverse responses during upwelling periods. The observed decrease in SST and concurrent increase in surface salinity indicate the upward transport of deeper water masses, supporting the physical mechanism of coastal upwelling as described by Simbolon et al., (2024). Temperature gradients are known to influence fish distribution and migration behavior, as many pelagic species actively seek optimal thermal habitats (Bahri et al., 2017). Similarly, salinity affects osmoregulatory balance in marine fishes, making abrupt changes a critical factor shaping habitat suitability (Tangke et al., 2016). The combination of lower SST and elevated salinity thus represents a strong diagnostic signal of upwelling occurrence and its ecological consequences.

Sea level height anomalies further reinforce the identification of upwelling events in the study area. Persistent negative SLH anomalies during the east monsoon and transition-2 seasons indicate surface water divergence, which promotes the ascent of subsurface water through Ekman pumping mechanisms. Such conditions are widely recognized as a precursor to coastal upwelling along the southern coast of Java (Atmadipoera et al., 2020; Sambah et al., 2021). The spatial dominance of negative SLH anomalies in nearshore stations suggests that upwelling intensity is strongest in coastal-oriented zones, consistent with classical eastern boundary upwelling systems. Spatial differences between coastal-oriented and offshore-oriented zones also contributed to variability in fishing productivity. Coastal-oriented areas experienced more persistent upwelling signals, characterized by lower SST, higher chlorophyll-a concentrations, elevated salinity, and negative SLH anomalies. These conditions likely enhanced local nutrient enrichment and prey availability, thereby supporting greater aggregation of pelagic fishes. In contrast, offshore-oriented areas exhibited weaker and less consistent upwelling signatures, which may reduce biological productivity and fish concentration. In addition to oceanographic variability, differences in fishing accessibility, operational range, sea conditions, and fish searching efficiency may also have contributed to spatial differences in CPUE between coastal and offshore zones.

Seasonal variability plays a critical role in controlling upwelling intensity in the southern waters of Palabuhanratu Bay. The west and transition-1 seasons were characterized by warm SST, low salinity, high SLH, and reduced chlorophyll-a concentrations, indicating unfavorable conditions for upwelling. In contrast, the east and transition-2 seasons exhibited oceanographic signatures strongly associated with upwelling-favorable conditions. Reduced cloud cover during these seasons enhances solar radiation availability, supporting phytoplankton growth once nutrients are supplied to surface waters. This seasonal contrast explains the pronounced temporal clustering of upwelling events between July and November.

Interannual climate variability further modulated upwelling intensity during the study period. The concurrent occurrence of El Niño and positive Indian Ocean Dipole (IOD+) events in 2023 likely amplified wind stress and surface water divergence along the southern coast of Java. Both phenomena are known to enhance upwelling by strengthening southeasterly winds and promoting offshore Ekman transport (Safinatunnajah et al., 2021). The combined influence of El Niño and IOD+ therefore contributed to stronger cooling, higher salinity, and more persistent negative SLH anomalies observed during the east and transition-2 seasons.

Nevertheless, the influence of broader climate variability on upwelling dynamics remains complex and may differ among years. Large-scale climate phenomena such as El Niño–Southern Oscillation (ENSO), the Indian Ocean Dipole (IOD), and long-term climate change may alter monsoon intensity, wind stress patterns, ocean circulation, and vertical mixing processes in different ways (Sprintall et al., 2014; Safinatunnajah et al., 2021). Consequently, the frequency and intensity of upwelling observed during the 2023 study period may not fully represent long-term oceanographic conditions in the southern waters of Palabuhanratu Bay. Future studies incorporating multi-year observations and climate variability indices are therefore needed to better understand the long-term stability and predictability of upwelling-based fishing zones.

The ecological implications of upwelling were clearly reflected in fishing productivity patterns. Higher CPUE values coincided spatially and temporally with frequent upwelling events, particularly in coastal-oriented zones (stations 1–5). This finding supports the hypothesis that upwelling enhances prey availability and concentrates pelagic predators, thereby increasing catch rates. Similar relationships between upwelling intensity and catch productivity have been reported in other Indonesian waters (Simbolon et al., 2024). Regression analysis further confirmed a statistically significant, albeit moderate, relationship between upwelling frequency and fish production, indicating that upwelling acts as a major, but not exclusive as driver of fishing success.

It is important to note that this study focused on trolling line fisheries targeting carnivorous pelagic species, primarily tuna. Tuna aggregation in upwelling zones is often an indirect response to increased abundance of forage fish that exploit elevated phytoplankton productivity (Tangke et al., 2016). However, the response of other pelagic and demersal species to upwelling dynamics remains insufficiently explored. Future studies should incorporate multi-gear fisheries data and species-specific analyses to better capture the broader ecological and fisheries impacts of upwelling processes.

Despite the significant relationship observed between upwelling and fishing productivity, this study has several limitations. The analysis relied primarily on CPUE from trolling line fisheries as a proxy for fish aggregation and did not directly incorporate independent biological indicators such as fish biomass estimates, acoustic surveys, or species-specific distribution data. Consequently, the ecological response to upwelling was inferred indirectly through catch productivity patterns. In addition, spatial accessibility, fishing behavior, and operational constraints may have influenced fishing effort distribution among seasons and locations. Future studies should integrate biological survey data, species composition analysis, and higher-resolution fisheries observations to improve validation of potential fishing zones derived from oceanographic indicators.

Overall, the findings demonstrate that upwelling serves as a critical physical–biological coupling mechanism that governs the formation of potential fishing zones in the southern waters of Palabuhanratu Bay. Integrating multi-parameter oceanographic indicators provides a scientifically robust approach for predicting fishing grounds and offers practical implications for improving fishing efficiency and supporting ecosystem-based fisheries management.

4. Conclusions

This study demonstrates that seasonal upwelling is a key environmental process influencing fishing productivity in the southern waters of Palabuhanratu Bay and can serve as a reliable indicator for identifying potential fishing zones and fishing seasons for trolling line fisheries. The integration of multi-parameter oceanographic indicators with fisheries productivity data provides a more structured and data-driven approach for identifying potential fishing zones. This approach can support ecosystem-based fisheries management by improving the accuracy of fishing ground prediction, increasing fishing efficiency, and reducing unnecessary search effort and operational costs. In the broader context of Indonesian fisheries management, the findings of this study may contribute to the development of adaptive and environmentally sustainable fishing strategies, particularly in regions strongly influenced by seasonal upwelling dynamics. Future research incorporating multi-year observations and biological survey data is recommended to improve the long-term reliability of upwelling-based fishing zone prediction.

Conflicts of Interest

The author declares that there are no conflicts of interest in this study.

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AI Writing Statement

During the preparation of this work, the author(s) used Chat GPT to help paraphrase paragraph and translaste in English. After using this tool/service, the author(s) reviewed and edited the content as needed and take(s) full responsibility for the content of the publication.

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