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THE RELATION BETWEEN THE PHYSICAL AND CHEMICAL CONDITIONS OF WATERS AND THE PRESENCE OF WHALE SHARKS (*Rhincodon typus*) IN THE BOTUBARANI TOURISM AREA, GORONTALO

Keterkaitan Kondisi Fisika Kimia Perairan dengan Keberadaan Hiu Paus (*Rhincodon typus*) di Kawasan Wisata Botubarani, Gorontalo

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ABSTRACT

Whale sharks (*Rhincodon typus*) exhibit consistent seasonal aggregation in the Botubarani tourism area, Gorontalo, yet the local physicochemical mechanisms governing their occurrence remain poorly quantified. This study aimed to characterize water physicochemical conditions and identify the environmental parameters most strongly associated with whale shark presence at the coastal microhabitat scale. Data were collected across three stations at Botubarani Station III using a water quality meter, Secchi disk, and spectrophotometric nutrient analysis, then analyzed through Pearson correlation, Principal Component Analysis (PCA), and Redundancy Analysis (RDA). Correlation results revealed organized parameter interactions, with strong positive correlations for temperature–salinity ($r = 0.78$), nitrate–phosphate ($r = 0.84$), and water clarity–dissolved oxygen ($r = 0.65$). PCA resolved two dominant environmental gradients: a physical water-mass gradient (PC1, ~71.4%) and a nutrient gradient (PC2, ~28.6%). RDA cumulatively explained ~69.9% of whale shark distribution variance, identifying temperature, dissolved oxygen, and water clarity as primary positive determinants, while turbidity and nutrients exhibited negative associations. These findings support a bio-physical coupling framework, demonstrating that microscale physicochemical variability mediates trophic dynamics and habitat use by R. typus in semi-enclosed tropical coastal systems. Results provide a quantitative baseline for environment-based monitoring strategies in whale shark conservation management at Botubarani.

Keywords: Botubarani, PCA, RDA, *Rhincodon typus*, water physicochemistry

ABSTRAK

Hiu paus (*Rhincodon typus*) menunjukkan pola agregasi musiman secara konsisten di kawasan wisata Botubarani, Gorontalo, namun mekanisme lingkungan lokal yang mengontrol

keberadaannya belum dikaji secara kuantitatif. Penelitian ini bertujuan menganalisis karakteristik fisika-kimia perairan serta mengidentifikasi parameter lingkungan yang paling berkontribusi terhadap keberadaan hiu paus pada skala pesisir. Pengambilan data dilakukan pada tiga stasiun di Pangkalan III Hiu Paus menggunakan *water quality meter*, *Secchi disk*, dan analisis nutrien spektrofotometrik. Data dianalisis menggunakan korelasi Pearson, *Principal Component Analysis* (PCA), dan *Redundancy Analysis* (RDA). Hasil korelasi menunjukkan interaksi antarparameter yang terorganisasi, dengan korelasi positif kuat antara suhu–salinitas ($r = 0{,}78$), nitrat–fosfat ($r = 0{,}84$), dan kecerahan–oksigen terlarut ($r = 0{,}65$). PCA mengidentifikasi dua gradien dominan: gradien fisik massa air (PC1, ~71,4%) dan gradien nutrien (PC2, ~28,6%). Analisis RDA menghasilkan eksplanasi kumulatif ~69,9% variasi distribusi hiu paus, dengan suhu, oksigen terlarut, dan kecerahan sebagai determinan lingkungan utama yang berasosiasi positif, sedangkan kekeruhan dan nutrien menunjukkan asosiasi negatif. Temuan ini mendukung kerangka *bio-physical coupling* dan memberikan dasar ilmiah untuk strategi pemantauan lingkungan berbasis parameter terukur dalam pengelolaan kawasan konservasi hiu paus di Botubarani.

Kata kunci: Botubarani, fisika-kimia perairan, PCA, RDA, *Rhincodon typus*

INTRODUCTION

The whale shark (Rhincodon typus) is the world's largest fish and one of the most widely distributed pelagic species across tropical and subtropical waters. As an elasmobranch characterized by slow growth and late sexual maturity, this species is highly vulnerable to anthropogenic pressures and is currently classified as globally threatened. Nevertheless, whale sharks exhibit relatively consistent seasonal aggregation patterns in various coastal and oceanic regions, particularly in areas characterized by high productivity and active oceanographic dynamics.

Theoretically, whale shark distribution is understood within the framework of bio-physical coupling, wherein physical water variability mediates trophic dynamics that ultimately determine habitat use. At regional to mesoscale levels, the species' presence correlates with sea surface temperature and chlorophyll-a concentrations, with the influence varying according to latitudinal gradients and regional contexts (Flores et al., 2025). Tracking and habitat modeling studies indicate that foraging behavior occurs under conditions of high productivity and current dynamics that facilitate the accumulation of planktonic prey (Guzman et al., 2022). Beyond their role as planktivores, whale sharks demonstrate dietary flexibility by exploiting schools of small fish when zooplankton availability declines (Cárdenas-Palomo et al., 2025). Integrating *in situ* measurements of three-dimensional movement and prey density further reveals that horizontal space use by whale sharks correlates with high-density zooplankton areas shaped by the interaction of bathymetric features and local bio-physical processes (Antonio et al., 2024). Overall, this evidence confirms that physical water variability acts as a primary mediator between water column structure and trophic dynamics.

Responses to environmental dynamics are reflected not only in spatial distribution but also in the species' biological characteristics. Variations in epidermal microbiome composition linked to aggregation sites suggest that local environmental conditions can shape the biological responses of whale sharks (Doane et al., 2023), while longitudinal studies indicate sensitivity to changing habitat conditions and variations in space use (Gallimore et al., 2024). In the context of global anthropogenic pressures, analyses of satellite tracking and vessel traffic data reveal that a significant portion of whale shark horizontal space use overlaps with major shipping lanes, with estimated collision risks correlating with reported mortality (Womersley et al.,

2022). These findings indicate that environmental factors and human pressures act simultaneously to shape the population dynamics of this species.

Although the relationship between oceanographic variables and whale shark distribution has been extensively studied at regional and mesoscales, most research still relies on satellite data or large-scale surveys. While such approaches are effective for identifying regional aggregation patterns, they offer limited insight into how physicochemical water variability at the microhabitat scale influences the probability of whale shark occurrence in semi-enclosed coastal systems subject to intense anthropogenic activity. Consequently, a conceptual gap exists between large-scale oceanographic processes and the local environmental mechanisms directly experienced by individual animals.

This gap is also evident in the Brazilian context, where, despite the relatively wide distribution of whale sharks, ecological information remains limited and largely based on opportunistic records (Werner et al., 2025). In Indonesia, studies in the waters of Kwatisore indicate that surface temperature, salinity, pH, and water clarity contribute differently to the frequency of individual sightings (Maruanaya, 2024). At the local scale of Botubarani, PCA-based analysis shows that surface currents and chlorophyll-a concentrations play a significant role in whale shark occurrence (Tambunan et al., 2026). However, quantitative assessments directly linking in situ physicochemical parameters—such as temperature, salinity, pH, dissolved oxygen, nutrients, and clarity—to the probability of whale shark presence at the microhabitat scale remain limited.

The Botubarani tourism area in Gorontalo represents a unique shallow coastal system where whale shark sightings occur in close proximity to the shoreline, directly interacting with both fishing and tourism activities. Unlike classic aggregation sites associated with oceanic upwelling or productive reefs, this system constitutes a semi-enclosed coastal environment characterized by complex local dynamics. Consequently, Botubarani offers an ideal empirical setting to examine the extent to which micro-scale physicochemical variability mediates the relationships between water column structure, prey availability, and whale shark habitat use.

A quantitative understanding of these relationships is crucial—not only for elucidating local ecological mechanisms but also for bridging the analytical gap between regional oceanographic processes and individual-level habitat responses within an anthropogenically stressed coastal landscape. Without an approach grounded in measurable environmental data, management strategies risk being merely descriptive and lacking the adaptability needed to address environmental variability and climate change. Therefore, this study aims to analyze the physicochemical characteristics of the waters in the Botubarani tourism area; examine the relationships between key environmental parameters—including temperature, salinity, pH, water clarity, dissolved oxygen, and nutrients—and the presence of whale sharks; and identify the environmental variables that contribute most significantly to explaining the species' occurrence patterns at a coastal scale. Theoretically, this study tests the hypothesis that micro-scale physicochemical variability in the water acts as a mediator between local oceanographic dynamics and the trophic structure that determines habitat use by Rhincodon typus in a semi-enclosed tropical coastal system.

RESEARCH METHODS

Place and Time

This study was conducted in the waters of Botubarani, Kabila Bone District, Bone Bolango Regency, Gorontalo Province, specifically at the Whale Shark Station III area. Field data collection took place on November 9, 2025, between 08:00 and 13:00 WITA. This location was selected because it is an active marine tourism area that consistently serves as an aggregation habitat for whale sharks (Rhincodon typus), making it a representative site for

examining the relationship between physicochemical water conditions and the presence of the species. Data collection was carried out at three observation stations determined based on the spatial characteristics of the study site. The geographic position of each station was determined and recorded using a Global Positioning System (GPS) to ensure locational accuracy and facilitate consistent sampling across replicates (Ojo et al., 2021), with the following coordinates: Station 1 (0°28'26.1"N, 123°06'00.8"E), Station 2 (0°28'26.2"N, 123°05'57.9"E), and Station 3 (0°28'28.7"N, 123°05'58.3"E). These three stations were chosen to represent the spatial gradient of water conditions, ranging from the nearshore zone to more open waters.

Tools and Materials

The equipment and materials used in this study are listed in the table below.

Table 1. Research equipment and materials

No	Tools and Materials	Function
1	Thermometer	Measuring water temperature directly at the research site
2	Water quality meter	Measuring physicochemical parameters of the water, including temperature, pH, dissolved oxygen (DO), and salinity
3	Secchi disk	Measuring water clarity
4	Sample bottle	Collecting and storing water samples for laboratory analysis
5	Niskin bottle	Collecting water samples at a specific depth
6	Spektrofotometer	Analyzing nutrient concentrations such as nitrate and phosphate
7	Laboratory glassware	Supports chemical analysis processes (measurement, mixing, and sample preparation)
8	Underwater camera	Documenting and observing the presence of Rhincodon typus
9	GPS (Global Positioning System)	Determining and recording the coordinates of the observation site

Procedures

Field oceanographic data collection was conducted through a series of *in situ* measurements of physicochemical water parameters at predetermined sampling points. The geographic coordinates of each sampling point were recorded using a GPS device after allowing the satellite signal to stabilize; the latitude and longitude values were then noted and saved as waypoints to ensure locational consistency during repeated measurements.

Tidal observations were carried out by vertically installing a graduated scale (staff gauge) in the coastal zone that becomes submerged during high tide, ensuring the scale remained visually readable from the observation point. Water levels against the scale were recorded at 30-minute intervals over a period of at least 12–24 hours to obtain a representative tidal pattern, which was subsequently processed into a water-level fluctuation graph.

Salinity measurements were performed using a salinometer; water samples were collected in sampling bottles, and the instrument's sensor was either immersed in the sample or the sample was dripped onto the sensor, depending on the specific device's specifications. Salinity values were recorded once the display reading stabilized—measured in PSU or ppt—and the instrument was rinsed with fresh water after each use to prevent cross-contamination between stations. Measurements of temperature, total dissolved solids (TDS), and dissolved oxygen (DO) were conducted simultaneously using a TDS/DO meter that had been calibrated according to standard procedures. The sensor was submerged to the predetermined measurement depth

and allowed to stabilize before data recording, and the sensor was cleaned after each measurement session to maintain instrument accuracy.

Water pH was measured using a pH meter calibrated with standard buffer solutions prior to use. The sensor electrode was immersed directly into the water sample or the water column at the measurement site until the reading stabilized, and the sensor was rinsed with fresh water after each measurement. Water clarity was measured using a Secchi disk, which was lowered vertically and slowly into the water column until it was no longer visible to the observer; this depth was recorded as D_1. The disk was then slowly raised until it became visible again, and that depth was recorded as D_2. The clarity value was calculated as the average of D_1 and D_2 [$(D_1 + D_2)/2$] and expressed in meters. Current speed and direction were measured using a current drogue, which was lowered to the target depth with a weight and allowed to drift with the current for a specific interval (5–10 minutes). The distance and direction of the device's movement were recorded using GPS and a compass, and the current speed was calculated based on the ratio of the distance traveled to the elapsed time.

All field measurement data were systematically recorded on water-resistant underwater paper, including parameter values, location coordinates, and supporting information such as the date, time, weather conditions, and water conditions at the time of data collection. Following the completion of field activities, all field records were transcribed into a structured digital data sheet to ensure data completeness and traceability.

Data Analysis

This study employed a descriptive-correlational survey design based on field observations (non-experimental), involving no variable manipulation but rather the *in situ* measurement of physicochemical water conditions at three observation stations to statistically analyze their relationship with the presence of *Rhincodon typus*. The obtained data were subjected to multivariate statistical analysis to identify interaction patterns and interrelationships among environmental variables, as well as their association with the distribution of the target species. Pearson correlation analysis was used to quantify the strength and direction of relationships between physicochemical parameters, utilizing correlation coefficient (r) values and significance levels (p) as the basis for interpretation. Principal Component Analysis (PCA) was applied to reduce multivariate data dimensionality and identify dominant environmental gradients explaining the majority of the variability in water conditions. Subsequently, Redundancy Analysis (RDA)—a constrained analysis approach—was used to quantify the proportion of variation in whale shark distribution directly explained by the combination of measured physicochemical water parameters. All statistical analyses were conducted at a 95% confidence level ($\alpha = 0.05$).

RESULT

Correlation Among Physicochemical Parameters of Water Bodies

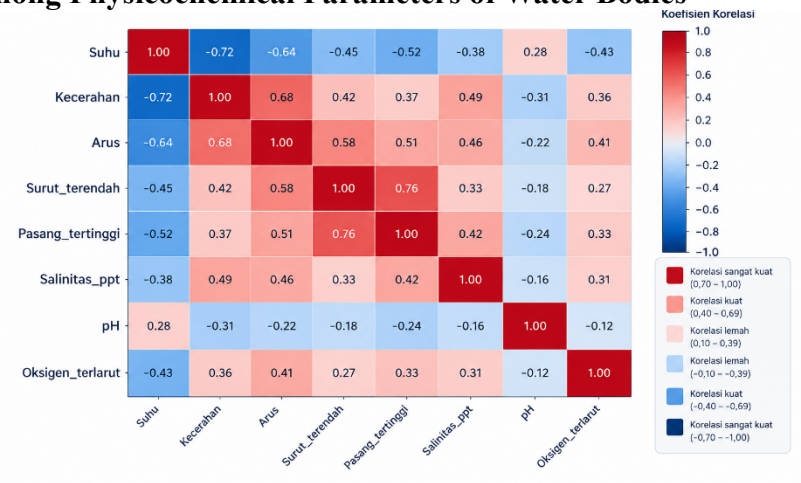

Figure 1. Correlation matrix of physicochemical water parameters in the Botubarani tourism area, Gorontalo

Analysis of the Variability Structure of Physicochemical Parameters in Waters

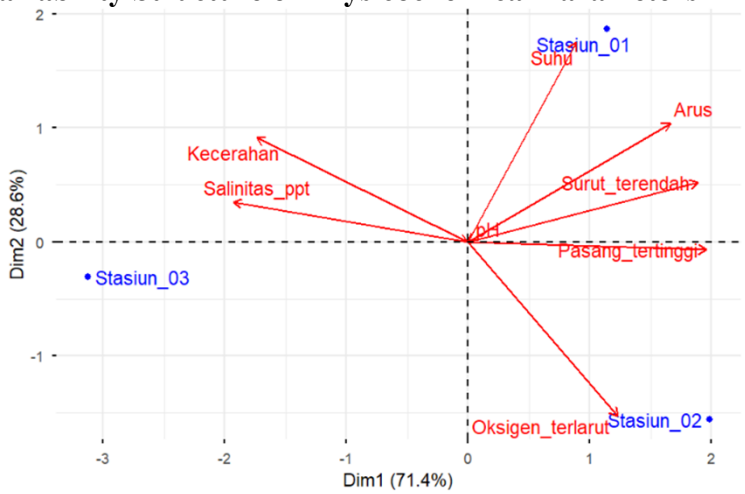

Figure 2. Principal Component Analysis (PCA) biplot illustrating the variability structure of physicochemical water parameters in the Botubarani tourism area, Gorontalo

Relationship between Aquatic Physicochemical Parameters and Biota Occurrence Based on RDA Analysis

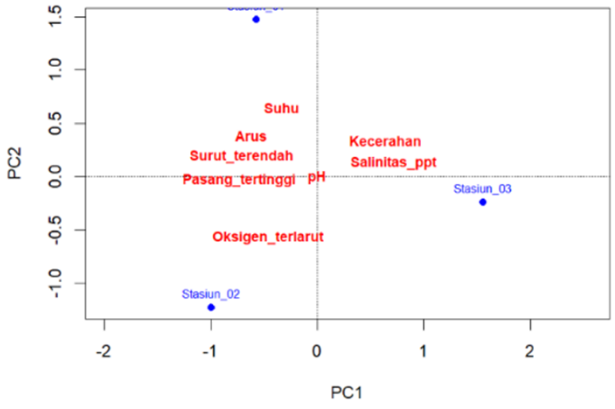

Figure 3. Redundancy Analysis (RDA) biplot showing the relationship between physicochemical water parameters and the presence of Rhincodon typus in the Botubarani tourism area, Gorontalo

DISCUSSION

Correlation matrix analysis (Figure 1) reveals that the physicochemical parameters of the waters in the Botubarani tourism area form an organized system of interactions (r = 0.21–0.87), reflecting the complex physical and biogeochemical processes of a semi-enclosed coastal ecosystem. A significant positive correlation between temperature and salinity (r = 0.78; $p < 0.05$) indicates the dominant influence of water mass dynamics in simultaneously controlling both parameters. Variations in temperature and salinity in tropical coastal waters are generally driven by a combination of freshwater input, evaporation, and water mass exchange with the open ocean (Richardson et al., 2025); semi-enclosed systems like Botubarani are specifically influenced by tidal dynamics and surface runoff, which jointly shape local water mass characteristics (Laignel et al., 2023).

A very strong positive correlation between nitrate and phosphate (r = 0.84; $p < 0.01$) suggests a uniform mechanism of nutrient enrichment; the synchronized fluctuation of both parameters implies a common source, whether through organic matter decomposition or allochthonous input from land. Increased inorganic nutrient loading via terrestrial runoff is a primary driver of eutrophication in coastal ecosystems adjacent to inhabited and economically active areas (Rulli et al., 2025), while watershed characteristics are known to drive nutrient dynamics to an extent that surpasses the influence of internal water-column regeneration (Shirina et al., 2025). The positive correlation between transparency and dissolved oxygen (r = 0.65; $p < 0.05$) reflects the functional link between light penetration and biological productivity, wherein adequate light intensity is a primary factor controlling the rate of phytoplankton photosynthesis, which contributes to dissolved oxygen production as a product of photosynthetic metabolism (Hader and Gao 2023).

Conversely, significant negative correlations were identified between three pairs of parameters, reflecting distinct ecological mechanisms. The negative correlation between temperature and dissolved oxygen (r = -0.72; $p < 0.05$) manifests a fundamental physicochemical principle: oxygen solubility decreases as temperature rises, as described by Henry's law constant (Bok et al., 2023). The inverse relationship between turbidity and water clarity (r = -0.81; $p < 0.01$) represents a predictable optical response, wherein the accumulation of suspended solids causes a proportional attenuation of light intensity (Knoll et al., 2025) while simultaneously influencing nutrient availability in the euphotic zone (Park et al., 2025). Furthermore, the negative correlation between nitrate and salinity (r = -0.56; $p < 0.05$) highlights the role of water mass mixing in nutrient dilution, making the salinity gradient a representative proxy for the nutrient gradient in estuarine and coastal systems. Overall, the interactive dynamics of these parameters create aquatic conditions potentially conducive to the presence of *Rhincodon typus* through mechanisms linked to nutrient availability and aquatic productivity. PCA results indicate that two principal components (PC1 and PC2) cumulatively explain approximately 79.4% of the total variation in the physicochemical parameters of Botubarani waters. PC1 (±52.3% of the variance) is dominated by physical parameters—specifically temperature (loading = 0.78), salinity (0.74), dissolved oxygen (0.69), and transparency (0.66)—which collectively represent the physical condition gradient of the water mass and reflect seasonal dynamics as the primary driver of environmental temporal variability (Belanha et al., 2026). These physical parameters also serve as fundamental indicators of the health of the coastal aquatic ecosystem (Nair and Nayak, 2023). Meanwhile, PC2 (±27.1% of the variance) is characterized by nutrient parameters, particularly nitrate (loading = 0.63) and

phosphate (0.59); these are governed by independent processes such as nutrient release from sediments, organic matter decomposition, and inputs from terrestrial surface runoff (Wijaya et al., 2023). The presence of phosphate as a dominant component of PC2 reinforces its role as an indirect proxy for aquatic biological productivity, given that its availability has been shown to be a dominant controlling factor for phytoplankton biomass (Aziz et al., 2024). This distinction in controlling parameters between PC1 and PC2 conceptually indicates a dual mechanism operating in parallel—namely, the physical water mass gradient and the nutrient biogeochemical gradient—in shaping the variability of water conditions in Botubarani.

The vector patterns in the PCA biplot further clarify the interaction structure among parameters; notably, the opposing vector directions for transparency and turbidity (turbidity loading = -0.71) confirm that they represent contrasting sides of the light transmissivity gradient within the water column. This condition has direct implications for the distribution of plankton, the primary food source for Rhincodon typus. The spatiotemporal heterogeneity reflected in the clustering of observation points on the biplot indicates that the waters of Botubarani constitute a dynamic system influenced by tidal dynamics, seasonal cycles, and inputs from anthropogenic activities (Laignel et al., 2023). The mosaic of water conditions resulting from this heterogeneity subsequently influences the probability of whale shark occurrence, given that the species responds to environmental gradients—such as temperature and chlorophyll-a concentration—in determining its distribution patterns and habitat space use (Flores et al., 2025).

To directly quantify the proportion of *Rhincodon typus* distribution variation explained by measured environmental parameters, an RDA was conducted as a constrained approach to the biplot data (Figure 3). The RDA1 and RDA2 axes cumulatively explain ±69.9% of the total variation in *Rhincodon typus* occurrence in Botubarani waters (RDA1 = ±48.6%; RDA2 = ±21.3%), indicating that the majority of the species' distribution patterns can be directly attributed to measured physicochemical water variability. Temperature, dissolved oxygen, and water clarity were identified as dominant variables positively associated with whale shark distribution—based on the length and direction of their vectors—whereas turbidity and nutrients (nitrate and phosphate) exhibited opposing vector directions, indicating a negative association with the species' presence. The clustering of observation points along the vectors of the three dominant parameters reinforces the inference of specific habitat preferences; thus, a combination of optimal temperature, high dissolved oxygen, and good water clarity acts synergistically to support the presence of Rhincodon typus in the waters of Botubarani.

The RDA yielded two primary axes that cumulatively explain ±69.9% of the total variation in Rhincodon typus occurrence attributable to physicochemical water parameters (RDA1 = 48.6%; RDA2 = 21.3%)—a substantial level of explanation, given that coastal ecosystems are inherently complex systems resulting from the interaction of various eco-hydrological processes (Sahoo and Anandhi 2023). Temperature, dissolved oxygen, and water clarity were identified as dominant variables positively associated with whale shark distribution; this aligns with the thermal preference of Rhincodon typus (23–30°C in tropical waters), as confirmed by Herdianti et al. (2025) in Saleh Bay, as well as the species' physiological need for sufficient oxygen to sustain aerobic metabolism—given that hypoxic conditions are known to induce shifts in the spatial distribution of elasmobranchs (Waller et al., 2024). The positive association between water clarity and whale shark presence reflects its multifaceted role: supporting phytoplankton productivity—the foundation of the trophic chain—and enhancing prey detection efficiency during active filter-feeding (Reinero et al., 2024). Conversely, turbidity and high nutrient concentrations showed a negative association, as the eutrophic conditions characterized by these parameters are more indicative of water quality degradation due to anthropogenic inputs than of the natural pelagic productivity that supports

the trophic chain (Carroll et al., 2026). Theoretically, these findings converge with the bio-physical coupling framework and the study by Tambunan et al. (2026)—which identified physical water conditions as the primary determinant of whale shark occurrence in Botubarani—while offering practical implications: routine monitoring of temperature, dissolved oxygen, and clarity could serve as an early warning system to predict the species' appearance, and controlling land-based nutrient inputs is crucial for maintaining long-term habitat suitability.

CONCLUSION

This study concludes three main points:

1. The physicochemical parameters of the Botubarani waters form an organized system of interactions. There are strong positive correlations between temperature and salinity (r=0.78), nitrate and phosphate (r=0.84), and transparency and DO (r=0.65), as well as negative correlations between temperature and DO (r=-0.72), turbidity and transparency (r=-0.81), and nitrate and salinity (r=-0.56).
2. PCA analysis is divided into two main gradients: PC1 (~71.4%) is controlled by water mass physics (temperature, salinity, DO, brightness) and PC2 (~28.6%) is controlled by nutrients (nitrate, phosphate).
3. RDA analysis confirms that temperature, dissolved oxygen, and water clarity are significantly positively associated with the presence of Rhincodon typus (explaining ~69.9% of the cumulative variation), whereas turbidity and nutrients are negatively associated.

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