Assessing Coral Reef Changes through Supervised Classification and its Correlation with SST and Chlorophyll-A: A Remote Sensing Approach.

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Summary

This study summarizes on a remote sensing techniques to monitor coral reefs and investigate their relationship with environmental indicators, particularly sea surface temperature (SST) and chlorophyll-A concentrations. By applying supervised classification algorithms, the research generated detailed maps of coral reefs, allowing for precise detection of changes in reef health over time. Time series analysis, coupled with ARIMA modeling, was used to analyze trends in SST and predict future patterns, offering insights into how temperature changes might impact coral ecosystems. The findings revealed a significant negative correlation between coral reefs and SST, indicating that rising sea temperatures are detrimental to coral health. Additionally, a weak positive correlation was observed between coral reefs and chlorophyll-A concentrations, suggesting a subtle but relevant connection between coral health and nutrient levels or water quality.

The study explored temporal changes in coral reefs and their correlation with environmental factors, providing a comprehensive understanding of the dynamics affecting these ecosystems. By integrating supervised classification, time series analysis, and predictive ARIMA modeling, the research assessed the current status of coral reefs and enhanced the ability to forecast future environmental changes and their potential impacts. These results underscore the critical role of remote sensing in monitoring coral reefs and contribute valuable insights for developing effective conservation strategies. Overall, the study advances the understanding of coral reef ecosystems and their response to environmental stressors, aiding in the preservation of these essential underwater habitats.

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1. INTRODUCTION

Coral reefs, despite occupying a small fraction of the world's oceans, are crucial to marine biodiversity, serving as habitats for a vast array of species (Pandolfi et al., 2011; Wang et al., 2021). These reefs are formed by corals that build three-dimensional calcium carbonate skeletons, which support an immense diversity of marine life, making them one of the most diverse and productive ecosystems on the planet (Wang et al., 2021). Beyond their ecological importance, coral reefs also provide significant cultural, economic, and recreational value to coastal communities globally, contributing to coastal protection and serving as sources of food and income for millions of people (Moberg & Folke, 1999).

However, coral reefs are facing severe stress, particularly from rising sea surface temperatures—a climate-induced phenomenon that threatens the delicate balance of these ecosystems in a non-uniform manner (Anthony et al., 2020; Boonnam et al., 2022). Rising temperatures lead to coral bleaching, where corals expel their symbiotic algae, known as zooxanthellae, resulting in the loss of their vibrant colors and, if the stress persists, leading to coral mortality (Pandolfi et al., 2011; Spalding & Brown, 2015). The increasing frequency of sea surface temperature anomalies poses a significant risk to the long-term survival of coral reef ecosystems, as it correlates with more frequent and severe coral bleaching events (Baker et al., 2008).

Coral bleaching is primarily triggered by prolonged exposure to elevated SST, disrupting the balance between corals and their symbiotic zooxanthellae algae (Torres et al., 2021) . Global bleaching events from 2014-2017 affected 70% of the world's coral reefs (Burdett et al., 2024). By 2050, 90% world coral reefs are projected to experience coral bleaching annually (Coral Bleaching - Coral Reef Alliance, n.d.)

To combat these challenges, innovative approaches that utilize technology and interdisciplinary collaboration are essential. Remote sensing technologies are particularly promising for the large-scale monitoring of coral reefs, offering cost-effective and efficient means of observing extensive reef areas and providing critical spatial and temporal insights into reef dynamics (Foo & Asner, 2019). Time series analysis of coral reefs, focusing on indicators such as coral cover and bleaching events, is vital for understanding the temporal dynamics and their correlation with sea surface temperatures (Little et al., 2022). Additionally, developing predictive models for sea surface temperature and chlorophyll-a concentrations helps anticipate future changes and their impact on coral reefs (Liu et al., 2015). Monitoring coral bleaching in relation to sea surface temperature enables the implementation of effective conservation strategies aimed at mitigating the impacts of temperature rise and protecting coral reef systems (Huisman, 2023).

This project is dedicated to expanding knowledge on the effects of sea surface temperature on coral bleaching and developing prediction models that can provide early warnings. By investigating the biological and ecological aspects of coral bleaching, this research aims to understand the underlying mechanisms and correlations between corals, temperature, and chlorophyll-a concentrations, ultimately contributing to the protection and preservation of these vital marine ecosystems.

2. METHODOLOGY

2.1.Study Area

The area of our study is Meatil Mearang Island, positioned in close proximity to Timor-Leste within the Coral Triangle, renowned for its exceptional marine biodiversity. Encompassing an expansive area of approximately 323 km², this island boasts a varied terrain, including coral reefs, algae formations, sandy beaches, and surrounding waters rich in marine life. Meatil Mearang Island serves as a miniature representation of the Coral Triangle's ecological wealth, hosting a diverse array of marine species vital to the ecosystem's health. However, this natural treasure is under considerable threat from climate change and human activities.

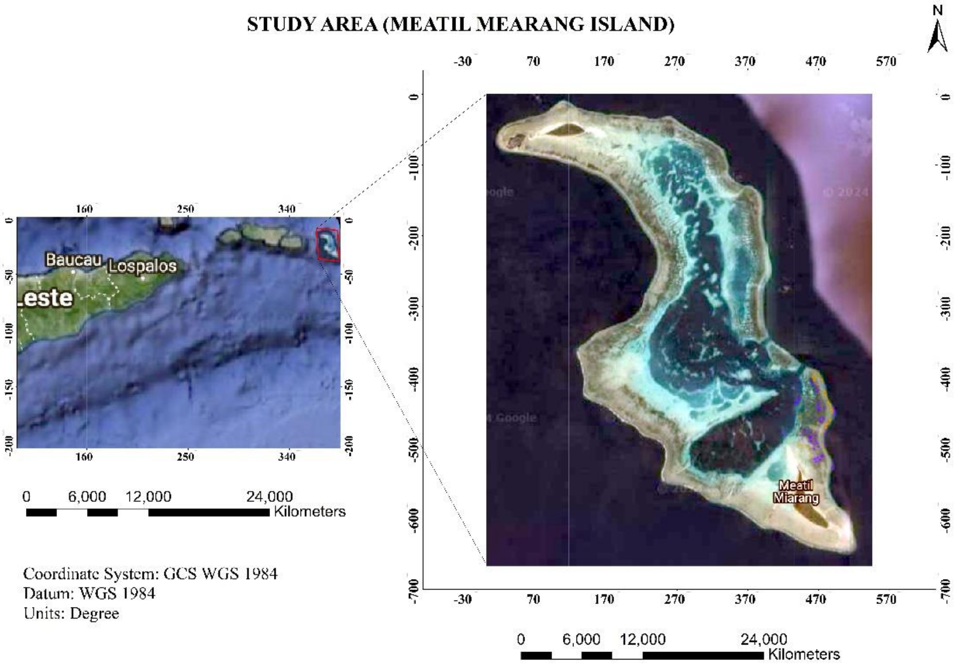

Figure 1: Study Area

2.2.Workflow

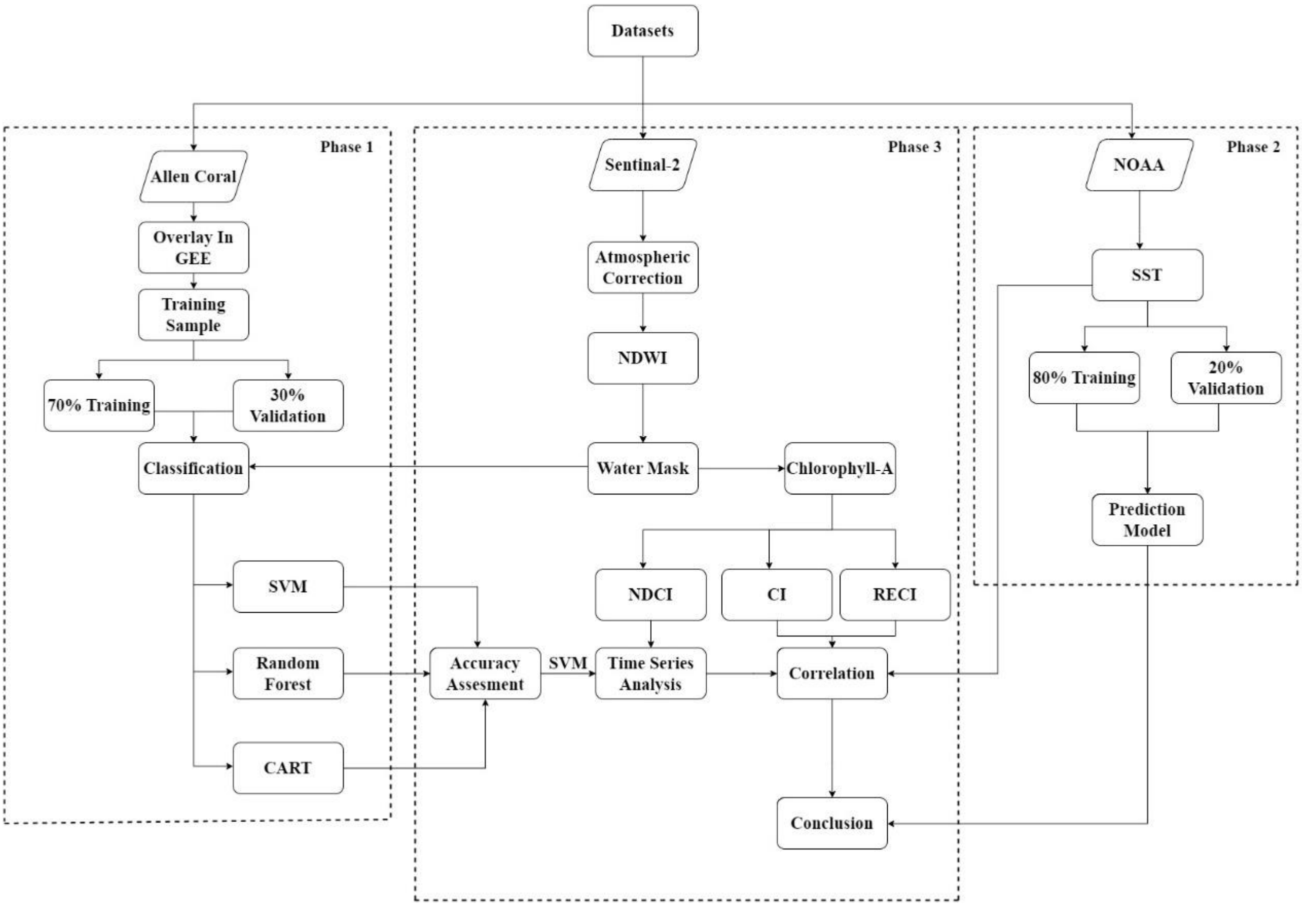

Figure 2: Workflow

2.2.1. Data Acquisition

Throughout the project, three main datasets were used. Firstly, satellite imagery was assessed from sources including LANDSAT 8, and Sentinel missions through the Copernicus website. This imagery was crucial for tasks such as image classification and change detection. Secondly, official coral data sourced from the Allen Coral website were integrated, which is renowned for its accuracy with a validation rate of 60-90%. This dataset, derived from in-situ observations and expert curation, facilitated our study's focus on coral monitoring and classification within our study area. Lastly, to investigate the relationship between sea surface temperature (SST) fluctuations and coral health, SST data from the National Oceanic and Atmospheric Administration (NOAA) website was obtained. This data aided in the development of prediction models and the exploration of correlations, enhancing our understanding of factors influencing coral ecosystems.

2.2.2. Image Classification

In this study, marine habitats were classified using satellite imagery, categorizing areas into five distinct classes: Corals (Pinkish Red), Rocks (Dark Yellow), Sand (Light Yellow), Seagrass (Dark Green), and Deep Water (Light Blue). Training data was derived from the Allen Coral Map and processed using Google Earth Engine (GEE). Following Baheti Pragati's (2021) methodology, data was split into 70% for training and 30% for validation to ensure model reliability.

Three algorithms—Random Forest (RF), Classification and Regression Tree (CART), and Support Vector Machines (SVM)—were employed to classify the imagery. RF utilized ensemble decision trees, CART created binary tree structures, and SVM established hyperplanes for class separation. The models were evaluated based on overall accuracy using JavaScript in GEE, with a focus on each algorithm's strengths and weaknesses for image classification.

For accuracy assessment, the study compared the performance of three algorithms—Random Forest (RF), Support Vector Machine (SVM), and Classification and Regression Tree (CART)—in classifying marine habitats. The overall accuracy of each algorithm was evaluated using the validation dataset within Google Earth Engine (GEE). This comparison allowed for the identification of the most effective algorithm, considering both strengths and weaknesses, to ensure reliable image classification and accurate representation of different marine features in the study area.

2.2.3. Prediction of SST

The study utilized an ARIMA (25, 2, 25) model for forecasting sea surface temperature (SST) using historical data from 1982 to 2023. Monthly averaged SST data was collected, cleaned, and tested for stationarity using the Augmented Dickey-Fuller Test. The data was differenced ($d = 2$) to stabilize it, and autocorrelation plots determined the AR and MA terms (p and q) as 25 each. Validation of the model, using SST predictions from 2021 to 2023, showed a Root Mean Square Error (RMSE) of 0.5 and a Percentage Error (PE) of 1.44%, indicating high accuracy. The model was then used to forecast SST values up to 2025.

2.2.4. Chlorophyll-A incdices

In this study, various chlorophyll indices, including the Normalized Difference Chlorophyll Index (NDCI), Chlorophyll Index (CI), and Red-Edge Chlorophyll Index (RECI), were calculated to monitor chlorophyll-a concentration in coral reefs, providing insights into ecosystem health. For 2023, these indices offered a detailed analysis of chlorophyll-a distribution and dynamics. Additionally, a time series analysis of NDCI from 2016 to 2023 revealed seasonal patterns and potential environmental stressors impacting the coral reef ecosystem, contributing to a comprehensive methodology for monitoring chlorophyll-a.

2.2.5. Time Series Analysis

This study conducted time series analysis on coral reef data from 2016 to 2023 using Landsat satellite imagery. The process involved several key steps: data collection, image preprocessing to remove distortions like clouds, and classification using a multi-class Support Vector Machine (SVM) model. The SVM model was trained on labeled data and validated on a testing set to ensure accuracy. Following classification, time series analysis was performed to examine trends, changes, and patterns in coral reefs over the study period, offering insights into environmental changes and human impacts on these marine ecosystems.

2.2.6. Correlation between SST, corals and chlorophyll-A

In this study, Pearson correlation coefficients were calculated to examine the relationships between average coral area and environmental variables such as Sea Surface Temperature (SST), Normalized Difference Chlorophyll Index (NDCI), Chlorophyll Index (CI), and Red-Edge Chlorophyll Index (RECI) from 2016 to 2023. Data were collected and averaged using Google Earth Engine, and the correlation analysis was conducted in Excel using the CORREL function. The correlation coefficients were then interpreted to assess the strength and significance of these relationships, providing insights into the impact of environmental factors on coral reef health.

3. RESULT AND DISCUSSIONS

The output of the study is presented and discussed in this section. The classified map, comparisons of algorithms, time series map, SST prediction and co-relations are discussed in this section.

3.1. Classification

Three different algorithms i.e. SVM, RF, and CART were used for to classify images into various benthic classes, such as coral/algae, rocks, seagrass, water, and sand. whose results are shown below.

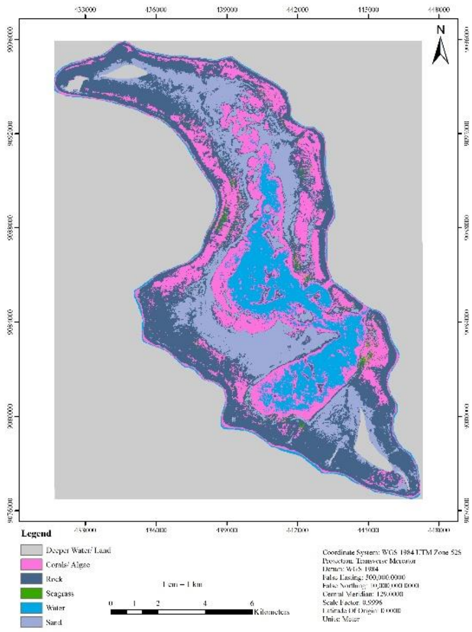

Figure 3: SVM Classification

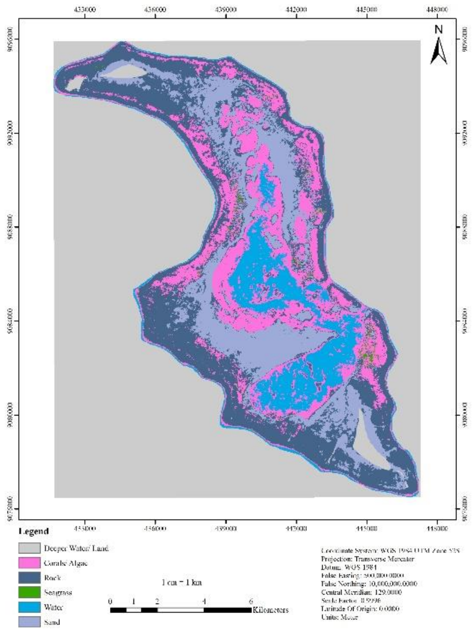

Figure 4: RF Classification

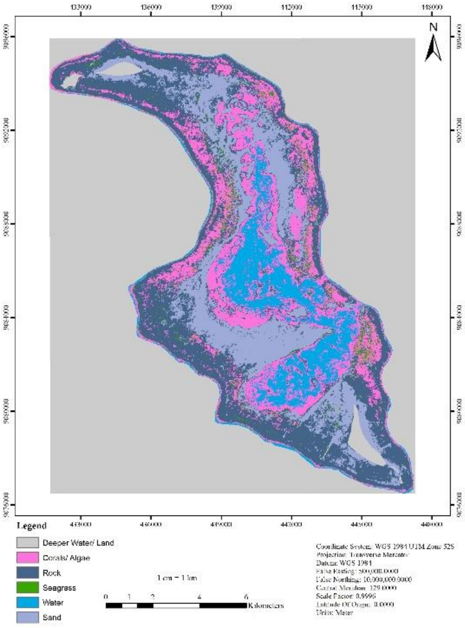

Figure 5: CART Classification

Among these, SVM provided the clearest separation between classes and demonstrated the highest overall accuracy, making it the preferred algorithm for further analysis. The SVM achieved an overall accuracy of 91.81% and a Kappa coefficient of 0.90, outperforming RF and CART. However, seagrass classification accuracy was notably low across all algorithms, likely due to its visual similarity to green algae and corals. The study highlights SVM as the most effective algorithm for image classification in this context, despite challenges in distinguishing certain classes.

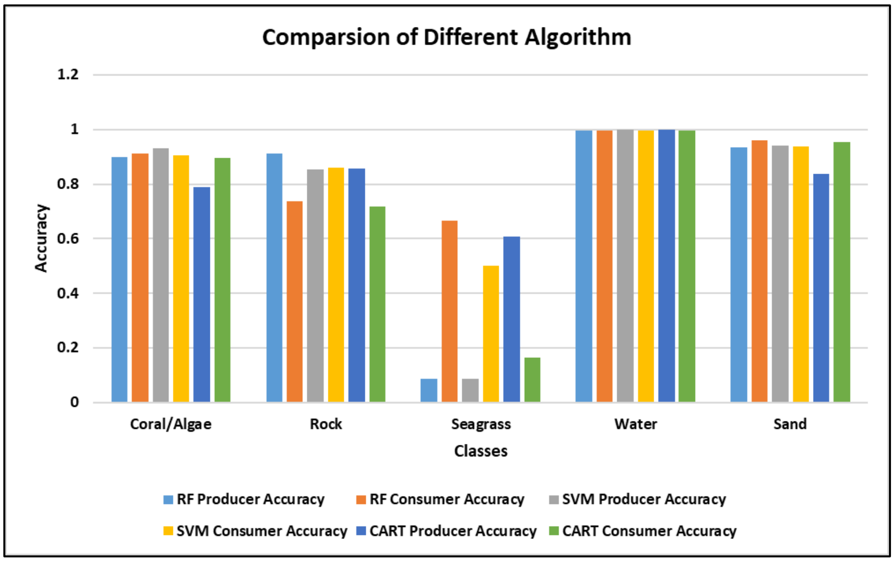

Figure 6: Comparison

3.2. Time Series Analysis

The study examines temporal changes in coral reef coverage from 2016 to 2023 using classified images generated by the Support Vector Machine (SVM) algorithm. The classification model was developed with training samples and applied to images from different years, revealing trends and patterns in coral reef ecosystems. Significant changes in coral coverage were observed over time, with initial recovery after a major bleaching event in 2016, followed by fluctuations in coral area.

Table 3.1. Data Analysis of Change in Coral Reefs.

S.N.	Year	Area (km²)	Area (%)
1	2016	27.20	8.42
2	2017	26.77	8.29
3	2018	27.80	8.61
4	2019	27.81	8.61
5	2020	26.73	8.28
6	2021	29.80	9.23
7	2022	25.94	8.03
8	2023	31.06	9.62

Table 3.1 shows that coral coverage decreased slightly from 27.20 km² in 2016 to 26.77 km² in 2017, then increased to 27.80 km² in 2018 and 27.81 km² in 2019. The area dropped again to 26.73 km² in 2020, saw a notable rise to 29.80 km² in 2021, decreased to 25.94 km² in 2022, and increased again to 31.06 km² in 2023. These fluctuations highlight the dynamic nature of coral reefs, influenced by environmental factors and human activities, showing periods of both resilience and degradation.

3.3. Cholorophyll-A Indices

As discussed earlier, the change in concentration of chlorophyll-A is also an indicator of coral bleaching. This is why different chlorophyll-A Indices like NDCI (Normalized Difference Chlorophyll Index), CI (Chlorophyll Index) and RECI (Red-edge Chlorophyll Index) were calculated in order to visualize the chlorophyll content in our study area.

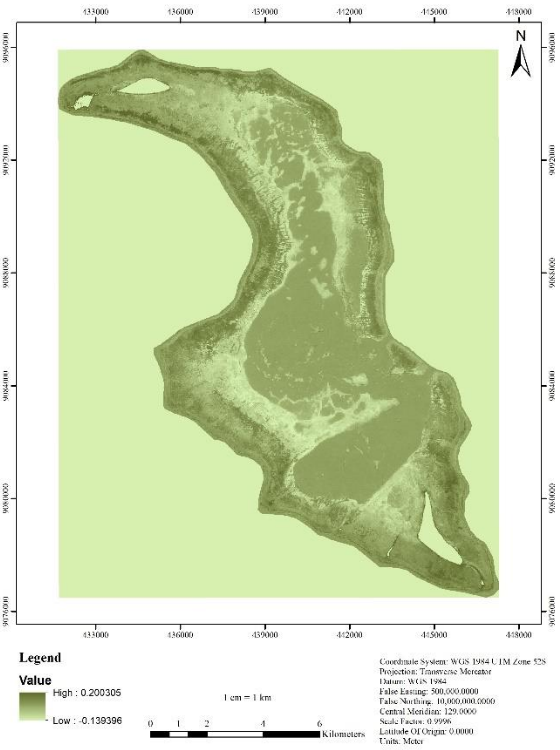

Figure 7: NDCI (2023)

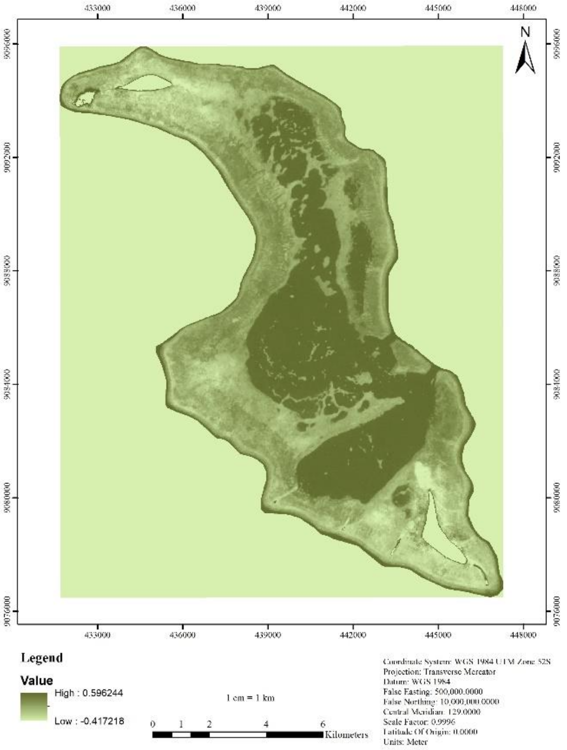

Figure 8: RECI (2023)

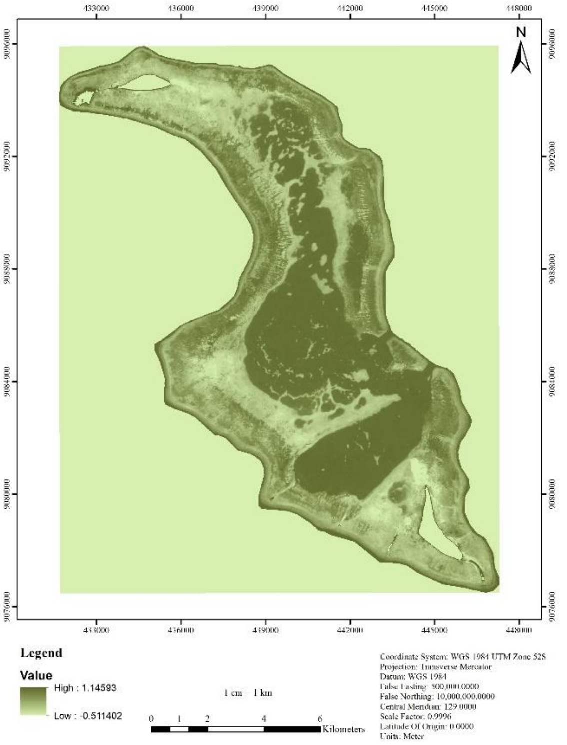

Figure 9: CI (2023)

The temporal analysis of the Normalized Difference Chlorophyll Index (NDCI) from 2016 to 2023 reveals fluctuating trends in chlorophyll-A content, reflecting the coral ecosystem's response to environmental changes. Initially, higher NDCI values indicate increased chlorophyll-A due to coral bleaching, followed by declines suggesting stress or degradation. The sharpest drop in NDCI occurs mid-period, indicating reduced bleaching, while the latter part shows significant recovery in chlorophyll levels, possibly due to renewed bleaching. Across the study period, chlorophyll-A content generally increases, with the Red Edge Chlorophyll Index (RECI) showing the most pronounced growth among all indices.

3.4. Sea Surface Temperature

The study utilized Sea Surface Temperature (SST) data from NOAA, revealing a global increase in SST over the years. Using monthly average data from 1982 to 2023, an ARIMA model was developed to forecast SST for the next five years.

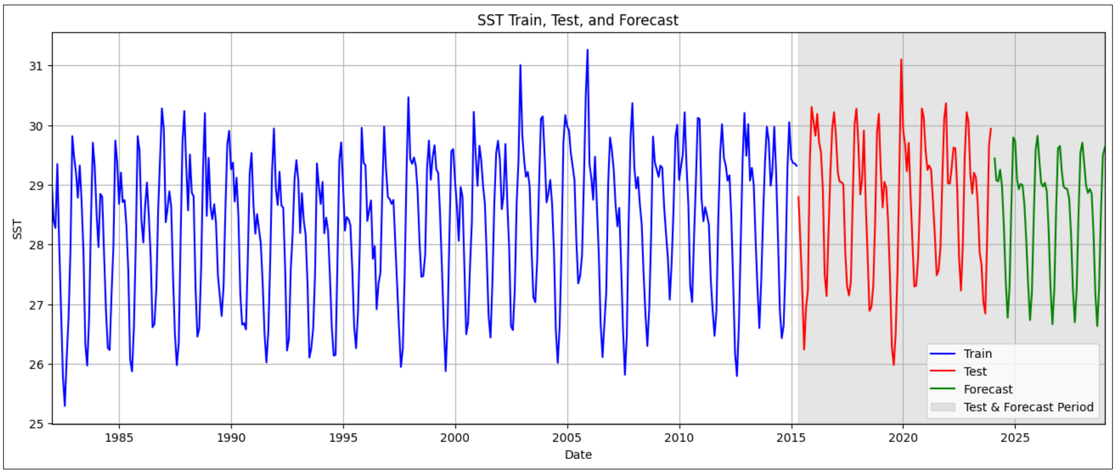

Figure 10: Sea Surface Temperature Forecast

The model, trained on data up to 2015 and validated with a Root Mean Square Error (RMSE) of 0.5 and a percentage error of 1.44%, predicted that SST will remain relatively stable between 26.63°C and 29.82°C over the next five years. However, despite this forecasted stability, the study emphasizes the continued threat of ocean heat waves, which can cause abrupt temperature spikes leading to coral bleaching and significant damage to marine ecosystems. Research shows that such heatwaves, exacerbated by climate change, pose a severe and ongoing risk to coral reefs, even if the overall SST trend appears stable.

3.5. Correlation between SST, Corals and Chlorophyll-A

The study analyzed the correlation between average coral area, sea surface temperature (SST), and chlorophyll-related indices (NDCI, CI, RECI) using Pearson correlation. The results revealed a weak negative correlation between coral area and SST (-0.270), indicating that higher SST is associated with reduced coral area, possibly due to the impacts of climate change. There were weak positive correlations between coral area and the chlorophyll indices (0.138–0.243), suggesting that healthier, nutrient-rich waters may support larger coral areas. SST exhibited minimal negative correlations with the chlorophyll indices, implying that other environmental or biological factors influence chlorophyll levels more significantly. Strong positive correlations among NDCI, CI, and RECI (0.92–0.99) highlighted the reliability of these indices for monitoring chlorophyll content. The findings underscore the complex interactions within coral ecosystems and emphasize the need for multi-faceted conservation strategies in the face of environmental changes.

3.6. Relevance with Land Governance

The study's findings on the correlations between sea surface temperature (SST), coral health, and chlorophyll indices highlight the critical role of land governance in coastal and island regions. Effective land governance, which includes managing coastal development, controlling deforestation, and minimizing agricultural runoff, is essential to protect coral reefs from sedimentation and nutrient pollution. Integrating land and marine spatial planning can help maintain coral resilience by enforcing regulations that protect coastal areas and preserve natural buffers. As climate change intensifies, land-based interventions, such as restoring coastal ecosystems and creating marine protected areas, must be coordinated with marine management to support coral reef conservation.

Remote sensing techniques offer a valuable tool for enhancing these governance efforts. These methods are cost-effective, scalable, and capable of providing real-time data on coral health, SST, and chlorophyll levels, making them ideal for monitoring vast and often inaccessible reef areas. Incorporating remote sensing into land governance strategies can lead to more informed decision-making and timely interventions, ultimately supporting the long-term sustainability of coral ecosystems and the communities that rely on them.Remote sensing techniques offer a promising tool for supporting these governance efforts. These techniques are effective, cost-efficient, and scalable, making them ideal for monitoring vast and often inaccessible coral reef areas. By utilizing satellite imagery and other remote sensing technologies, land and marine managers can obtain real-time data on coral health, SST, and chlorophyll levels, enabling more informed decision-making and timely interventions. Integrating remote sensing into land governance strategies can enhance the monitoring and management of coral ecosystems, contributing to their long-term sustainability.

4. CONCLUSION

This study underscores the intricate relationship between coral reef ecosystems, sea surface temperature (SST), and chlorophyll-a levels, emphasizing the importance of both land and marine governance in preserving these vital habitats. Coral reefs, which are crucial for marine biodiversity and provide significant economic and cultural benefits, are increasingly threatened by climate-induced phenomena such as rising SST and subsequent coral bleaching. The research highlights that effective land governance, including the management of coastal development and agricultural practices, is essential in mitigating the impact of sedimentation and nutrient pollution on coral reefs. Additionally, the study stresses the need for integrated land and marine spatial planning to enhance coral resilience and protect these ecosystems in the face of climate change.

Remote sensing techniques are identified as a key tool in these conservation efforts, offering a cost-effective and scalable method for monitoring coral health, SST, and chlorophyll-a concentrations across extensive reef areas. By incorporating remote sensing into land governance strategies, stakeholders can improve the accuracy and timeliness of their interventions, thereby supporting the long-term sustainability of coral ecosystems. The study concludes that a combination of technological innovation, interdisciplinary collaboration, and robust governance is crucial for the effective conservation and management of coral reefs, ensuring their continued contribution to marine biodiversity and human livelihoods.

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