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TEMPORAL ANALYSIS OF BIO-OPTICAL INDICATORS RELATED TO WATER QUALITY AT SEIXAS BEACH, NORTHEASTERN BRAZIL: AN EXPLORATORY STUDY USING SENTINEL-3 OLCI

ANÁLISE TEMPORAL DE INDICADORES BIO-ÓPTICOS RELACIONADOS À QUALIDADE DA ÁGUA NA PRAIA DO SEIXAS, NORDESTE DO BRASIL: UM ESTUDO EXPLORATÓRIO COM SENTINEL-3 OLCI

ANÁLISIS TEMPORAL DE INDICADORES BIOÓPTICOS RELACIONADOS CON LA CALIDAD DEL AGUA EN LA PLAYA DE SEIXAS, NORESTE DE BRASIL: UN ESTUDIO EXPLORATORIO CON SENTINEL-3 OLCI

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Abstract

This study investigates the temporal behavior of bio-optical parameters related to water quality at Seixas Beach, Paraíba, Brazil, using remote sensing data from the Ocean and Land Colour Instrument (OLCI) onboard Sentinel-3. The area is a shallow tropical coastal environment influenced by seasonal rainfall, estuarine discharge, and urban inputs, making it suitable for evaluating satellite-based monitoring in optically complex waters. The study assumes an exploratory character, focusing on the interannual variability of optical proxies between October 2016 and January 2020, a period chosen to represent conditions of lower rainfall and greater water column stability. Six indices were analyzed: Bottom Reflectance Index (BRI), Normalized Difference Chlorophyll Index (NDCI), Normalized Floating Algal/Harmful Algal Bloom Index (NFHI), Turbidity Index (TBI), Algal Carbon Index (ACI), and Sea Surface Temperature (SST). The results reveal consistent spatial gradients between nearshore and offshore zones. Statistical analysis indicated significant interannual differences for BRI and TBI, suggesting variations in apparent transparency and suspended particle influence. Given the absence of in situ data, the results are interpreted as indicative of changes in the region's optical regime. The study establishes a methodological baseline for using OLCI as a screening tool in monitoring tropical coastal environments in northeastern Brazil.

Keywords: Bio-optical indices; coastal monitoring; OLCI; remote sensing; water quality.

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Resumo

Este estudo investiga o comportamento temporal de parâmetros bio-ópticos relacionados à qualidade da água na Praia do Seixas, Paraíba, Brasil, utilizando dados de sensoriamento remoto do Ocean and Land Colour Instrument (OLCI) a bordo do Sentinel-3. A área é um ambiente costeiro raso e tropical, influenciado por chuvas sazonais, descargas estuarinas e aportes urbanos, o que a torna adequada para avaliar o monitoramento por satélite em águas opticamente complexas. O estudo assume um caráter exploratório, focando na variabilidade interanual de proxies ópticos entre outubro de 2016 e janeiro de 2020, período escolhido por representar condições de menor pluviosidade e maior estabilidade da coluna d'água. Seis índices foram analisados: Índice de Refletância de Fundo (BRI), Índice de Diferença Normalizada de Clorofila (NDCI), Índice Normalizado de Algas Flutuantes/Florações de Algas Nocivas (NFHI), Índice de Turbidez (TBI), Índice de Carbono Algal (ACI) e Temperatura da Superfície do Mar (SST). Os resultados revelam gradientes espaciais consistentes entre as zonas costeira e oceânica. A análise estatística indicou diferenças interanuais significativas para o BRI e o TBI, sugerindo variações na transparência aparente e na influência de partículas em suspensão. Dada a ausência de dados in situ, os resultados são interpretados como indicativos de mudanças no regime óptico da região. O estudo estabelece uma linha de base metodológica para o uso do OLCI como ferramenta de triagem no monitoramento de ambientes costeiros tropicais no nordeste brasileiro.

Palavras-chave: Índices bio-ópticos; monitoramento costeiro; OLCI; sensoriamento remoto; qualidade da água.

Resumen

Este estudio investiga el comportamiento temporal de parámetros bioópticos relacionados con la calidad del agua en la Playa de Seixas, Paraíba, Brasil, utilizando datos de teledetección del Ocean and Land Colour Instrument (OLCI) a bordo del Sentinel-3. El área es un ambiente costero tropical poco profundo influenciado por lluvias estacionales, descargas estuarinas y aportes urbanos, lo que la hace adecuada para evaluar el monitoreo por satélite en aguas ópticamente complejas. El estudio asume un carácter exploratorio, centrándose en la variabilidad interanual de proxies ópticos entre octubre de 2016 y enero de 2020, período elegido por representar condiciones de menor pluviosidad y mayor estabilidad de la columna de agua. Se analizaron seis índices: Índice de Reflectancia de Fondo (BRI), Índice de Diferencia Normalizada de Clorofila (NDCI), Índice Normalizado de Algas Flotantes/Floraciones de Algas Nocivas (NFHI), Índice de Turbidez (TBI), Índice de Carbono Algal (ACI) y Temperatura de la Superficie del Mar (SST). Los resultados revelan gradientes espaciales consistentes entre las zonas costera y oceánica. El análisis estadístico indicó diferencias interanuales significativas para el BRI y el TBI, sugiriendo variaciones en la transparencia aparente y en la influencia de partículas en suspensión. Dada la ausencia de datos in situ, los resultados se interpretan como indicativos de cambios en el régimen óptico de la región. El estudio establece una línea de base metodológica para el uso del OLCI como herramienta de detección en el monitoreo de ambientes costeros tropicales en el noreste brasileño.

Palabras clave: Índices bioópticos; monitoreo costero; OLCI; teledetección; calidad del agua.

1. Introduction

Coastal ecosystems are among the most productive and vulnerable components of the Earth system, as they are simultaneously exposed to climate variability, land-sea interactions, urbanization, river discharge, and nutrient enrichment (MATTHEWS; ODERMATT, 2015). These combined pressures can

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modify turbidity, phytoplankton biomass, water transparency, and thermal structure, often over short temporal scales and heterogeneous spatial gradients. For this reason, continuous monitoring of coastal waters is essential to detect ecological deterioration, support environmental management, and identify emerging risks, such as eutrophication and harmful algal blooms (LOPEZ BARRETO et al., 2024).

Traditional in situ monitoring remains indispensable, but its spatial and temporal coverage is frequently limited, especially in developing regions and dynamic coastal settings. Satellite remote sensing partially overcomes these limitations by providing repeated synoptic observations over large areas, allowing the reconstruction of spatial gradients and temporal trajectories of optically active water constituents (YAN et al., 2025).

Among the currently available sensors, the Ocean and Land Colour Instrument (OLCI) onboard Sentinel-3 has proven especially useful for water quality applications due to its spectral configuration, 300 m spatial resolution, and high revisit capacity (LAPUCCI et al., 2023). Recent studies have demonstrated that Sentinel-3 OLCI supports frequent monitoring of coastal water quality and ecological condition, even in optically complex waters where suspended sediments, colored dissolved organic matter, and phytoplankton jointly influence the spectral signal (SILVA et al., 2021).

However, the literature also emphasizes that interpretations based on remote sensing proxies in coastal waters must be made with caution. Algorithm performance can be affected by optical complexity, atmospheric correction uncertainties, and regional bio-optical variability (WINDLE et al., 2022). In particular, atmospheric correction in coastal waters is a significant challenge, as low Signal-to-Noise Ratio (SNR) levels over water and the presence of complex aerosols can introduce substantial errors into reflectance products (MACIEL et al., 2025).

This issue is particularly relevant in Brazil, a country containing highly diverse aquatic environments. Although important progress has been made in the remote sensing of Brazilian coastal waters, studies focusing on the northeast coast remain comparatively scarce (CESAR et al., 2023). Seixas Beach, located in João Pessoa,

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Paraíba, is a relevant site for this type of analysis. Besides being situated in a region with marked seasonal rainfall variability, the area is influenced by coastal circulation, estuarine inputs associated with the Sanhauá River system, shallow bottom effects, and nearby urban occupation (PEREIRA; CUNHA; VIEIRA, 2016).

Within this context, the objective of this work is to conduct an exploratory analysis of the spatial organization and interannual variability of OLCI-derived optical proxies related to water quality at Seixas Beach between October 2016 and January 2020. The study aims to establish a methodological baseline for using remote sensing as a screening tool in tropical coastal environments, recognizing the limitations inherent to the absence of concurrent in situ data.

2. Literature Review

The monitoring of optical proxies related to water quality in coastal zones through remote sensing has evolved significantly with the launch of new-generation sensors, such as the Sentinel-3 Ocean and Land Colour Instrument (OLCI). OLCI's ability to capture fine spectral details, especially in the red and near-infrared (NIR) bands, has been fundamental for the development of more robust bio-optical indices for coastal applications (Goellner et al., 2025). The selection of appropriate spectral indices is a critical step in studies of optically complex waters (Case 2).

The Normalized Difference Chlorophyll Index (NDCI) has been widely used as a relative proxy for chlorophyll-a concentration in turbid productive waters, leveraging the reflectance peak in the NIR associated with phytoplankton scattering (Mishra & Mishra, 2012). For assessing surface features, the Floating Algae Index (FAI) demonstrates sensitivity to the presence of floating algal biomass and macroalgae, with particular advantages in reducing variability from aerosols and environmental conditions (Hu, 2009).

Despite advancements, the application of these indices in tropical coastal waters faces significant challenges. The absence of in situ data for local calibration limits the ability to derive absolute concentrations of water quality constituents

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(Petiteau et al., 2025). Furthermore, atmospheric correction in coastal areas remains the most complex methodological challenge in ocean color remote sensing, especially due to the mixture of marine and continental aerosols, and the severe adjacency effects from nearby land that contaminate the water signal (Wang et al., 2021). As highlighted by recent reviews, strong absorption by colored dissolved organic matter (CDOM) in coastal waters can also negatively interfere with atmospheric correction schemes, leading to turbidity overestimations or chlorophyll underestimations (Lapucci et al., 2023).

Recently, the use of Sentinel-3 OLCI time series has proven to be a promising alternative to partially overcome these limitations. Studies in southern Brazil, such as in the Mirim-Patos-Mangueira coastal lagoon system, have demonstrated that integrated spatial and temporal approaches using OLCI data can capture water quality dynamics even in optically complex scenarios through optical water type classification and semi-empirical algorithms (Contreras Rojas et al., 2025). Therefore, studies in regions with a scarcity of continuous in situ data, such as the northeast coast of Brazil, should adopt an exploratory approach, using indices as robust relative indicators of spatial and temporal variability, recognizing that they reflect the apparent optical regime rather than isolated absolute concentrations (Salama & Stein, 2022; Goellner et al., 2025).

Turbidity and the presence of suspended particulate matter are frequently evaluated through red and NIR-band-based indices, such as the Turbidity Index (TBI), which correlates well with scattering by inorganic particles (MATOS et al., 2024). In shallow coastal environments, such as those at Seixas Beach, the bottom contribution cannot be ignored. The Bottom Reflectance Index (BRI) is utilized to assess the apparent reflectance of the water column, serving as an indirect indicator of relative transparency, although it is heavily influenced by bathymetry and benthic composition.

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limits the ability to derive absolute concentrations of water quality constituents (PETITEAU; VEA; RICHARDSON, 2025). Furthermore, atmospheric correction in coastal areas remains the most complex methodological challenge in ocean color remote sensing, especially due to the mixture of marine and continental aerosols, and the severe adjacency effects from nearby land that contaminate the water signal (WANG, 2021; KUDELA et al., 2005). As highlighted by Llodra-Llabres et al. (2023), strong absorption by colored dissolved organic matter (CDOM) in coastal waters can also negatively interfere with atmospheric correction schemes, leading to turbidity overestimations or chlorophyll underestimations.

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3. Methodology

3.1. Study Area and Spatial Analysis Units

3.1.1 Geographic Location

The study area encompasses the coastline of João Pessoa, Paraíba, Brazil (approximately 7°09’S, 34°47’W), focusing on Seixas Beach. This is a shallow tropical coastal zone characterized by coral reefs, seagrass beds, and the influence of the Sanhauá River estuary.

3.1.2. Seasonal Selection

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The analysis concentrated on four complete seasonal cycles spanning from October to January (2016–2017, 2017–2018, 2018–2019, and 2019–2020). The seasonal window from October to January was selected based on climatological data from João Pessoa, Paraíba (INMET, 2016–2020), which identifies this period as the driest season. This selection minimizes the influence of terrestrial discharge and maximizes water column stability, enabling clearer detection of optical patterns related to coastal processes and interannual variability.

3.1.3. Spatial Zones

For spatial analysis, the area was operationally divided based on distance from the coastline: - Nearshore zone: 0–600 m from the coast (approx. 2 pixels wide) - Midshore zone: 600–1200 m from the coast (approx. 2 pixels wide) - Offshore zone: >1200 m from the coast. This separation was based on expected gradients in sediment, CDOM, and freshwater influence. The primary sampling pixel for time series analysis was located at 7.155°S, 34.790°W.

Figure 1. Reference map of the study area at Seixas Beach, João Pessoa, Paraíba, Brazil. The red marker indicates the primary sampling pixel (7.155°S, 34.790°W). Rocky reef

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formations and turbid coastal waters characterize the coastal zone. Data period: October 2016 to January 2020. Spatial resolution: 300 m. Basemap source: Esri Imagery.

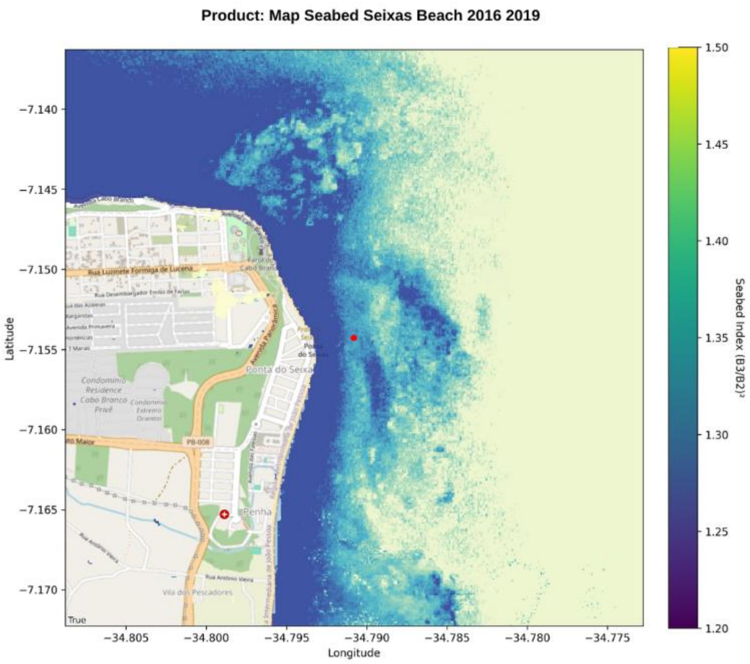

Figure 2. Seabed Index (S2) Map at Seixas Beach - Average from October 2016 to January 2020. Higher values (yellow/light green) indicate greater apparent clarity and bottom contribution, while lower values (dark blue) indicate greater water attenuation and lower bottom visibility. Data period: October 2016 to January 2020. Spatial resolution: 300 m. Data source: Sentinel-3 OLCI Level-2 Water Reflectance.

3.2. Data Processing and Quality Control

3.2.1. Data Source and Product Specifications

Data from the Sentinel-3A and Sentinel-3B OLCI sensors were utilized. The specific product used was the Level-2 Water Full Resolution (OL_2_WFR), processed with the standard ESA baseline. The spatial resolution is approximately 300 m at nadir. Sea Surface Temperature (SST) was derived from the Sea and Land Surface Temperature Radiometer (SLSTR) onboard the same satellites, using the Level-2 WST product.

3.2.2. Image Selection and Filtering

A total of 342 scenes were initially retrieved for the study period (October 2016 to January 2020). Following the application of quality masks, approximately 45% of

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the scenes were discarded due to extensive cloud cover, sunglint, or atmospheric correction failures, which are common in tropical coastal regions. An average of 47 valid scenes per seasonal window (October-January) were effectively used in the final analysis.

3.2.3. Quality Masks Applied

Pre-processing included the application of standard ESA quality flags (WQSF). Pixels were excluded if they met any of the following criteria: CLOUD, CLOUD_MARGIN, CLOUD_AMBIGUOUS, INVALID, COSMETIC, SATURATED, SUSPECT, HISOLZEN, HIGHGLINT, SNOW_ICE, or AC_FAIL. Additionally, pixels with negative reflectance values in the visible bands were removed to mitigate sensor artifacts.

3.3. Bio-Optical Indices

Six spectral indicators (Fig.3) were calculated to serve as proxies for different aspects of the coastal optical regime. Table 1 details the formulas, bands, and interpretations for each index.

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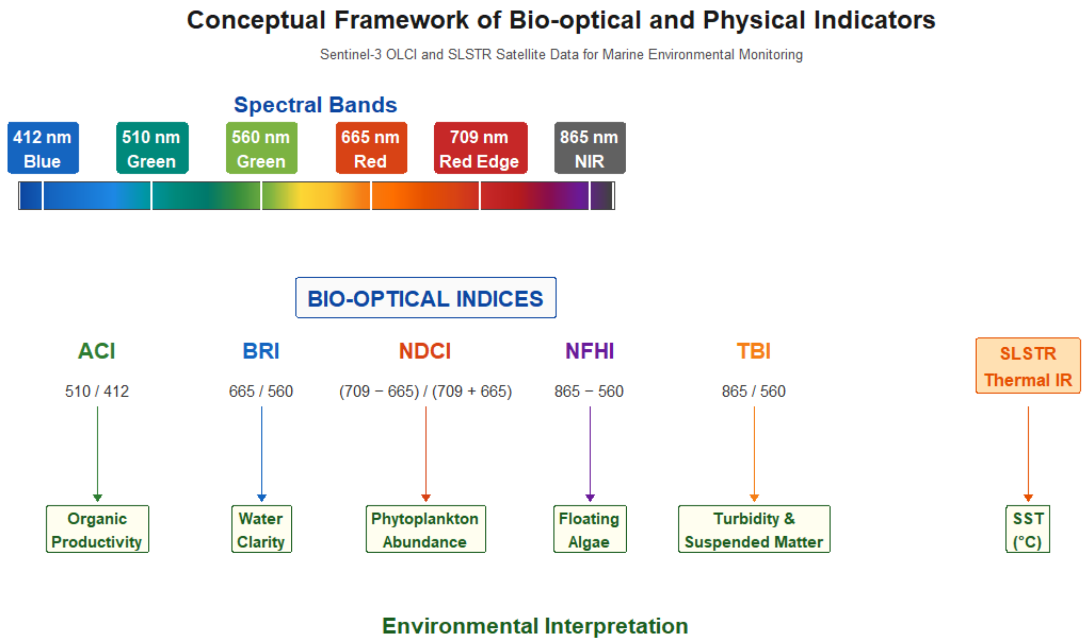

Figure 3. Conceptual framework of the bio-optical and physical indicators used in this study. The figure shows the Sentinel-3 spectral bands used to derive the Algal Carbon Index (ACI), Bottom Reflectance Index (BRI), Normalized Difference Chlorophyll Index (NDCI), Normalized Floating Algal Index (NFHI), Turbidity Index (TBI), and Sea Surface Temperature (SST), along with their corresponding environmental interpretations.

Table 1. Bio-Optical Indices Specifications

Index	Formula / Bands Used	Units	Environmental Interpretation	Principal Limitation
BRI (Bottom Reflectance Index)	Rrs(665) / Rrs(560)	Dimensionless	Proxy for apparent water clarity and bottom contribution	Strongly affected by depth, substrate, and tidal state
NDCI (Normalized Difference Chlorophyll Index)	[Rrs(709) - Rrs(665)] / [Rrs(709) + Rrs(665)]	Dimensionless	Proxy for relative phytoplankton concentration	Interference from CDOM and suspended sediments
NFHI (Normalized Floating Algal Index)	Rrs(865) - [Rrs(665) + (Rrs(865) - Rrs(665)) * ((865-665)/(865-665))]	Dimensionless	Indicator of surface algal biomass features	Sensitive to atmospheric correction errors in NIR
TBI (Turbidity Index)	Rrs(865) / Rrs(560)	Dimensionless	Proxy for suspended particulate matter	Influenced by bottom reflectance in shallow areas

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ACI (Algal Carbon Index)	Rrs(510) / Rrs(412)	Dimensionless	Indicator of organic productivity	Highly sensitive to CDOM absorption
SST (Sea Surface Temperature)	SLSTR Level-2 WST product	°C	Physical driver associated with water column processes	Skin temperature only, influenced by diurnal warming

3.4. Spatial and Statistical Analysis

Seasonal mean maps were generated to evaluate the spatial structure and identify persistent coast-ocean gradients. The statistical analysis focused on interannual variability within the October to January windows. Given the non-normality of the data, the non-parametric Kruskal-Wallis test (significance level $\alpha = 0.05$) was used to assess differences between the four seasonal periods. Multiple comparison correction was applied using Bonferroni adjustment ($\alpha\_corrected = 0.05/15 = 0.0033$ for 15 pairwise comparisons among 4 periods). Post-hoc pairwise comparisons were conducted using Dunn's test.

Although the short temporal window (4 seasonal cycles) is insufficient for detecting long-term biogeochemical trends, we conducted exploratory ordinary least squares (OLS) linear regression to examine short-term patterns within the observation period. This analysis is presented for completeness but should not be interpreted as evidence of sustained directional change.

4. Results and Discussion

4.1 Spatial and Temporal Variability

The spatial distributions of the six indices revealed patterns consistent with the coastal geomorphology and hydrodynamics of the surf zone. The coastal strip consistently exhibited higher TBI values and lower BRI values compared to oceanic areas. This pattern is compatible with a greater influence of suspended sediments, strong light attenuation, and reduced apparent bottom visibility in shallow coastal waters, a typical behavior of environments subjected to estuarine forcings and wind resuspension (CESAR et al., 2023). Conversely, oceanic waters showed lower turbidity and greater apparent clarity. These gradients confirm that, even without in

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situ calibration, Sentinel-3 OLCI-based indices can qualitatively delineate coastal and oceanic water masses in the region, corroborating the observations of Contreras et al. (2025) for other Brazilian coastal systems.

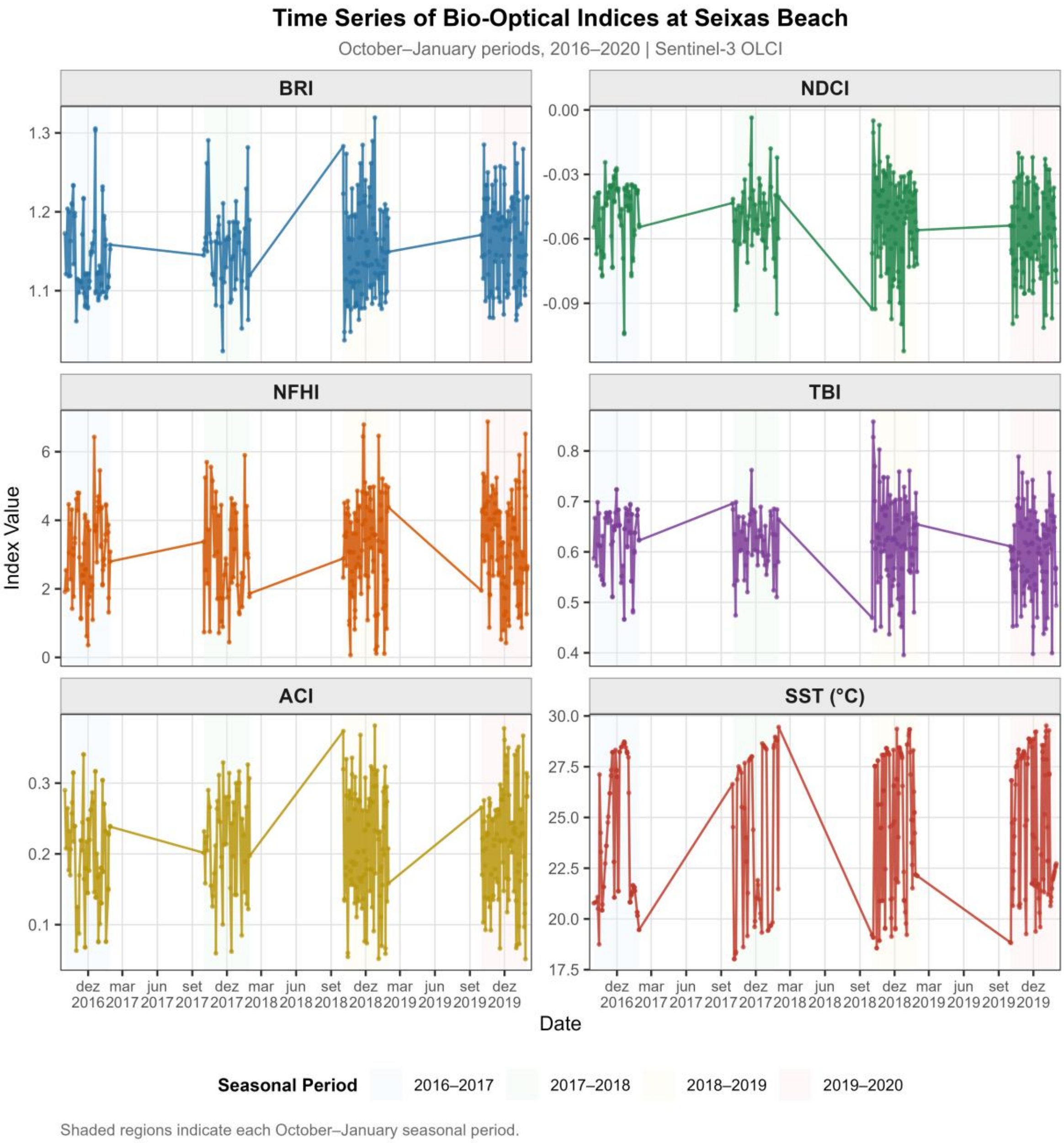

Figure 4. Time series of the six bio-optical indices at Seixas Beach during the October-January periods from 2016 to 2020. Shaded regions indicate each October-January seasonal period. Solid lines represent smoothed trends for visualization. Data period: October 2016 to January 2020. Units: Dimensionless (except SST in °C).

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4.2 Interannual Variability and Exploratory Trends

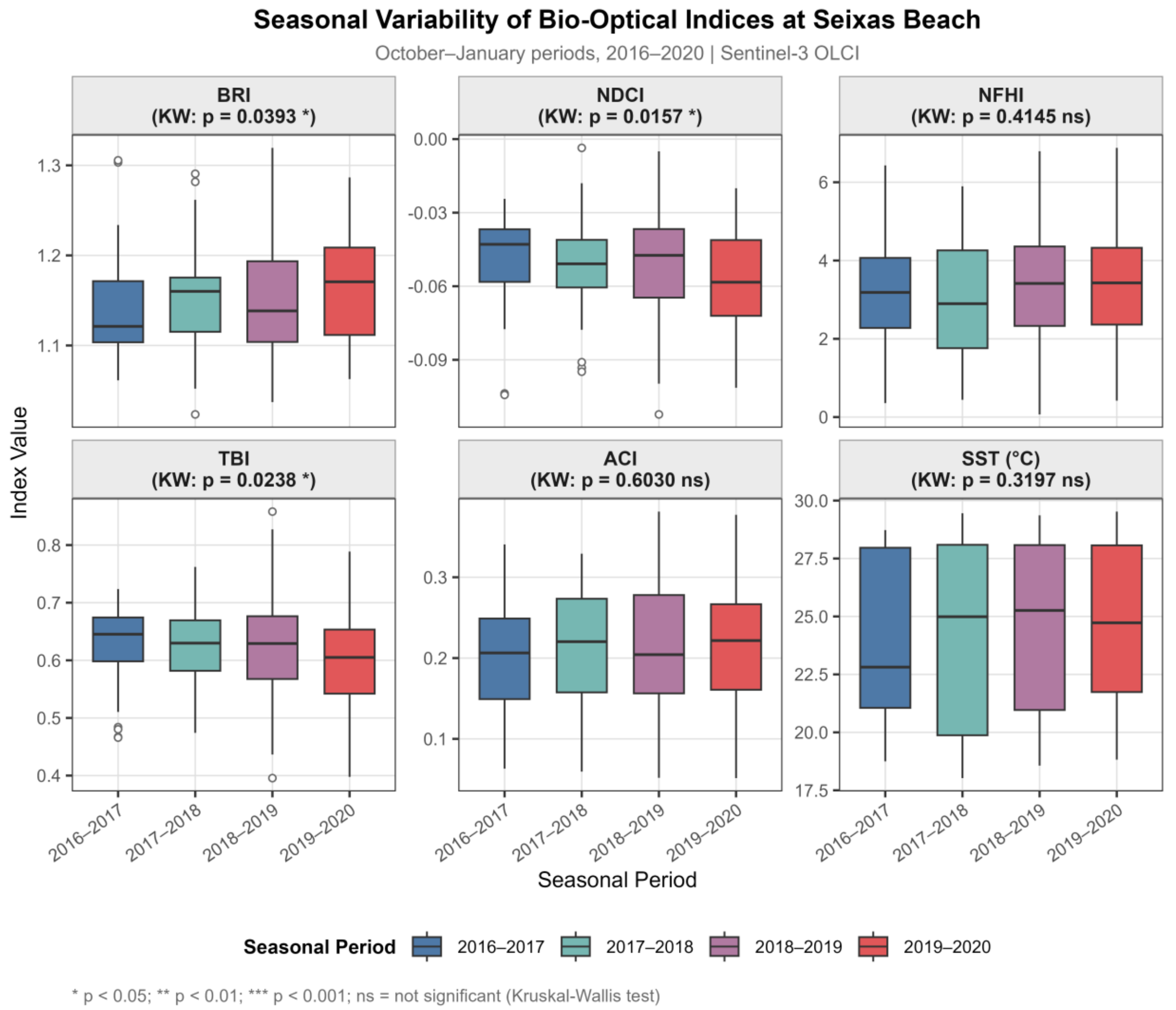

Figure 5. Comparative boxplots of the six bio-optical indices across the four October-January seasonal periods (2016-2017, 2017-2018, 2018-2019, 2019-2020). Kruskal-Wallis test p-values are presented in each panel. Asterisks indicate statistical significance: * $p < 0.05$; ns = not significant. Data period: October 2016 to January 2020.

The descriptive statistics and results of the Kruskal-Wallis tests are detailed in Table 2. The interannual variability analysis revealed statistically significant differences for BRI ($H = 8.34$, $p = 0.0393$) and TBI ($H = 9.45$, $p = 0.0238$) over the four analyzed periods. Post-hoc Dunn tests indicated that the most significant differences occurred between the 2016-2017 and 2019-2020 periods.

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Table 2. Descriptive Statistics and Kruskal-Wallis Test Results for Bio-Optical Indices

Index	Period	n	Median	IQR	Min-Max	K-W Test (H, p-value)
BRI	2016-17	45	1.12	0.06	1.06-1.31	H=8.34, p=0.0393*
	2017-18	48	1.16	0.06	1.02-1.29	
	2018-19	46	1.14	0.09	1.04-1.33	
	2019-20	49	1.17	0.10	1.06-1.29	
TBI	2016-17	45	0.65	0.08	0.46-0.73	H=9.45, p=0.0238*
	2017-18	48	0.63	0.09	0.47-0.76	
	2018-19	46	0.63	0.11	0.39-0.84	
	2019-20	49	0.61	0.11	0.40-0.79	

(Note: NDCI, NFHI, ACI, and SST did not show statistically significant differences across the periods, p > 0.05).

An exploratory short-term increasing trend in BRI and a corresponding decrease in TBI were observed during the analyzed period (Figure 5). This joint behavior is physically plausible, as a lower influence of suspended particles tends to reduce attenuation and increase the apparent contribution of bottom reflectance in shallow areas. The observed variability may be linked to fluctuations in interannual precipitation and consequent changes in terrigenous sediment input from the Sanhauá River system, a well-documented controlling factor for coastal water optics in Northeastern Brazil (PEREIRA; CUNHA; VIEIRA, 2016).

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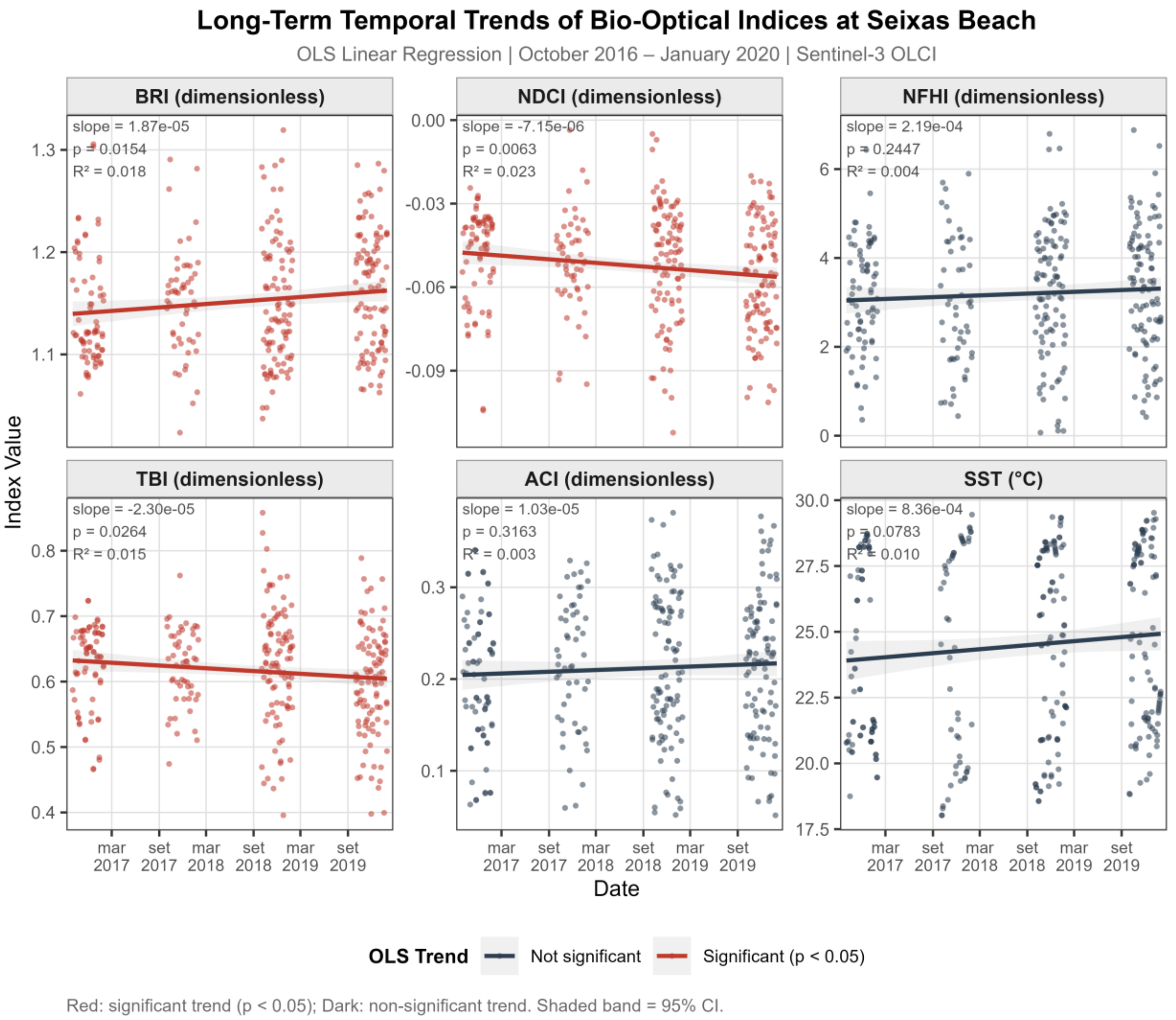

Figure 6. Exploratory Short-Term Trends of the six bio-optical indices at Seixas Beach from October 2016 to January 2020, using ordinary least squares (OLS) linear regression. Note: Due to the limited temporal window (4 seasonal cycles), these trends should be interpreted as short-term patterns and NOT as long-term biogeochemical trends. Red lines indicate significant trends ($p < 0.05$), while dark lines indicate non-significant trends. The shaded band represents the 95% confidence interval.

However, given the absence of a concurrent in situ dataset for local validation, these interpretations must be made with caution. In shallow coral reef and seagrass environments, the Bottom Reflectance Index (BRI) is particularly sensitive to substrate composition, water depth, and tidal state. Variations in BRI should not be interpreted as direct measures of water transparency but rather as changes in apparent bottom contribution, which is influenced by multiple factors including actual transparency, bathymetry, benthic composition, and subpixel mixing. The 300 m

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OLCI pixel size may integrate contributions from both water and substrate, particularly in the nearshore zone. Table 3 summarizes the cautious interpretations and potential confounding factors for the analyzed indices.

Table 3. Bio-Optical Indices: Interpretations and Sources of Uncertainty.

Index	Observation	Cautious Interpretation	Potential Confounding Factors
BRI	Increase	Higher apparent bottom contribution, compatible with greater relative transparency	Water depth, tidal state, benthic composition, solar-sensor geometry, adjacency effects
TBI	Decrease	Lower reflectance in NIR, compatible with lower apparent concentration of suspended sediments	Lower terrigenous input, deposition, changes in sediment composition, bottom influence
NDCI	Variation	Changes in relative absorption in red vs. green, compatible with apparent phytoplankton variations	Presence of CDOM, detritus, suspended sediments, atmospheric correction errors

The seasonal differences identified here are best understood as robust remote sensing evidence of changes in optical water conditions, rather than direct measurements of constituent concentrations.

The absence of significant trends in NFHI, ACI, and SST suggests relative stability of these indicators or limited sensitivity of the available time series to detect subtle changes. The short study period reinforces the need for longer observations to resolve slower biogeochemical trends. Furthermore, as pointed out by Maciel et al. (2025), the bio-optical complexity of Brazilian waters requires the development of specific regional algorithms to mitigate uncertainties in retrieving parameters such as algal carbon and phytoplankton biomass.

Despite these limitations, the results demonstrate that, even in a shallow and tropical coastal sector influenced by estuarine discharges and urban pressure, OLCI time series can resolve significant spatial gradients and consistent temporal fluctuations. The exploratory approach based on relative indices proved to be a viable strategy to circumvent the challenges of severe atmospheric correction and the lack

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of in situ calibration that frequently limit remote sensing in Case 2 waters (WANG, 2021).

5. Study Limitations

This study faces several important limitations that must be acknowledged when interpreting the results. First and foremost, the absence of concurrent in situ measurements represents a fundamental constraint. Without field-based radiometric data, water quality samples, or optical measurements, we cannot perform quantitative validation or calibration of the satellite-derived indices. This limitation means that the indices should be interpreted as relative indicators of optical regime changes rather than absolute measurements of water constituents. The results reflect the apparent optical properties as detected by the satellite sensor, which may be influenced by multiple confounding factors including atmospheric aerosols, adjacency effects from nearby land, and the complex bio-optical properties of Case 2 waters (LLODRA-LLABRES et al., 2023).

Second, the restricted temporal window (October to January only) and the short analysis period (2016-2020, representing only 4 complete seasonal cycles) limit our ability to detect long-term trends or to account for multi-year climate oscillations. A 3-year observation period is insufficient to distinguish between natural variability and systematic trends in coastal water properties. Longer time series, ideally spanning 10-20 years, would be necessary to resolve decadal-scale changes and to separate seasonal patterns from interannual and longer-term signals (PETITEAU; VEA; RICHARDSON, 2025).

Third, the spatial resolution limitation (300 m pixels) may be inadequate for resolving fine-scale coastal processes, particularly in the immediate nearshore zone where rapid transitions between water masses occur. Additionally, the cloud cover and atmospheric conditions inherent to tropical regions can result in frequent data gaps, reducing the effective temporal resolution of the time series and potentially introducing sampling biases.

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Fourth, the atmospheric correction uncertainty remains a critical source of error in coastal remote sensing (WANG, 2021). The standard ESA Level-2 products use global atmospheric correction algorithms that may not be optimized for the specific aerosol characteristics and adjacency effects present at Seixas Beach. The presence of strong colored dissolved organic matter (CDOM) absorption in these tropical coastal waters can interfere with atmospheric correction schemes, potentially leading to systematic biases in the derived indices (MACIEL et al., 2025).

Finally, the bio-optical complexity of the study area introduces ambiguity in the interpretation of spectral indices. Changes in a single index may result from multiple confounding factors (for example, a decrease in TBI could reflect either reduced sediment input or increased CDOM absorption) making it difficult to attribute observed variations to specific physical or biological drivers without independent validation data.

Despite these limitations, the exploratory approach adopted here provides a methodological framework and establishes a baseline for future monitoring efforts. The study demonstrates that satellite-based indices can detect coherent spatial and temporal patterns in coastal optical properties, even under challenging conditions. Future research should prioritize the collection of concurrent in situ data to enable quantitative validation and the development of region-specific algorithms tailored to the bio-optical characteristics of northeastern Brazilian coastal waters.

6. Conclusion

This exploratory study established a methodological baseline for monitoring optical proxies related to water quality using Sentinel-3 OLCI time series data at Seixas Beach, northeastern Brazil. While the analysis demonstrates that satellite-derived optical indices can detect spatial and interannual patterns in coastal optical conditions, the absence of concurrent in situ validation limits our ability to make quantitative inferences about water quality constituents. The study should be viewed as a preliminary screening tool for identifying areas and periods of interest for future

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field-based investigations, rather than as an operational water quality monitoring system.

The integration of spatial mapping with seasonal comparison revealed a coherent pattern characterized by coast-ocean gradients and significant interannual variations in indices related to apparent turbidity (TBI) and bottom reflectance (BRI).

Future research should prioritize: 1. Integration of concurrent in situ measurements of turbidity, chlorophyll-a, CDOM, and suspended solids to validate the satellite proxies. 2. Development of region-specific atmospheric correction algorithms optimized for the bio-optical characteristics of northeastern Brazilian coastal waters. 3. Extension of the time series to 10–20 years to resolve decadal-scale biogeochemical trends. 4. Incorporation of auxiliary hydrodynamic data (precipitation, wind, tidal state, discharge) to contextualize optical variations. 5. Validation of spatial patterns using high-resolution hyperspectral data or airborne surveys.

Data Availability Statement

The Sentinel-3 OLCI and SLSTR data used in this study are openly available through the Copernicus Open Access Hub. The processed data and scripts supporting the findings of this study are available from the corresponding author upon reasonable request.

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