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HABITAT ASSESSMENT OF WHALE SHARKS (*RHINCODON TYPUS*) IN SALEH BAY, INDONESIA: LINKING CHLOROPHYLL-A AND SEA SURFACE TEMPERATURE USING AQUA MODIS DATA

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ABSTRACT

Saleh Bay is between Sumbawa Regency and Dompu Regency in Nusa Tenggara Barat (NTB) Province, Indonesia. It is spanning approximately 2,123 km². This semi-enclosed marine environment, designated as a protected marine area, connects directly to the Flores Sea and serves as a critical habitat for whale sharks (*Rhincodon typus*), an endangered species fully protected in Indonesia since 2013. This study aims to assess whale shark habitats by investigating their appearances and analyzing the relationship between Sea Surface Temperature (SST), Chlorophyll-a (Chl-a) concentration, and whale shark occurrences using Aqua Moderate Resolution Imaging Spectroradiometer (Aqua MODIS) data in the marine waters of Saleh Bay. The Inverse Distance Weighting (IDW) interpolation method in Quantum Geographic Information System (QGIS) was applied to process Chl-a and SST data, while field surveys provided records of whale shark sightings. From February, March, and April 2024, a total of 36 whale shark sightings were documented, corresponding to Chl-a concentrations ranging from 0.20 to 3.45 mg/m³ and SST values between 29.47-33.85°C. The analysis revealed significant relationships between whale shark occurrences and environmental factors, with coefficients of determination (R^2) of 0.9055 for February, 0.8959 for March, and 0.4638 for April. These results emphasize the importance of food availability (indicated by Chl-a) and SST in shaping whale shark distribution and behavior. The study underscores the importance of integrating SST and Chl-a monitoring into conservation and management strategies. By identifying key environmental drivers that shape whale shark habitats, this research offers valuable insights to support sustainable ecotourism initiatives and ensure the long-term protection of whale sharks in Saleh Bay.

Key-words: *Aqua MODIS; Chlorophyll-a (Chl-a); Saleh Bay; Sea Surface Temperature (SST); Whale Shark.*

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1. INTRODUCTION

Saleh Bay is between Sumbawa Island and lies within the administrative territories of Sumbawa Regency and Dompu Regency in the Nusa Tenggara Barat (NTB) Province, Indonesia. It spans approximately 2,123 km² (Asrial et al., 2021). Designated as a protected marine area, the marine waters of Saleh Bay are developing to enhance its fisheries potential, particularly through cultivating reef fish and promoting marine fishing activities (Yulius et al., 2018; Kusumawati et al., 2019). The bay has gained national recognition as a prime location for observing whale sharks which inhabit the area year-round due to their distinctive home range movement patterns. This behavior positions the marine waters of Saleh Bay as a crucial congregation site for whale sharks throughout the year, distinguishing it as the only area in Indonesia to exhibit such a unique phenomenon (Faridet al., 2021).

Whale sharks or Rhincodon typus are classified as endangered on the International Union for Conservation of Nature and Natural Resources (IUCN) Red List (Djunaidi et al., 2020). Since 2002, they have been listed in Appendix II of the Convention on International Trade in Endangered Species of Wild Fauna and Flora (CITES) (Gallimore et al., 2024). The Convention on Migratory Species (CMS) also identifies whale sharks as migratory species requiring international protection due to their ability to traverse national boundaries (Fowler et al., 2021; Rumisha et al., 2024). In Indonesia, whale sharks have been fully protected since 2013 under Ministerial Decree No. 18/KEPMEN-KP/2013, issued by the Ministry of Marine Affairs and Fisheries (Lelono et al., 2024; Yasir et al., 2024).

Farid et al. (2021); Womersley et al. (2024) highlighted that the marine waters of Saleh Bay offer optimal conditions for whale shark visitation, largely due to its plentiful food resources. This is evident from the frequent annual sightings of whale sharks in the area, supported by the high biological productivity of the waters, which include abundant plankton, fish spawning grounds, and increased concentrations of Chlorophyll-a (Chl-a). Sianipar (2019); Adhitia (2023) reported that whale shark movement patterns vary depending on the unique environmental features of different water bodies. Sea Surface Temperature (SST) also plays a role in influencing the metabolism of marine organisms as well as the distribution of plankton, which is the main food source for whale sharks (Yunus et al., 2019; Reinero et al., 2024).

This study prioritizes two environmental parameters for SST and Chl-a. Both parameters are crucial for coastal and marine ecosystems as they play an essential role in sustaining fisheries and facilitating the growth of marine aquaculture (Doydee et al., 2010; Putri et al., 2025). Furthermore, these parameters are instrumental in identifying areas where fish are likely to be found (Enita et al., 2017).

Remote sensing technology offers an effective approach to obtaining data on SST and Chl-a concentration. Aqua Moderate Resolution Imaging Spectroradiometer (Aqua MODIS), a satellite equipped with an imaging spectroradiometer sensor, can detect and map SST and Chl-a concentrations in specific areas. This satellite provides high-resolution data that enables continuous and periodic monitoring of trends and variations in SST and Chl-a concentrations (Yulius et al., 2021). A critical aspect of this effort is understanding the occurrence and distribution of whale sharks, which depend on factors such as movement patterns, food availability, and favorable SST.

This study aims to assess whale shark habitats by investigating their appearances and analyzing the relationship between SST, Chl-a concentration, and whale shark occurrences using Aqua MODIS data in the marine waters of Saleh Bay. As part of this research, the focus is on mapping whale shark appearances alongside the distribution of phytoplankton abundance, SST, and Chl-a concentration in the marine waters of Saleh Bay, with a novelty in revealing a strong relationship between environmental parameters and whale shark habitat preferences through spatial overlay and linear regression analysis highlighted by R^2 values which demonstrates the potential use of these variables as predictors of whale shark distribution in the future.

2. STUDY AREA

The study area is situated within the marine waters of Saleh Bay, which is administratively shared between Sumbawa Regency and Dompu Regency in NTB Province, Indonesia. Saleh Bay is a semi-enclosed water body that directly connects to the Flores Sea. The bay is geographically positioned at coordinates 117°–118° East Longitude and 8.8°–8.1° South Latitude. The marine waters of Saleh Bay cover an area of approximately 2,123 km² and span a length of about 282 km, encompassing the waters of Empang, Plampang, Lape/Lopok, and Moyo Hilir in Sumbawa Regency. This area coverage was determined through spatial analysis using Geographic Information System (GIS) techniques, which involved digitizing the bay boundary and calculating the water surface area. Parts of Saleh Bay also fall within the Manggelewa and Kempo Districts of Dompu Regency. Several small islands within the bay, including Gili Panjang, Gili Meriam Besar, Gili Tapan, Gili Lipan, Gili Dompo, Gili Sentigi, and Gili Dangar Ode, have recently gained popularity among tourists. Coral reefs fringe nearly the entire bay and can be found at depths up to 15 meters below sea level. A map illustrating the distribution of whale shark sighting locations is provided for better understanding. For a more detailed visualization, refer to **Figure 1** below.

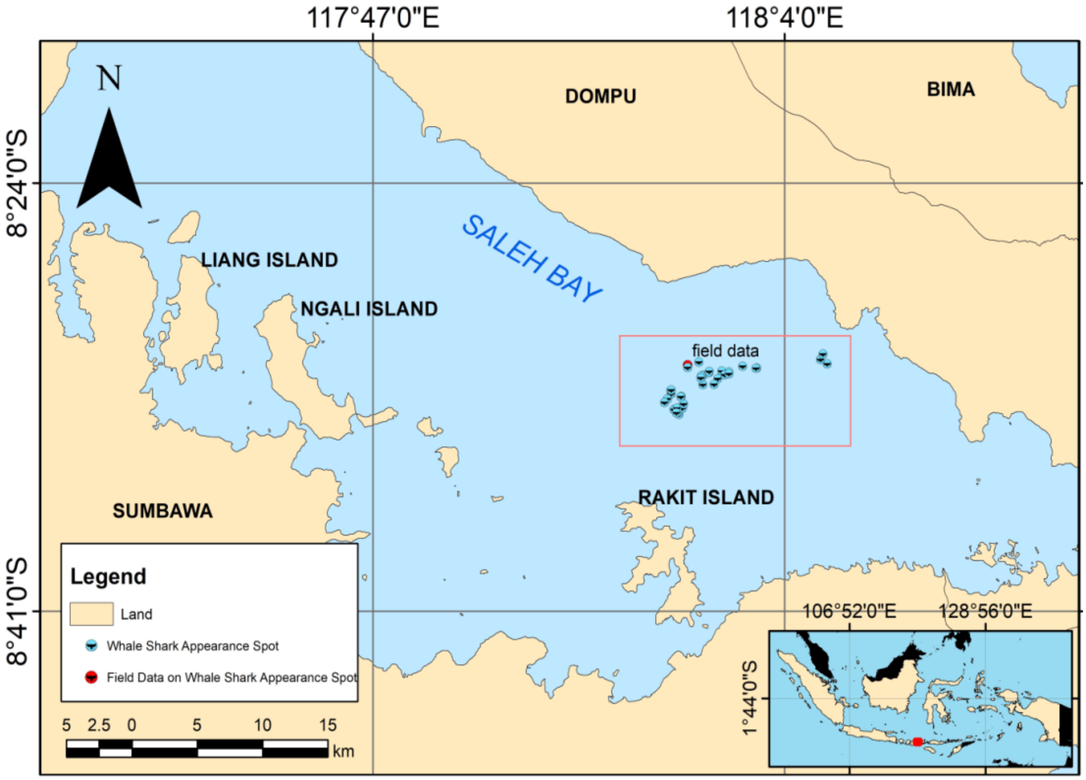

Fig. 1. Location map of Saleh Bay for whale shark sightings

3. DATA AND METHODS

3.1. Data Collections

This study employed Level-3 Aqua MODIS data, which provided information on SST and Chl-a concentrations for the period from February, March, and April 2024. The data was obtained from NASA's Ocean Color website (https://oceancolor.gsfc.nasa.gov/l3/) and processed using Quantum Geographic Information System (QGIS).

Bathymetry data was sourced from the Tanah Air Indonesia platform (https://tanahair.indonesia.go.id/) and processed using QGIS. Additionally, whale shark sighting data was collected through field surveys, recorded in MS Excel, and later converted into a format suitable for integration with QGIS.

3.2. Data Analysis Techniques

3.2.1. Processing of SST Data

The initial step in processing SST data involves cropping the research area from the Aqua MODIS dataset using Ocean Data View (ODV) software. The next phase involves interpolating the data using the Inverse Distance Weighting (IDW) method with the support of QGIS software. The IDW interpolation technique offers the advantage of giving greater weight to nearby input points, resulting in a more detailed surface. However, it has a limitation: it cannot estimate values beyond the maximum or below the minimum of the input sample points (Yudanegaraet al., 2021).

3.2.2. Processing of Chl-a Data

The method applied to process Chl-a data closely mirrors the approach used for SST data. Initially, the Chl-a data is cropped to focus on the research area using ODV software and then exported for further processing. Interpolation is subsequently conducted using the IDW method in QGIS software. This map serves as an indicator of primary productivity, a crucial element in marine ecosystems, which can significantly impact the occurrence of whale sharks.

3.2.3. Processing Whale Shark Sightings Data

Whale shark occurrence data from the study area was initially gathered through field surveys, organized using Excel software, and subsequently processed in QGIS. The occurrence points were mapped and overlaid onto spatial layers representing SST variability and Chl-a concentrations. SST and Chl-a values corresponding to each mapped occurrence point were then extracted, creating a dataset that linked environmental parameters to whale shark sightings.

3.2.4. Processing Bathymetry Data

In addition to SST and Chl-a, bathymetry data (sea depth) was processed using QGIS. This data was obtained from platform (https://tanahair.indonesia.go.id/) to create a detailed map of the underwater depth in the study area.

3.3. Data Analysis

After compiling data on SST, Chl-a, bathymetry, and whale shark sightings, a simple linear regression analysis was performed using Excel software. This analysis evaluated the strength and significance of the relationship between environmental variables, specifically SST and Chl-a, and whale shark occurrences. This analysis provided deeper insights into the environmental factors shaping whale shark habitat preferences.

4. RESULTS AND DISCUSSION

The photos in **Figure 2** capture whale shark sightings recorded during field observations conducted in July 2024. These observations emphasize the interaction between whale sharks and their surrounding environment, demonstrating their consistent presence in the marine waters of Saleh Bay.

Fig. 2. Photos of whale shark activity at the water surface 1) Whale sharks are observed near the platform, interacting mainly for feeding or observation; and 2) Whale sharks are seen farther away, positioned vertically, with their tails more visible.

Figure 2 above depicts whale shark activity near shallow platforms, suggesting that these areas identified on the bathymetry map at a depth of approximately -400 m may function as preferred zones for feeding or resting. By combining field observations, as depicted in the photographs, with the detailed seabed topography provided by the bathymetry map (**Figure 3**), this study underscores the importance of environmental factors such as sea depth and seabed structure in influencing whale shark behavior and habitat preferences within the marine waters of Saleh Bay.

The observed interactions between humans and whale sharks in these shallow areas highlight the urgency of implementing sustainable tourism practices and robust conservation strategies to protect the species natural environment. As illustrated in **Figure 1** (see Methods), a map showing whale shark appearance spots recorded 36 sightings of whale sharks between February, March, and April 2024. These sightings were based on field surveys, with additional data points collected in July 2024. The link between whale sharks and surface-feeding activities is supported by the findings of Mottaet al. (2010); Syahet al. (2018); Dove & Pierce (2022), who report that whale sharks' surface to feed on zooplankton, including sergestids, copepods, arrow worms, crab larvae, mollusks, crustaceans, coral eggs, and fish larvae.

Observations conducted between 05:00-09:00 AM documented whale sharks actively feeding, likely attracted by the strong scent of pelagic fish. It is hypothesized that the frequent sightings during these morning hours are due to the availability of abundant food resources (Suruanet al., 2024). As the day progresses, whale sharks are no longer observed near the surface, likely diving to greater depths in search of food. This behavior aligns with findings by Suprapti (2015), who highlights that whale sharks prefer deeper waters but surface when feeding.

Bathymetry data, which provides information on ocean depth, is essential for understanding oceanographic dynamics such as currents, navigation, habitat analysis, temperature variations, and plankton distribution. These factors indirectly influence the distribution of large marine species, including whale sharks (Almaret al., 2021). **Figure 3** presents the bathymetry map of Saleh Bay and its surrounding waters, derived from the National Bathymetry Database in platform https://tanahair.indonesia.go.id/ and processed using QGIS software. Analysis of the bathymetry data reveals that the marine waters of Saleh Bay reach a maximum depth of -400 m. This aligns with previous research showing that whale sharks are often found in nutrient-rich productive zones. Such zones are shaped by seabed topography and upwelling currents, which bring nutrients from the deep ocean to the surface, creating favorable feeding grounds for whale sharks (Ryanet al., 2017).

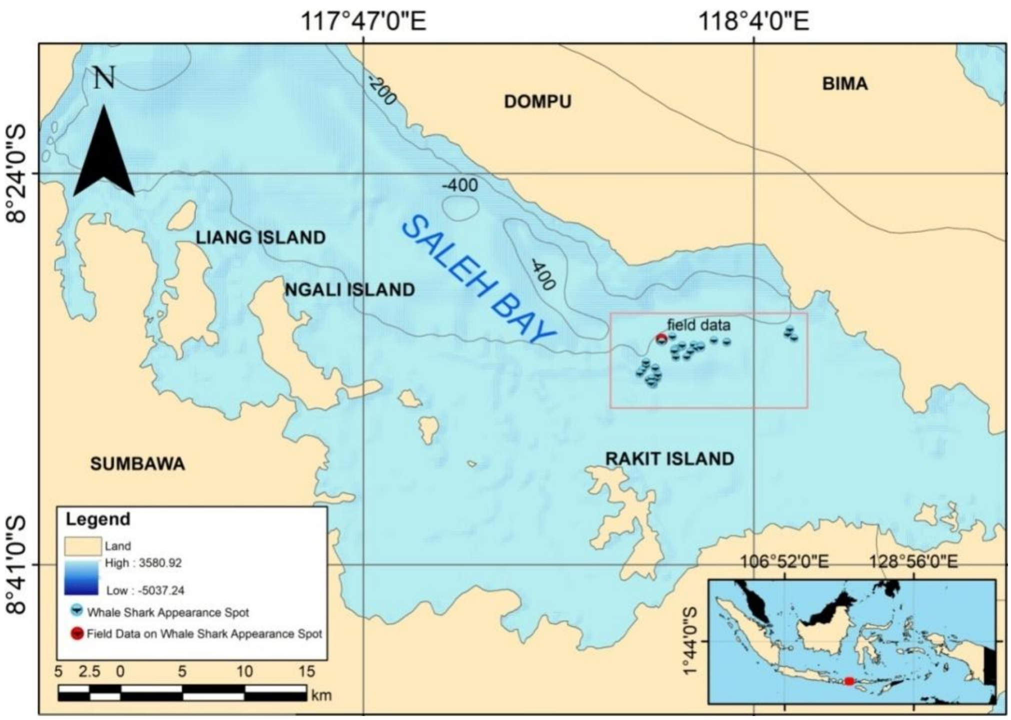

Fig. 3. Bathymetry map of Saleh Bay for whale shark sightings.

4.1. Chl-a Distributions and Whale Shark Sightings

The maps presented in **Figure 4** show the spatial distributions of Chl-a concentrations in the marine waters of Saleh Bay during different periods. The highlighted whale shark appearance spots, marked in blue, correspond to areas with varying levels of Chl-a concentration, as indicated by the gradient from low (light green) to high (dark green) values. Additionally, red markers indicate field data points where whale shark sightings were recorded. For more details see **Figure 4** below.

Figure 4 shows the distributions of Chl-a concentrations in the marine waters of Saleh Bay, which range from 0.20 to 3.45 mg/m³, alongside recorded whale shark appearance spots. The data reveals that whale shark sightings are concentrated in areas with elevated Chl-a levels, indicating high marine productivity. This correlation suggests that environmental factors, such as the availability of zooplankton and fish larvae, significantly influence whale shark presence in these areas (Foxet al., 2013). As McKinney (2012) notes, Chl-a is a critical indicator of marine productivity, closely linked to phytoplankton abundance. An increase in Chl-a levels leads to higher phytoplankton concentrations, which subsequently support greater densities of zooplankton and fish larvae in the water column. This trophic cascade directly aligns with whale shark sightings, as these organisms form their primary diet.

While whale sharks are generally solitary creatures, Cruzet al. (2013) observe that they tend to aggregate in areas abundant with food resources. As migratory species, they traverse areas in search of food, often following plankton concentrations in marine ecosystems. In the marine waters of Saleh Bay, whale shark surface appearances, as documented by Farid (2021), are frequently associated with the presence of small fish near the water's surface. The presence of small fish serves as a reliable indicator of plankton abundance, highlighting the interdependence of these organisms and the ecological dynamics at play. The patterns presented in **Figure 4** underscore the pivotal role of Chl-a concentrations in shaping whale shark distributions, emphasizing the importance of high-productivity zones in the marine waters of Saleh Bay. This relationship further highlights the ecological significance of plankton distributions, which initiates cascading effects across trophic levels, sustaining the dynamic marine ecosystem observed in the bay.

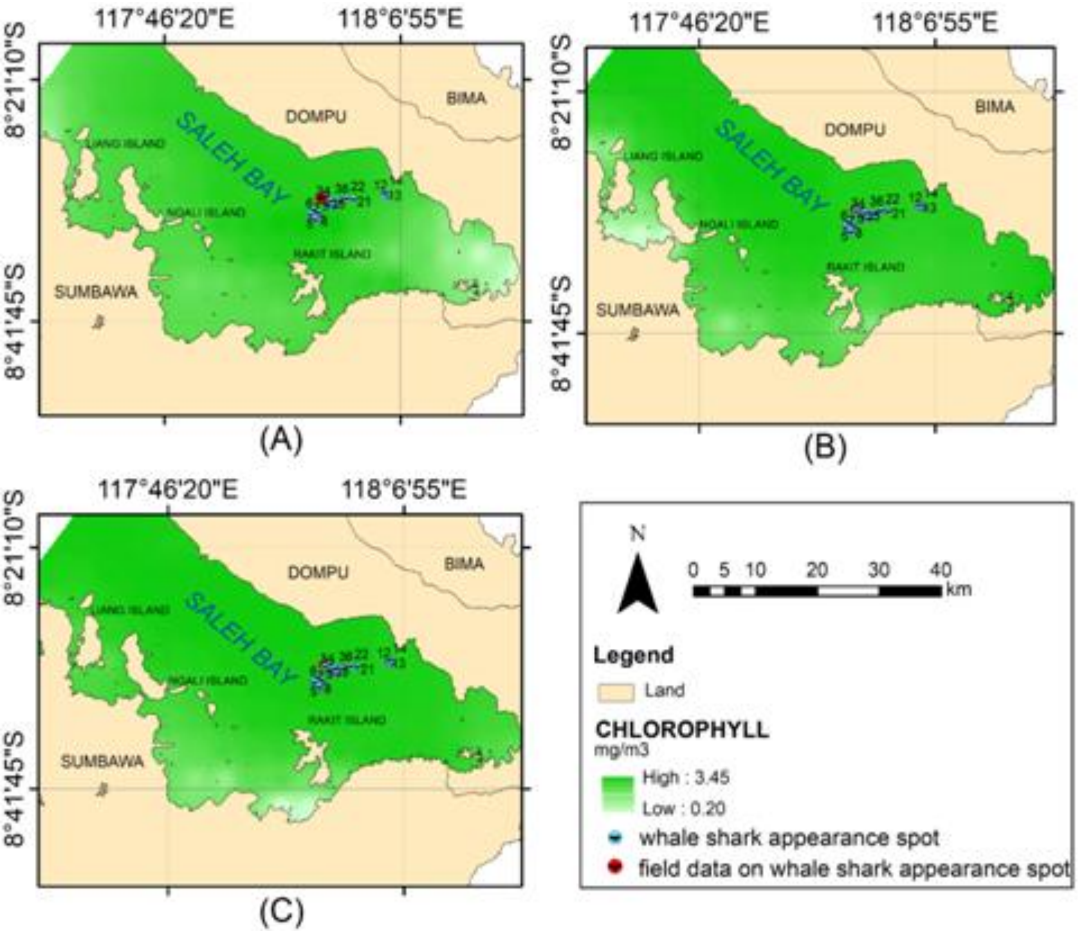

Fig 4. Chl-a distributions and whale shark sighting locations (A, B, C)

4.2 Sea Surface Temperature (SST) Distributions and Whale Shark Sightings

The maps presented in **Figure 5** show the spatial distributions of SST in the marine waters of Saleh Bay during different periods. The SST gradient ranges from low (blue) to high (red), reflecting variations in temperature across the area. The highlighted whale shark appearance spots, marked in blue, indicate locations where whale sharks were observed, while the red markers represent field data points confirming these sightings. These maps provide critical insights into the relationship between SST variability and the spatial patterns of whale shark appearances. For more details, refer to **Figure 5** below.

Figure 5 shows the distributions of SST in the marine waters of Saleh Bay, ranging from 29.47°C (blue) to 33.85°C (red), along with whale shark sighting locations (blue) and field observation data points (red). The variation in SST highlighted in **Figure 5** underscores its crucial role in influencing physical conditions within the water, which, in turn, can significantly impact marine organisms. As noted by Richmond (2011), SST affects metabolic rates, behavior, reproduction, and even broader meteorological patterns. Furthermore, temperature variability directly impacts oxygen solubility, with higher temperatures leading to increased oxygen consumption in aquatic organisms. Rahmanet al. (2017) reported that whale sharks typically inhabit waters with temperatures ranging from 18-30°C, while Murdaniet al. (2018) identified their preference for waters within 28-32°C.

The consistency between these ranges and the observed SST in the marine waters of Saleh Bay suggests that the area provides optimal thermal conditions for whale sharks, enabling them to thrive in these waters over extended periods.SST variability also plays a pivotal role in whale shark distribution and migration. According to Binderet al. (2011), temperature influences migratory behavior as part of thermoregulation, a process that organisms use to maintain their body temperature. Stewart (2011) emphasized that whale sharks avoid surface temperatures exceeding those in deeper waters, favoring habitats with warm but moderate SST.

Additionally, Staceyet al. (2008) noted that whale sharks are frequently observed in surface waters with SSTs above 29°C, with 90% of solitary sightings occurring in waters where SST ranges between 25-35°C. Interestingly, whale sharks demonstrate the ability to tolerate extreme temperatures during deep dives and tolerances as low as 10°C. Conversely, these sharks have also been observed in exceptionally high SSTs, such as in Fundy Bay on the eastern coast of North America, where SST reached 44°C. Nevertheless, the preferred temperature range of 28-32°C observed in the marine waters of Saleh Bay supports their metabolic processes and ensures sufficient food availability, making the bay an ideal habitat for these migratory giants.

The findings presented in **Figure 5** highlight the critical role of SST in influencing whale shark habitat preferences, migratory behavior, and thermoregulatory adaptations. By offering optimal thermal conditions, the marine waters of Saleh Bay sustain a dynamic ecosystem that attracts whale sharks, linking SST variability to broader ecological processes affecting marine life in the area.

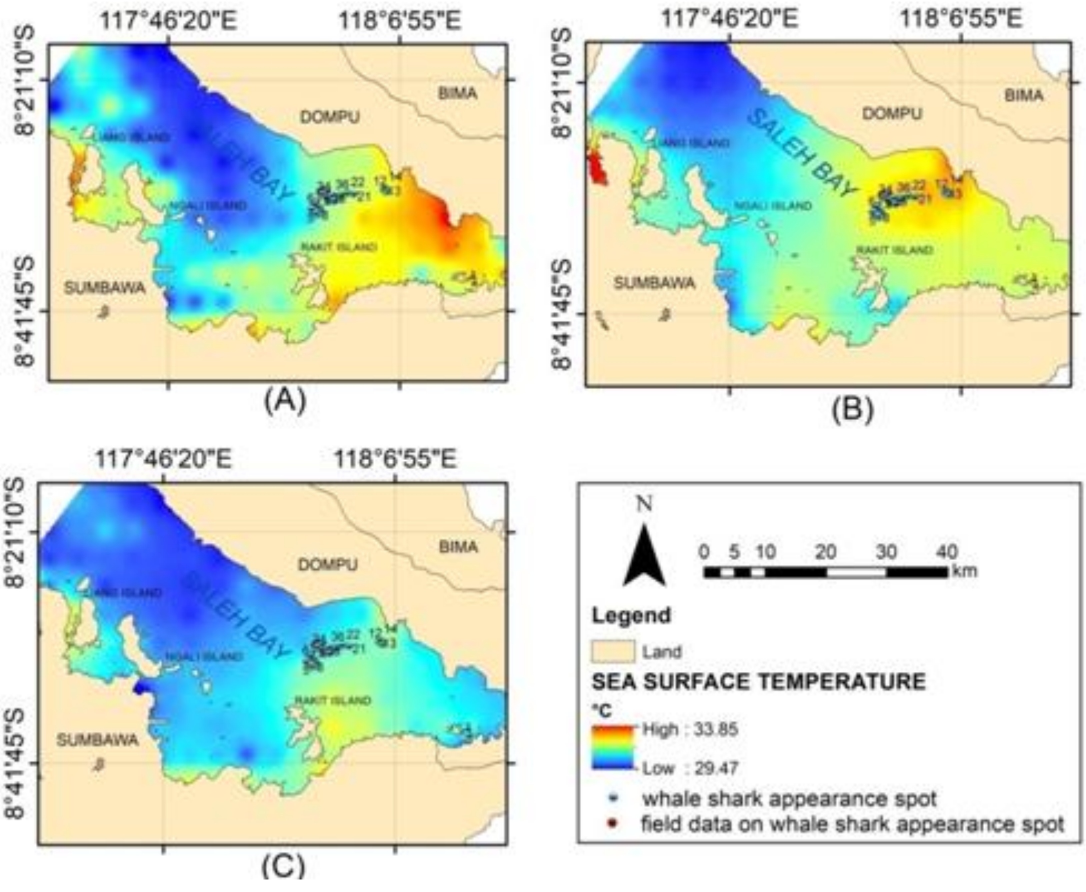

Fig. 5. SST distributions and whale shark sighting locations (A, B, C).

4.3 Linear Relationship (SST and Chl-a) Concentration in February, March, and April 2024

The relationship between SST and Chl-a concentration for February, March, and April 2024 in the marine waters of Saleh Bay was analyzed using linear regression.

The analysis revealed variations in the positive relationship between SST and Chl-a for each month, as indicated by the regression coefficients and R² values presented in the graphs. The findings highlight month-to-month differences in the strength and direction of the relationship. These variations may reflect changes in environmental conditions, such as nutrient availability, seasonal patterns, or phytoplankton dynamics within the Saleh Bay ecosystem. For more details, refer to **Figure 6** below.

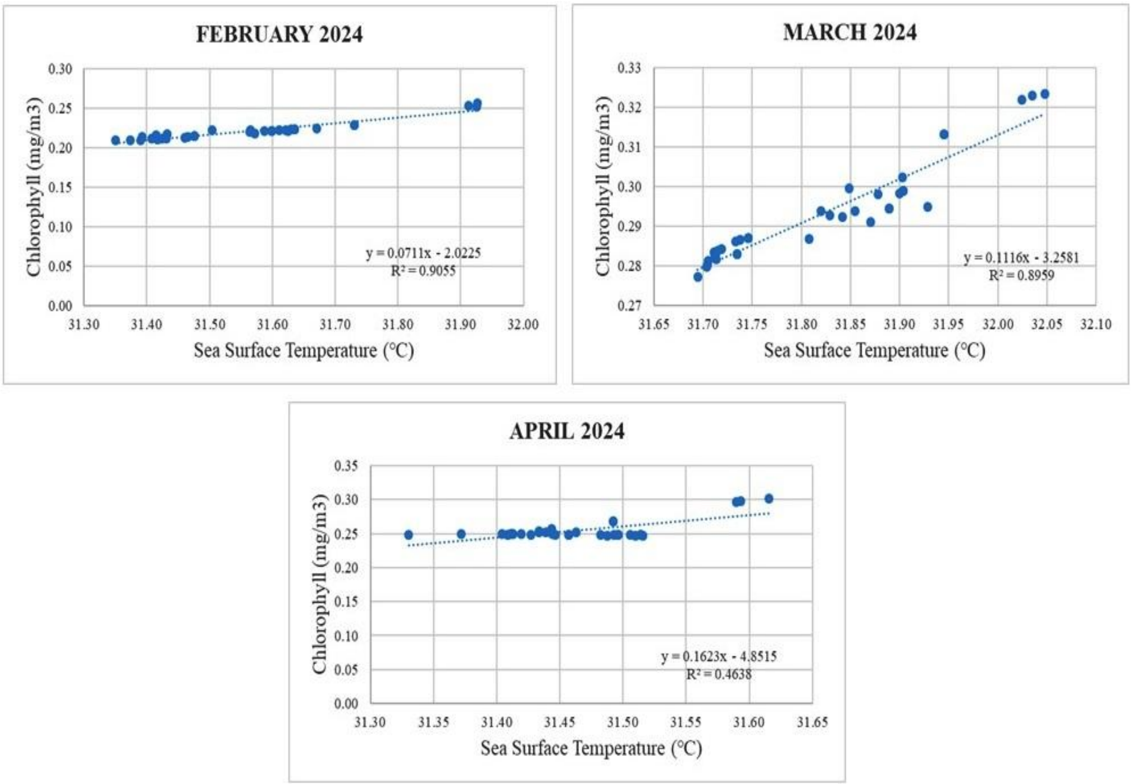

Fig. 6. Relationship between and Chl-a concentrations (February, March, and April 2024).

The graphs in **Figure 6** above show simple linear regression results between Chl-a concentrations and SST with the observed occurrence of whale sharks from February, March, and April 2024. The coefficient of determination (R^2) serves as a measure of how well the variability in whale shark occurrences can be explained by these environmental factors.

- February 2024: The R^2 value of 0.9055 indicates a very strong relationship, where nearly 90.55% of the variability in whale shark occurrences can be explained by Chl-a and SST. This suggests that the model provides a highly accurate representation of the factors influencing whale shark habitat preferences during this period.
- March 2024: The R^2 value of 0.8959 represents a similarly high correlation between Chl-a, SST, and whale shark occurrences. This finding supports research by Sequeiraet al. (2012), which identified temperature and productivity gradients as key determinants in whale shark aggregation sites globally.
- April 2024: The R^2 value of 0.4638 indicates a moderate relationship, suggesting that while Chl-a and SST still influence whale shark occurrences, additional factors may play a more significant

role during April. This aligns with observations by Normanet al. (2017), who noted that whale sharks might adapt their movements based on temporal prey availability or changes in water quality.

Chl-a acts as a proxy for primary productivity, representing the abundance of phytoplankton that forms the base of the marine food chain and serves as a primary food source for whale sharks. Taylor & Pearce (1999) highlight that higher Chl-a concentrations often correlate with increased prey density, attracting megafauna like whale sharks.

Similarly, SST influences metabolic rates, plankton activity, and the suitability of feeding and breeding conditions for whale sharks. Optimal SST ranges between 28-32°C are preferred for foraging and migration (Arrowsmith et al., 2021), as supported by Colman (1997), who reported that whale sharks frequently inhabit warm, productive waters where food availability is maximized.These findings emphasize the predictive potential of SST and Chl-a as key environmental indicators in identifying suitable whale shark habitats, particularly during peak aggregation periods. The consistency of high R^2 values in February and March also supports the integration of remote sensing data in ecological monitoring and habitat modeling, enabling more targeted conservation and ecotourism management strategies in regions like Saleh Bay.

5. CONCLUSIONS

In conclusion, the marine waters of Saleh Bay, located in NTB, Indonesia, serve as a vital habitat for whale sharks and hold significant ecological and economic importance. The observed Chl-a concentrations (0.20–3.45 mg/m^3) and SST ranges (29.47–33.85°C) align closely with the ecological preferences of whale sharks, ensuring a consistent environment for feeding and aggregation. The regression analysis conducted in this study reveals a strong relationship between environmental variables and whale shark occurrences. The high R^2 values recorded in February (0.9055) and March (0.8959) indicate a robust predictive correlation, while the moderate value in April (0.4638) suggests the influence of additional ecological or oceanographic factors. These findings highlight the importance of considering both primary drivers and supplementary environmental variables when analyzing whale shark habitat preferences.

This study provides a novel insight by demonstrating that satellite-derived SST and Chl-a data, combined with bathymetric information and field observations, can serve as reliable indicators for predicting whale shark distribution in semi-enclosed tropical marine ecosystems. The practical implications of this research are significant.

First, in terms of marine conservation, the strong correlation between environmental variables and whale shark occurrences supports the integration of remote sensing data into conservation planning. This can assist authorities in identifying and prioritizing critical habitats for protection, especially in areas facing increasing human activity.

Second, for sustainable marine ecotourism, the identification of aggregation zones can inform the spatial regulation of tourism activities to ensure that interactions with whale sharks occur in ecologically appropriate areas while minimizing anthropogenic disturbances.

Third, the methodology used in this study offers potential for real-time habitat monitoring and the development of early warning systems based on SST and Chl-a variability. Such systems could help forecast seasonal whale shark presence, optimize tourism management, and detect environmental threats such as habitat degradation. Based on these implications, it is recommended that marine resource management agencies incorporate satellite-based oceanographic data into their monitoring and planning frameworks.

Further research should expand upon these findings by integrating additional environmental variables such as current patterns, salinity, or prey abundance and applying advanced modeling techniques to improve prediction accuracy. Collaboration between scientists, policymakers, and local communities will be essential to ensure the long-term conservation and sustainable utilization of whale shark habitats in Indonesia.

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