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Long-Term Dynamics Influencing Recovery Processes under Environmental Constraints of Coral Reef Ecosystems in Southeast Asia, Phu Quoc, Vietnam (2014–2023)

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ABSTRACT

This study investigated the temporal changes in coral reef cover and seawater quality in the Phu Quoc Marine Protected Area, Vietnam, from 2014 to 2023. Based on long-term monitoring data, marine environmental parameters were evaluated according to Vietnamese standards, and trends in coral reef ecosystem health were assessed. Coral reef benthic communities, reef-associated benthic invertebrates, reef fish assemblages, and physicochemical water quality parameters were surveyed annually at the beginning of the rainy season and monitored during both the dry and rainy seasons. A Comprehensive Reef Ecosystem Condition (CREC) index integrating five key biological components was developed to evaluate the overall ecological status of the coral reef ecosystem. Mean live coral cover increased from 38.6% in 2014 to 58.0% in 2023, indicating substantial reef recovery. No outbreaks of the coral-feeding crown-of-thorns starfish (*Acanthaster cf. solaris/planci*) were recorded during the study period, while benthic invertebrate communities were dominated by long-spined black sea urchins (*Diadema* spp.), which may have contributed to macroalgal control and coral recovery. Water quality remained generally stable, with pH (7.85–7.95), dissolved oxygen (>5 mg/L), and

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most nutrient concentrations within Vietnamese regulatory thresholds for coral reef development. However, nitrate, ammonium, phosphate, and coliform concentrations were consistently higher during the rainy season than during the dry season. CREC values indicated a good ecological condition. The results suggest that stable water quality has supported coral reef recovery in Phu Quoc, whereas increasing nutrient inputs and microbial contamination during the rainy season may pose future risks. The proposed CREC framework provides a practical tool for long-term reef monitoring and supports evidence-based conservation and adaptive management of tropical coral reef ecosystems.

Keywords: Coral Reef Health; Water Quality; Reef Fish Assemblages; Benthic Invertebrates; Long-Term Monitoring; Marine Protected Area; Phu Quoc; Vietnam

1. Introduction

Coral reefs are among the most biologically diverse and productive marine ecosystems, providing essential ecological services, including biodiversity conservation, coastal protection, fisheries production, carbon cycling, and tourism development. Located in the Gulf of Thailand, Phu Quoc Island supports one of the most important coral reef ecosystems in southwestern Vietnam, contributing substantially to regional marine biodiversity and the livelihoods of coastal communities. However, despite their ecological and economic importance, coral reef ecosystems are increasingly threatened by the combined effects of local and global stressors. Coastal development, overexploitation of marine resources, land-based pollution, and climate change have intensified pressures on coral reefs worldwide [1,2]. Global assessments have documented widespread coral reef degradation driven primarily by ocean warming, ocean acidification, and increasing anthropogenic disturbances [3,4]. In Southeast Asia, coral reefs are particularly vulnerable because of increasing sedimentation, nutrient enrichment, coastal urbanization, and rapid socio-economic development [5,6].

Although several coral reef areas in Vietnam have shown relatively stable spatial distributions in recent years, the persistence of coral cover alone does not necessarily reflect ecosystem integrity. Long-term changes in community composition, ecological functions, trophic interactions, and ecosystem resilience may occur even when the spatial extent of reefs remains relatively unchanged, potentially leading to gradual ecosystem degradation. Consequently, comprehensive ecological assessment requires evaluation of multiple biological components together with environmental conditions rather than relying solely on live coral cover.

Among the environmental factors influencing reef ecosystems, water quality is widely recognized as one of the principal drivers of coral reef condition. Seasonal rainfall and terrestrial runoff increase the input of nutrients, suspended sediments, and organic matter into coastal waters, thereby reducing light availability, affecting coral growth and recruitment, and altering benthic community structure [7,8]. Under nutrient-enriched conditions, macroalgae may proliferate and compete with corals for space and resources, potentially leading to changes in reef community composition [9]. Environmental disturbances also influence reef-associated biological communities. Coral-dependent fishes, particularly butterflyfishes, are highly sensitive to reductions in live coral cover and habitat complexity and frequently decline following reef degradation [10]. In contrast, opportunistic and disturbance-tolerant species may increase in abundance, resulting in simplified community structures [11]. Similar responses have been documented for large benthic macroinvertebrates, where sensitive taxa such as giant clams and sea cucumbers often decline under conditions of sedimentation and pollution, whereas some echinoderms, particularly sea urchins, may become more abundant under nutrient-enriched conditions and further influence benthic ecological processes [12].

Recent international studies have increasingly emphasized the importance of long-term ecological monitoring for understanding coral reef resilience under accelerating climate change and increasing anthropogenic pressures. Global monitoring initiatives coordinated by the Global Coral Reef Monitoring Network (GCRMN) have demonstrated that repeated observations over decadal timescales provide substantially greater insight into reef trajectories than short-term surveys because they capture ecological variability, disturbance, and recovery through time [13,14]. Similarly, studies from the Great Barrier Reef, the Caribbean, and the Indo-Pacific have shown that coral reef resilience results from complex interactions among coral recruitment, herbivory, habitat complexity, water quality, climate disturbances, and local management effectiveness rather than any single ecological factor [14,15]. Consequently, integrated ecological assessment has become increasingly important in coral reef monitoring. International programs, including Reef Check, the GCRMN protocol, and the Atlantic and Gulf Rapid Reef Assessment (AGRRA), combine multiple biological indicators, such as live coral cover, reef fish assemblages, benthic communities, and indicator taxa, while recent ecological integrity frameworks increasingly employ composite indicators that integrate ecosystem structure, ecological function, and resilience into a single assessment system [16–18].

Despite these advances, several important knowledge gaps remain. Most coral reef studies in Southeast Asia have focused on short-term assessments of live coral cover or individual biological components, whereas long-term ecosystem-based studies integrating coral communities, reef fishes, benthic macroinvertebrates, sponges, macroalgae, and environmental conditions remain limited. Furthermore, many existing assessment frameworks were developed primarily for regional monitoring or require extensive datasets that are difficult to obtain consistently in long-term monitoring programs, particularly in developing countries. As a result, relatively few practical ecological indices are available that integrate the principal biological components of coral reef ecosystems into a transparent, reproducible, and management-oriented framework suitable for routine long-term monitoring. In addition, many existing frameworks evaluate individual ecosystem components independently and therefore provide limited information on overall ecosystem condition or temporal ecosystem trajectories. These limitations reduce their applicability for integrated ecological assessment and adaptive management at local and regional scales [14–18].

To address these limitations, the present study proposes the Coral Reef Ecosystem Condition (CREC) framework, which follows the ecological integrity concept, recognizing that no single biological indicator can adequately represent overall coral reef condition because different ecosystem components respond to environmental stressors across spatial and temporal scales [16]. Accordingly, the framework integrates five complementary biological indices representing the principal ecological compartments of coral reef ecosystems, including live coral cover, reef fishes, large benthic macroinvertebrates, sponges, and algae. Equal weighting was adopted because current ecological evidence does not consistently demonstrate that any single ecological component contributes more strongly than the others to overall ecosystem condition, thereby following internationally accepted principles for composite ecological indicator construction while minimizing subjective bias and maintaining transparency and reproducibility [14,16–19].

Accordingly, this study aimed to (i) quantify long-term changes in coral reef condition; (ii) evaluate temporal variation in reef fish assemblages and benthic macroinvertebrate communities; (iii) examine seasonal variations in water quality and their relationships with coral reef ecosystem components; and (iv) develop and evaluate integrated assessment frameworks for coral reef condition, reef fish assemblages, benthic macroinvertebrate communities, and the proposed Coral Reef Ecosystem Condition (CREC) index within the Phu Quoc Marine Protected Area during 2014–2023. The findings provide new information on long-term ecological changes in coral reef ecosystems in southwestern Vietnam and contribute to improving ecosystem-based monitoring, integrated ecological assessment, and evidence-based conservation and management of coral reef ecosystems in Vietnam and other tropical reef regions facing similar environmental challenges.

2. Materials and Methods

2.1. Study Area and Survey Designs

The study, initiated in 2014, aimed to survey coral reef cover and establish permanent monitoring stations at ten reef sites (**Figure 1**): Hon Xuong, Hon Mong Tay, Hon Gam Ghi, Dong Hon Dong, Hon Dam Trong, Hon Roi, Tay Hon Thom, Hon Vang, Hon May Rut Trong, and Ganh Dau, all located outside the core zone of the Phu Quoc Marine Protected Area.

At each survey station, two 100-m transects were established parallel to the coastline across two depth zones: a shallow zone (2–5 m) and a deeper zone (6–10 m), depending on local reef topography. Each transect was divided into 20-m segments with 5-m intervals between consecutive segments (**Figures 2** and **3**).

(**a**) Coral reef ecosystem. (**b**) Manatee. (**c**) Hawksbill turtle.

Figure 1. Coral reef ecosystems and rare species in the Phu Quoc Marine Protected Area, Vietnam.

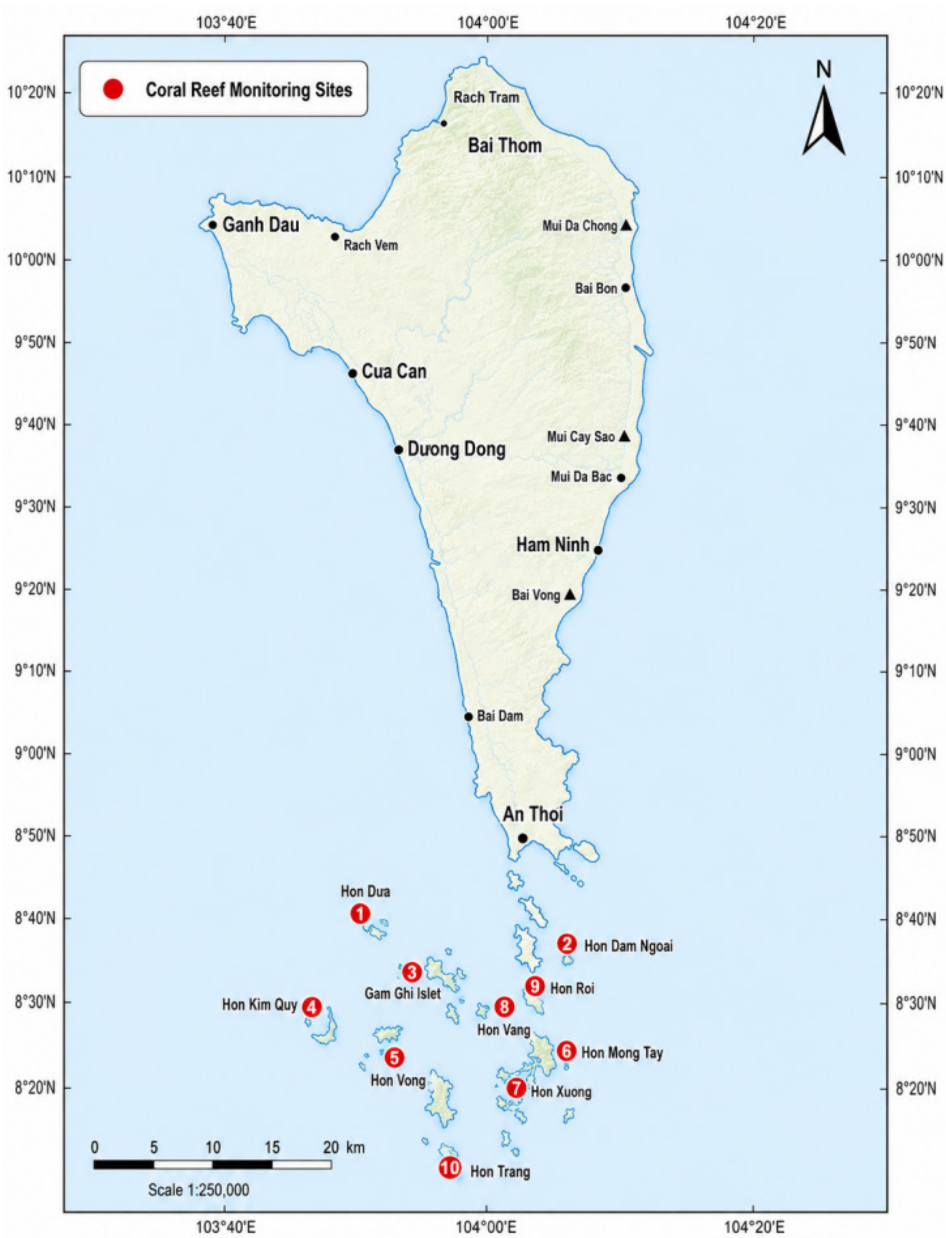


Figure 2. The sites of survey coral reef (2014–2023).

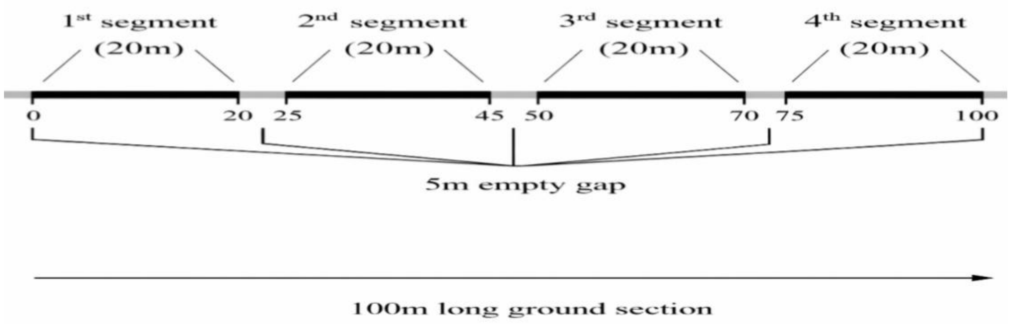


Figure 3. Layout diagram of 4 sections along a 100-m research transect line.

Accordingly, the shallow zone included four samples from flat reef areas and four samples from deeper reef areas, resulting in a total of eight samples collected at each reef site. These samples were treated as replicates for statistical analysis. The monitored parameters included benthic cover composition, reef fish assemblages, large benthic invertebrate communities, and seasonal water samples for water quality analysis, which were compared against Vietnamese regulatory standards.

All surveys were conducted following the methodologies of the Global Coral Reef Monitoring Network (GCRMN), with all parameters measured along the same transects at each monitoring station [20,21].

2.2. Biological Surveys

2.2.1. Sampling Design and Survey Methods

Survey sites were selected to represent the main coral reef habitats within the study area and were consistently revisited throughout the study period using Global Positioning System (GPS) coordinates. At each site, three replicate 100-m transects were established at a fixed depth, with a minimum spacing of 10 m between transects to ensure spatial independence.

Coral reef benthic communities were surveyed using the Line Intercept Transect (LIT) method to estimate live coral cover and substrate composition. Reef fish assemblages were assessed using Underwater Visual Census (UVC) along belt transects (100 m × 5 m) (500 m^2) per survey plot, recording species composition, abundance, and size classes. Large benthic invertebrates were surveyed along the same transects within a 2-m belt, with all target organisms identified and counted.

All surveys were conducted by the same trained research team, following standardized monitoring protocols of the Institute of Oceanography, Vietnam Academy of Science and Technology, and staff from the Phu Quoc Marine Protected Area Management Board, to ensure methodological consistency and comparability across sites and sampling periods [20,21].

2.2.2. Benthic Cover Assessment

Benthic composition was quantified as the percentage cover of major substrate categories, including hard corals, soft corals, recently dead corals, algal assemblages, sponges, rocks, coral rubble, sand, silt/clay, and other substrates. Cover was recorded at 0.5-m intervals along each transect segment. Coral bleaching conditions observed during the study period were also recorded as an additional indicator of coral reef condition. A total of 40 data points per 20-m transect segment were recorded.

The long-term monitoring program was conducted from 2014 to 2023, and several survey sites were replaced due to adjustments in management zoning and habitat conditions, which may limit strict temporal comparability. Therefore, this study evaluates long-term trends for the 2014–2023 period [22,23].

2.2.3. Benthic Surveys

Benthic surveys were conducted following standardized coral reef monitoring protocols [24,25]. At each survey site, each 100-m transect was divided into four 20-m segments. Benthic data were collected using the point-intercept method at 0.5-m intervals, resulting in 160 sampling points per transect. This method is widely applied for estimating benthic community structure and ensures comparability among survey sites and sampling periods [26,27].

The benthic substrate categories included live hard corals, recently dead corals, algae-covered dead corals, coral rubble, sand, rock, and other substrate types, following standard coral reef classification systems [28].

2.2.4. Large Benthic Invertebrate Surveys

Large benthic invertebrates were surveyed along the same transects used for reef fish assessments. Target taxa included giant clams (*Tridacna* spp.), pencil sea urchins (*Heterocentrotus mammillatus*), long-spined sea urchins (*Diadema* spp.), sea cucumbers (Holothuriidae), crown-of-thorns starfish (*Acanthaster planci*), triton snails (*Charonia tritonis*), banded coral shrimps (*Stenopus hispidus*), spiny lobsters (*Panulirus* spp.), and top shells (*Trochus* spp.).

Reef fish and large benthic invertebrates were surveyed using the Underwater Visual Census (UVC) method along 20 m × 5 m belt transects, a standard approach widely used in coral reef ecology. Species identity and abundance were recorded for all observed individuals [29,30]. Likewise, benthic invertebrate groups such as sea urchins, giant clams, and sea cucumbers are widely recognized as key bioindicators of coral reef condition and ecosystem functioning [31,32].

2.2.5. Coral Reef Fish Surveys

Reef fishes were classified into ecological functional groups, including coral-associated species, herbivorous species, and commercially important species, following established ecological classification frameworks [33,34].

Fish data were collected by slowly swimming along each transect and recording all individuals observed within each survey segment, following the Reef Check methodology, with additional inclusion of several ecologically important reef fish families to better represent local reef conditions in Phu Quoc, Vietnam [28].

2.2.6. Statistical Analysis

One-way Analysis of Variance (One-way ANOVA): The Single-Factor ANOVA method is used to analyze differences among the mean values across years for several investigated indicators. In this approach, observations for each value are treated as independent groups, and the test evaluates the following hypotheses:

H0. *All repeated yearly mean values are equal* ($\mu_1 = \mu_2 = \ldots = \mu_k$).

H1. *At least one factor differs. The method is based on comparing the variation between groups and the variation within groups, using the F-statistic defined as* $F = MS_{between}/MS_{within}$. *If $p < 0.05$* or $F > F_{crit}$, *the null hypothesis is rejected, indicating a statistically significant difference among the investigated factors* [35].

Correlation analysis and simple linear regression: Simple linear regression means that there is one independent variable X being studied to examine its effect on a dependent variable Y, where the relationship is defined as a straight line. This implies that when X increases or decreases, Y also increases or decreases proportionally in a linear form.

The general equation is:

$$Y = A + BX.$$

Multiple linear regression: In practice, the dependent variable Y is influenced by multiple independent variables (X_i). In this case, to estimate the dependent variable Y, a multiple regression model is constructed in order to more accurately represent and predict the estimated value of Y. The general equation is:

$$Y = a_0 + b_1X_1 + b_2X_2 + \ldots + b_nX_n.$$

R^2 is the coefficient of determination representing the squared correlation. It reflects the relationship between coral reef conditions and macroinvertebrate communities affecting coral cover. It is calculated as the percentage contribution of impacted communities and reef fish assemblages that influence coral reef cover.

The collected data were compiled into a summary table to calculate the average values for the study area and the reporting year. The percentage coral reef cover represents the dependent variable (Y).

The independent variables include X_1, which represents large invertebrate communities that have an impact on coral reefs, and X_2, which represents reef fish assemblages, expressed as the percentage of fish that influence coral reef conditions. Using were applied to evaluate fixed and random effects. Statistical significance was set at $p < 0.05$ [36,37].

2.3. Water Quality

2.3.1. Water Quality Monitoring

Water samples were collected twice annually, during the dry and wet seasons, to capture seasonal variations in environmental conditions. The monitored parameters included nutrients, suspended solids, organic pollution indicators, and microbial contamination [38].

Seasonal sampling is widely applied in coastal environmental monitoring programs to assess broad-scale temporal variability; however, it may not fully capture short-term fluctuations in water quality [37,38]. This limitation was taken into consideration when interpreting the results.

The analyzed parameters included pH, dissolved oxygen (DO), total suspended solids (TSS), biochemical oxygen demand (BOD), chemical oxygen demand (COD), ferrous iron (Fe^{2+}), chloride (Cl^-), salinity, nitrite ($N–NO_2^-$), nitrate ($N–NO_3^-$), ammonia ($N–NH_3$), phosphate (PO_4^{3-}), and coliform bacteria. Sampling was conducted annually between mid-March and mid-September from 2014 to 2023 in accordance with standard procedures issued by the Vietnamese Ministry of Natural Resources and Environment.

Following collection, samples were preserved and transported to the An Giang Provincial Center for Environmental and Natural Resources Monitoring for laboratory analysis. The resulting data were incorporated into the Center's environmental monitoring database, which supports environmental quality assessment and pollution warning systems at both provincial and national levels.

2.3.2. Classification of Environmental Parameters

The environmental variables examined in this study included pH, dissolved oxygen (DO), total suspended solids (TSS), biochemical oxygen demand (BOD), chemical oxygen demand (COD), ferrous iron (Fe^{2+}), chloride (Cl^-), salinity, nitrite ($N–NO_2^-$), nitrate ($N–NO_3^-$), ammonia ($N–NH_3$), phosphate (PO_4^{3-}), and coliform bacteria. These parameters were used to evaluate marine environmental quality in Phu Quoc and to assess their potential influence on coral reef development within the Phu Quoc Marine Protected Area, Vietnam.

Water quality parameters were compared with the Vietnamese National Technical Regulation on Marine Water Quality (QCVN 10-MT:2015/BTNMT), which specifies the permissible limits for pH (6.5–8.5), dissolved oxygen (DO, ≥5 mg/L), biological oxygen demand (BOD, ≤6 mg/L), chemical oxygen demand (COD, ≤15 mg/L), total suspended solids (TSS, ≤30 mg/L), ammonium (NH_4^+, ≤0.3 mg/L), nitrite (NO_2^-, ≤0.05 mg/L), nitrate (NO_3^-, ≤5 mg/L), phosphate (PO_4^{3-}, ≤0.2 mg/L), and coliforms (≤ 5,000 MPN/100 mL) [39].

2.3.3. Statistical Analysis

Statistical analyses were performed to compare the mean values of environmental parameters between the dry and rainy seasons. Prior to hypothesis testing, the normality of the data distribution was evaluated using the Shapiro–Wilk test. When the assumption of normality was satisfied, Student's *t*-test was applied.

For paired observations (e.g., measurements collected from the same monitoring stations in the dry and rainy seasons), a paired-samples *t*-test was used to determine whether the mean difference between paired observations was statistically significant. For independent datasets, an independent-samples *t*-test was employed. Statistical significance was determined at a confidence level of 95% ($p < 0.05$) [37].

This study presents the temporal changes in coral reef conditions, reef fish assemblages, and benthic invertebrate communities only up to 2023 (**Table 1**).

Table 1. Geographic coordinates of coral reef monitoring stations in the Phu Quoc Marine Protected Area, 2014–2023.

Monitoring Station	Latitude	Longitude
Ganh Dau	10.36588	103.83333
Hon Dam Trong	10.00475	104.02888
Hon Roi	09.97478	104.01682
West Hon Thom	09.95688	104.01172
Hon Vang	09.92794	104.02058
Hon Xuong	09.91877	104.02032
Hon Mong Tay	09.90641	104.02094
Hon Gam Ghi	09.91443	104.01713
North Hon Vong	09.92272	104.00275
Northeast of Hon May Rut Trong	09.91345	103.99287

3. Results

3.1. Current Status of Coral Reefs from 2014–2023

3.1.1. Assessment of Coral Reef Status (2014–2023): Changes in Coral Reef Cover during

The average live coral cover (LC) across the surveyed reefs showed a generally increasing trend during the period 2014–2023. Live coral cover increased from 38.59% in 2014 to 58.0% in 2023, representing an overall increase of 19.41 percentage points. This improvement was primarily driven by the recovery and expansion of hard coral cover (HC), which increased from 38.41% in 2014 to 57.0% in 2023. Soft coral cover (SC) remained consistently low throughout the study period, generally accounting for only 0–1% of the benthic community.

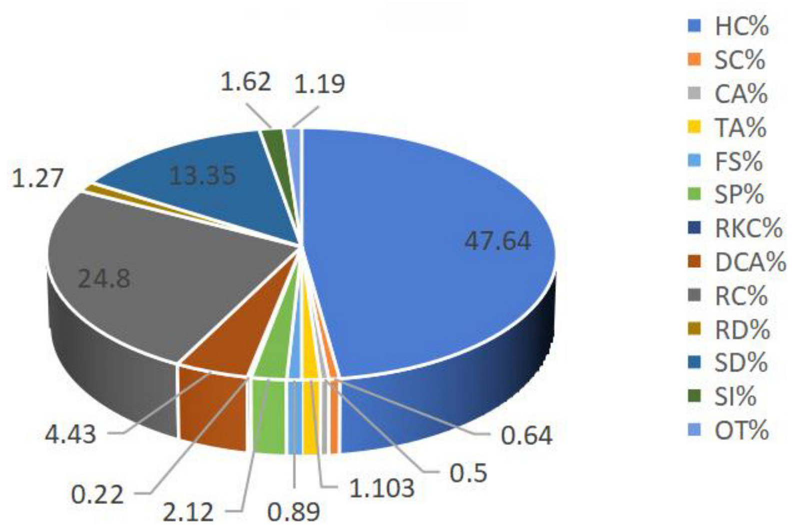
The increase in live coral cover was accompanied by a decline in non-living reef substrates. Rock cover (RC), which represented the dominant non-coral substrate, decreased markedly from 41.4% in 2014 to 22.0% in 2023. Similarly, dead coral covered by algae (DCA) declined from 8.25% in 2014 to 0% in 2023, indicating a gradual reduction in coral mortality and post-disturbance algal colonization. The coverage of macroalgae and filamentous algae remained generally low, suggesting limited competitive pressure from algae on coral recruitment and recovery.

Although some annual fluctuations were observed, particularly during 2019–2020, when live coral cover decreased to approximately 45%, the overall trajectory from 2014 to 2023 indicates substantial reef recovery and improved coral community condition. The highest live coral cover was recorded in 2023 (58%), which corresponds to a reef condition classified as good according to common coral reef assessment criteria.

3.1.2. Ecological Characteristics of the Phu Quoc Coral Reef Ecosystem

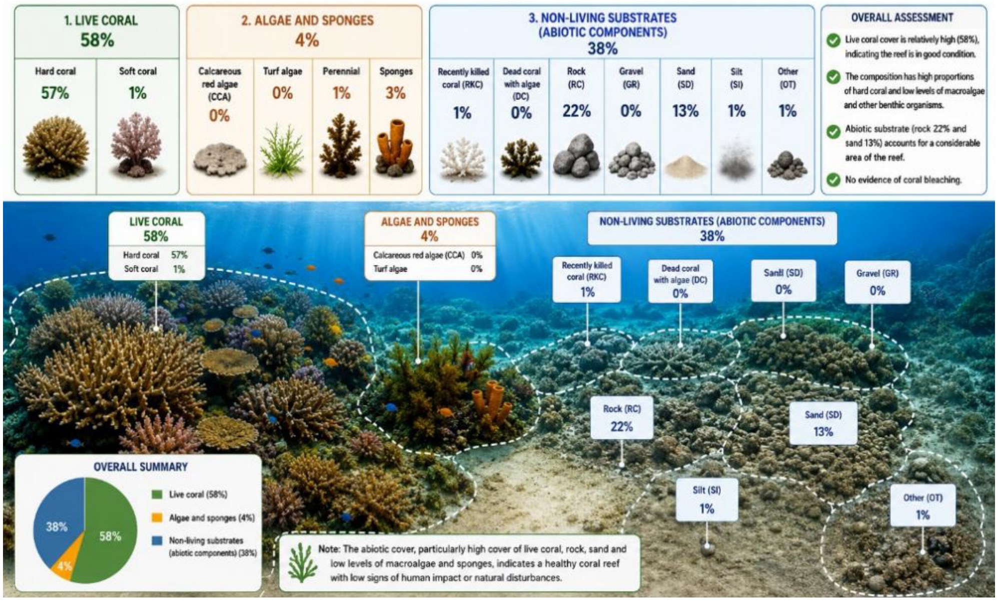
The Phu Quoc coral reef ecosystem comprises both benthic flora and fauna. Based on **Figure 4**, the benthic community was classified into three major components.

The first component consists of live corals (hard and soft corals). Hard and soft corals are the dominant reef-building organisms and thrive under suitable environmental conditions, including appropriate seawater temperature, light availability, salinity, water depth, substrate characteristics, and water quality. By 2023, the total live coral cover reached 58%, comprising 57% hard corals and 1% soft corals, indicating that hard corals were the dominant benthic component and played the principal ecological role in the coral reef ecosystem (**Figure 5**).



(**a**) Spatial distribution of coral reef components during the 2014–2023 period.

Figure 4. *Cont.*



(**b**) Ecological Status of Phu Quoc Coral Reef in 2023 (Benthic Cover of Major Components, %).

Figure 4. Benthic Community Composition and Its Spatiotemporal Variation in the Phu Quoc Coral Reef Ecosystem (2014–2023).

Figure 5. Current status of coral reefs in the Phu Quoc Marine Protected Area.

The second component includes algae and sponges. In 2023, the cover of crustose coralline algae (CCA) and turf algae was 0%, while macroalgae and sponges accounted for 1% and 3%, respectively. The very low macroalgal cover suggests that there was no evidence of macroalgal proliferation associated with eutrophication. Likewise, the low sponge cover indicates that sponges were not competing significantly with corals for space and therefore were unlikely to adversely affect coral growth.

The third component comprises non-living benthic substrates. In 2023, these consisted of recently killed coral (RKC, 1%), dead coral with algae (DCA, 0%), rock (22%), coral rubble (0%), sand (13%), silt (1%), and other substrates (1%).

Overall, the benthic composition indicates that the Phu Quoc coral reef remained in a relatively good ecological condition in 2023. Live coral cover was relatively high (58%), whereas macroalgae and sponge cover remained very low, suggesting limited biological competition with reef-building corals. Approximately 35% of the reef substrate consisted of exposed rock and sand, representing naturally available substrate rather than areas occupied by opportunistic algae. Consequently, there was no evidence of macroalgal overgrowth or algal blooms that would indicate reef degradation during the study period.

Pearson correlation analysis demonstrated a strong positive relationship between survey year and live coral cover ($r = 0.825$, $p = 0.003$). Linear regression indicated that live coral cover increased at an average rate of approximately 1.56 percentage points per year ($R^2 = 0.681$), suggesting a significant long-term recovery trend of coral reef communities during 2014–2023. Nevertheless, temporary declines observed during 2019–2020 indicate that reef recovery was not linear but was likely influenced by short-term environmental disturbances and ecological variability (**Table 2**).

Table 2. Current status of average coral reef on 10 sites surveyed in the southwestern sea region of Vietnam, 2014–2023.

Year	Living and Deceased Coral			Allgea and Spong				Coral Reef Substrate						
	LCC%	HC%	SC%	CA%	TA%	FS%	SP%	RKC%	DCA%	RC%	RB%	SD%	SI%	OT%
2014	38.59	38.41	0.19	0	0.03	0.41	0.75	0.16	8.25	41.4	0.72	8.5	0.19	0.84
2015	45.3	45	0.25	0	0	0.5	0.41	0	16.1	22.6	2.03	0	13	0.06
2016	45	45	0	1	5	1	1	0	2	27	2	12	0	2
2017	49	48	0	1	0	1	3	0	2	29	1	13	0	1
2018	50	50	1	2	1	0	4	0	2	21	0	15	1	1`
2019	45	44	1	0	2	2	2	0	5	24	3	17	0	2
2020	45	44	1	0	2	2	2	0	5	24	3	17	0	2
2021	50	50	1	1	1	1	2	1	2	20	1	21	0	0
2022	56	55	1	0	0	0	3	0	2	17	0	17	1	1
2023	58	57	1	0	0	1	3	1	0	22	0	13	1	1
Average	48.13	47.64	0.64	0.5	1.103	0.89	2.12	0.22	4.43	24.8	1.27	13.35	1.62	1.19
$p < 0.05$	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01
SE	1.81	1.76	0.15	0.22	0.5	0.22	0.36	0.13	1.49	2.13	0.37	1.84	1.27	0.28

Note: LCC: living coral cover; HC: hard coral; SC: soft coral; CA: calcareous algae; TA: filamentous algae; FS: large algae; SP: sponge; RKC: recently deceased coral; DCA: recently deceased coral covered in algae; RC: rock; RB: fragment coral; SD: sand; SI: silt; OT: other.

Linear Regression Equation

Let:

$$X = \text{the number of years since 2014}$$
$$(\text{i.e., } 2014 = 0,\ 2015 = 1,\ \ldots,\ 2023 = 9),$$

then the linear regression equation is:

$$LC = 41.16 + 1.56X$$

where:

LC = Live coral cover (%).

41.16 = The intercept, representing the estimated live coral cover (%) at the baseline year (2014).

1.56 = The regression coefficient (slope), indicating that live coral cover increased by an average of 1.56 percentage points per year over the study period (2014–2023).

Multiple linear regression analysis indicated that live coral cover was significantly explained by the combined effects of large benthic invertebrates and corallivorous reef fishes ($R^2 = 0.741$, Adjusted $R^2 = 0.667$, $F = 10.02$, $p = 0.008$). The fitted regression model was:

$$LCC = 49.84 - 0.33(Blu) + 0.45(Bu)$$

The abundance of large benthic invertebrates showed a significant negative relationship with live coral cover ($\beta = -0.33$, $p = 0.011$), whereas corallivorous reef fish exhibited a positive but marginally non-significant relationship ($\beta = 0.45$, $p = 0.065$). Overall, the model explained approximately 74.1% of the temporal variation in live coral cover, indicating that these two biological indicators were important predictors of coral reef condition during the study period.

Multiple Linear Regression Equation

$$LCC = 49.84 - 0.33\,X_1 + 0.45\,X_2$$

where:

LCC = Live Coral Cover (%).

X_1 = Abundance of large benthic invertebrates (Blu. (In.)).

XI_2 = Abundance of corallivorous reef fishes (Bu. (In.)).

3.2. Temporal Dynamics of Benthic Invertebrates (2014–2023)

3.2.1. Status of Benthic Invertebrates in Coral Reefs from 2014 to 2023

During the period 2014–2023 (**Table 3**), reef-associated invertebrates of ecological and economic importance exhibited relatively low taxonomic diversity, with only a limited number of taxa recorded. Throughout the study period, black sea urchins consistently represented the dominant component of the community, accounting for 56–99% of total invertebrate abundance each year. Their population dynamics showed marked interannual variability, with a peak recorded in 2014 (46 individuals), followed by a sharp decline to 0.3 individuals in 2019–2020, and a subsequent increase to 5.8 individuals in 2023.

Table 3. Invertebrate data in the coral reef (2014–2023).

Years	Coral-Feeding Group	Intermediate Group		Non-Coral-Feeding Group					
	Crs. (In.)	Blu. (In.)	Trt. (In.)	Gic. (In.)	Flc, (In.)	Cls. (In.)	Spl. (In.)	Cou, (In.)	Sec. (In.)
2014	0	46	0	0.188	0.187	0	0	0	0
2015	0	8.3	0	0	0.25	0	0	0	0.1
2016	0	5.4	0	0.125	0.125	0	0	0	0
2017	0	0.9	0	0	0.113	0	0	0	0
2018	0	1.6	0	0	0.063	0	0	0	0
2019	0	0.3	0	0.125	0.113	0	0	0	0
2020	0	0.3	0	0.125	0.113	0	0	0	0
2021	0	5.6	0	0.175	0.175	0	0	0	0.1
2022	0	3.2	0	0.15	0.113	0	0	0	0
2023	0	5.8	0	0.063	0.063	0	0	0	0.1
Average	0	7.74	0	0.09	0.13	0	0	0	0.03
$p < 0.05$	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01
SE	0	4.34	0	0.023	0.018	0	0	0	0.15

Note: Crs.: Crown-of-thorns starfish; Blu.: Black sea urchin; Trt.: Triton's trumpet; Gic.: Giant clam; Flg.: Fluted giant; Cls.: Cleaner shrimp; Spl.: Spiny lobster; Cou.: Collector urchin; Sec.: Sea cucumber; In.: Number of individuals per 500 m^2.

Giant clams and fluted giant clams were persistently present but at consistently low densities, typically ranging from zero to approximately 0.25 individuals. Sea cucumbers occurred only sporadically and at very low abundance (0–0.1 individuals). In contrast, Triton's trumpet, cleaner shrimps, spiny lobsters, collector urchins, and crown-of-thorns starfish were not observed throughout the entire study period.

The assemblage was characterized by low species richness and a strong numerical dominance of black sea urchins. The absence of crown-of-thorns starfish indicates that no outbreak events of this coral predator occurred during the monitoring period. Nevertheless, the limited occurrence or complete absence of several ecologically and economically important taxa highlights the necessity for continued monitoring and strengthened conservation strategies to support reef biodiversity.

The persistently high proportion of black sea urchins may have contributed to suppressing algal proliferation through grazing activity, potentially facilitating coral recovery observed between 2014 and 2023. However, further investigation into density thresholds and associated bioerosion processes is required to clarify whether their long-term dominance exerts net positive or negative effects on reef resilience.

For analytical purposes, reef-associated invertebrates were categorized into three functional groups. The corallivorous group comprised crown-of-thorns starfish (*Acanthaster* spp.), which directly consume coral tissue and may severely reduce coral cover during population outbreaks. The intermediate group included black sea urchins, collector urchins, Triton's trumpet, cleaner shrimps, and spiny lobsters, which indirectly influence reef dynamics through grazing, predation, and trophic regulation. The non-corallivorous group consisted of giant clams, fluted giant clams, and sea cucumbers, which function primarily as filter feeders or detritivores and do not feed on coral tissue.

Among all large benthic invertebrates, black sea urchins consistently dominated the assemblage, contributing more than 90% of individuals in most years. Notably, their relative dominance declined only in 2019 and 2020, when their contribution dropped to approximately 56%, reflecting temporary shifts in community structure.

3.2.2. Sea Urchin Grazing and Algal Control

Black sea urchin density in the Phu Quoc coral reefs varied considerably during 2014–2023 (**Table 3**), declining from 46.0 individuals/500 m^2 in 2014 to generally low levels (<6 individuals/500 m^2) after 2016, with a slight increase to 5.8 individuals/500 m^2 in 2023 before decreasing again to 1.6 individuals/500 m^2 in 2024. This trend suggests that sea urchin grazing pressure remained relatively low throughout most of the monitoring period.

Although temporal changes in macroalgal, turf algal, and crustose coralline algal cover indicate that algal assemblages fluctuated over time, the observed low density of black sea urchins suggests only limited grazing pressure. Based on visual inspection of the long-term data, no strong statistical relationship between sea urchin abundance and algal cover was evident, indicating that additional drivers, such as nutrient availability, herbivorous fishes, and habitat conditions, likely contributed to algal dynamics.

The average black sea urchin density recorded in this study (generally below 6 individuals/500 m^2 after 2016) is substantially lower than the approximate threshold of 10–15 individuals/500 m^2 that has been associated with significant bioerosion on Indo-Pacific reefs. Therefore, the current population is more likely to provide modest ecological benefits through algal grazing than to cause detrimental substrate erosion. Nevertheless, this interpretation should be regarded as preliminary because direct measurements of grazing rates and bioerosion were not conducted, and future studies integrating these processes are needed to clarify the ecological role of sea urchins in Phu Quoc coral reefs.

From 2014 to 2023, the reef-associated benthic invertebrate community in Phu Quoc was characterized by low species diversity and was consistently dominated by black sea urchins, which accounted for 56–99% of the total abundance. Coral-feeding invertebrates, including crown-of-thorns starfish, were absent throughout the monitoring period, indicating no outbreak events, while giant clams and fluted giant clams were present only at low densities, and several ecologically important taxa were rarely or never recorded. The dominance of black sea urchins may have contributed to controlling algal growth and supporting coral recovery through grazing activity; however, continued long-term monitoring is needed because excessively high sea urchin densities could increase bioerosion and negatively affect the structural stability and resilience of coral reef ecosystems (**Figure 6**).

Figure 6. Benthic invertebrates in the study area.

3.3. Temporal Trends in Reef Fish Assemblages (2014–2023): Assessment of Reef Fish Assemblages on the Coral Reefs of Phu Quoc, Vietnam

From 2014 to 2023, the reef fish assemblage was dominated by corallivorous fishes, together with a smaller contribution from intermediate and non-corallivorous groups (**Table 4**, **Figure 7**).

Butterflyfish were consistently the most abundant corallivorous taxon, with recorded values ranging from 11.96 to 25.35 individuals across the survey years. In contrast, angelfish and humpback parrotfish were not observed during the study period, while parrotfish were recorded only at low abundance in 2014 and 2015.

The proportion of corallivorous fishes remained high throughout most of the monitoring period, accounting for 66–90% of the recorded fish assemblage, except in 2021 when it decreased to 50%. This pattern indicates that butterflyfish and other coral-associated species consistently represented a major component of the surveyed reef fish community.

Table 4. Fish assemblage data (2014–2023).

Years	Corallivorous Fishes				Intermediate Group and Non-Corallivorous Group									
	Bu. (In.)	An. (In.)	Hu. (In.)	Pa. (In.)	Wr. (In.)	Wr. 20 cm (In.)	SE. (In.)	Sn. (In.)	Go. (In.)	Ra. (In.)	Gr. (In.)	Gr. > 30 cm (In.)	Hu. (In.)	Po. (In.)
2014	12.62	0	0	0.9	0	0	0	0.09	0.41	0.15	0.89	0	0	0
2015	14.22	0	0	0.27	0	0	0	0.13	0	0	1.85	0	0	0
2016	13.06	0	0	0	0	0.33	0	0.03	1.1	0.21	1.78	0	0	0
2017	13.17	0	0	0	0	0	0	0.11	1.23	0.13	0	0	0	0
2018	19.57	0	0	0	0	0.24	0	0.08	4.19	2.16	3	0	0	0

Table 4. *Cont.*

Years	Corallivorous Fishes				Intermediate Group and Non-Corallivorous Group									
	Bu. (In.)	An. (In.)	Hu. (In.)	Pa. (In.)	Wr. (In.)	Wr. 20 cm (In.)	SE. (In.)	Sn. (In.)	Go. (In.)	Ra. (In.)	Gr. (In.)	Gr. > 30 cm (In.)	Hu. (In.)	Po. (In.)
2019	25.35	0	0	0	0	0.77	0	2.96	1.79	3.75	3	0	0	0
2020	23.35	0	0	0	0	0.77	0	2.96	1.79	3.75	3	0	0	0
2021	11.96	0	0	0	0	0.13	0	3.11	7.1	0.74	1.03	0	0	0
2022	19.2	0	0	0	0	0.1	0.013	0.09	0.36	0.41	1.18	0.013	0	0
2023	17.77	0	0	0	0	0.25	0	0.28	0.98	0.31	0.74	0.2	0	0
Aver.	17.03	0	0	0.12	0	0.26	0.001	0.98	1.89	1.61	1.65	0.02	0	0
$p < 0.05$	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01
SE	1.507	0	0	0.09	0	0.09	0.001	0.44	0.69	0.47	0.33	0.02	0	0

Note: Bu.: Butterflyfish; An.: Angelfish; Hu.: Humpback parrotfish; Pa.: Parrotfish; Wr.: Wrass; Wr.: Wrasse > 20 cm; Se.: Sergeant major/Damselfish; Sn.: Snapper; Go.: Goatfish; Ra.: Rabbitfish; Gr.: Grouper; Hu.: Humphead grouper; Po.: Pomfret/Chub mackerel. In.: Number of individuals per 500 m^2.

Figure 7. Representative reef fish species.

Intermediate and non-corallivorous fishes, including groupers, snappers, goatfish, rabbitfish, and wrasses, showed variable abundances among years but generally occurred at lower levels than the corallivorous group. Large wrasses and groupers exceeding 30 cm were recorded only occasionally and at low abundance, whereas humphead groupers were absent throughout the surveys.

The reef fish assemblage between 2014 and 2023 was characterized by a predominance of corallivorous fishes, particularly butterflyfish (**Table 4**). However, the observed composition and relative abundance of these functional groups alone are insufficient to evaluate coral reef health and should be interpreted in conjunction with other ecological indicators, including live coral cover, benthic composition, and environmental conditions.

3.4. Development of the Framework for Equations for Coral Reef Assessment in Phu Quoc, Vietnam (Drafted and Proposed by Luom Thanh Thai, Including the Formulation and Subsequent Revisions)

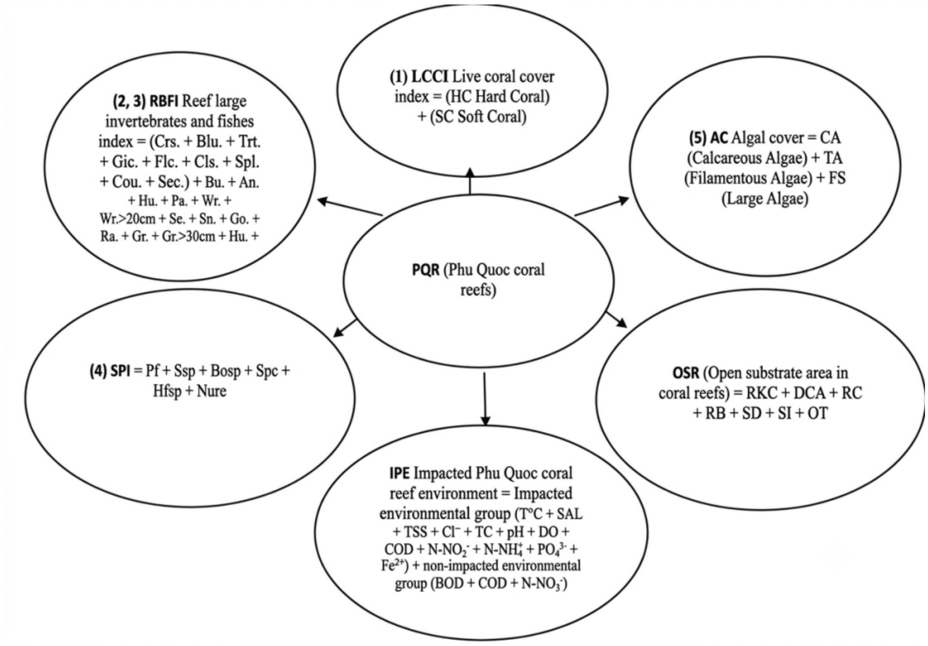
3.4.1. Identification of Coral Reef Assessment Indices for Phu Quoc

The current status of the major biological components of the Phu Quoc coral reef ecosystem was assessed based on the principal ecological indicators representing the living biological components of the reef. The proposed Phu Quoc Reef Index (PQR) comprises five component indices: (1) the Living Coral Cover Index (LCCI); (2) the Reef Benthic Invertebrate Index (RBI); (3) the Reef Fish Index (RFI); (4) the Algal Cover Index (ACI), including calcareous algae, turf algae (filamentous algae), and fleshy macroalgae; and (5) the Sponge Index (SPI).

These five indices represent the principal biological components that directly influence the growth, development, and survival of living corals and therefore serve as key ecological indicators of the health of the Phu Quoc coral reef ecosystem. Accordingly, this study proposes a three-level classification framework (Good, Moderate, and Poor) for assessing each of these biological indices.

In addition, the Open Reef Substrate (ORS), consisting of sedimentary substrates and coral reef degradation products, was considered an indirect ecological component. Therefore, only its percentage cover was recorded and reported, without being included in the biological assessment framework.

Similarly, the Impacted Phu Quoc Environment (IPE) represents environmental factors that indirectly affect coral reef ecosystems. It was therefore evaluated separately according to seawater environmental conditions during different monitoring periods, including parameters that remained within acceptable threshold values and those exceeding the prescribed environmental standards. Depending on the degree of exceedance, these environmental variables may adversely affect coral reef health (**Figure 8**).



(**a**) Phu Quoc Coral Reef Ecological Health Assessment Indicator System Diagram.

(**b**) Conceptual framework of key components influencing coral reef condition in Phu Quoc Marine Protected Area.

Figure 8. Theoretical basis for the overall assessment of coral reefs: A case study of Phu Quoc.

Note: Crs., Blu, Trt., Gic., Flc., Cls., Spl., Cou., Sec. = Coral reef invertebrate groups; Bu., An., Hu., Pa., Wr., Se., Sn., Go., Ra., Gi., Gr. > 30 cm; Hu. = Fish functional groups and size classes; Ff, Ssp, Bosp, Spc, Hfsp, Nure = Sponge functional and indicator groups; HC = Hard coral; SC = Soft coral; CA = Calcareous algae; TA = Filamentous algae; FS = Large algae; RKC = Rock; DCA = Dead coral with algae; RC = Recent dead coral; RB = Rubble; SD = Sand; SI = Silt; OT = Other substrate. Environmental variables are grouped into impacted and non-impacted components based on their ecological relevance to coral reef condition.

3.4.2. Proposed Development of a Coral Reef Status Formula under the Conditions of Phu Quoc, Vietnam (Drafted and Proposed by Luom Thanh Thai): Assessment of Live Coral Cover in Phu Quoc

According to previous studies, coral reef condition based on live coral cover is classified into four categories: Excellent (>75% live coral cover), Good (50–75%), Fair (25–50%), and Poor (<25%) [40].

The Living Coral Cover Index (LCCI) for the coral reefs of Phu Quoc is calculated as follows (Equation (1)):

$$LCCI = HC + SC \quad (1)$$

where: LCCI = Living Coral Cover Index (%); HC = Hard Coral cover (%); SC = Soft Coral cover (%).

The LCCI represents the total percentage cover of living corals, including both hard and soft corals, and is used to evaluate the growth status and ecological condition of living coral communities in the coral reefs of Phu Quoc (**Table 5**).

3.4.3. Proposed Benthic Invertebrate Index for Coral Reefs in Phu Quoc, Vietnam (Drafted and Proposed by Luom Thanh Thai)

1. Development of the Benthic Invertebrate Assessment Index (RBI)

Among the large benthic invertebrates influencing coral reef health, the crown-of-thorns starfish (*Acanthaster cf. solaris/planci*) and the long-spined sea urchin (*Diadema* spp.) were identified as the two principal indicator taxa. Numerous studies have demonstrated that outbreaks of crown-of-thorns starfish represent one of the most serious biological threats to coral reefs because of their extensive predation on reef-building corals. In contrast, although *Diadema* spp. may occasionally cause localized damage to living corals during intensive grazing, their direct impact on coral mortality is generally much lower. Under normal population densities, they play an important ecological role by controlling macroalgal growth and maintaining ecological balance within coral reef ecosystems. However, unusually high population densities of *Diadema* spp. may adversely affect reef condition through excessive grazing and bioerosion. Therefore, in the present study, both crown-of-thorns starfish and *Diadema* spp. were incorporated as potential biological indicators of coral reef disturbance when their populations reached outbreak levels, thereby supporting the long-term monitoring and management of coral reef ecosystem health. This classification was developed based on published scientific evidence [41].

Based on the survey results of large benthic invertebrates, a Benthic Invertebrate Assessment Index (RBI) was developed to characterize the ecological structure of benthic invertebrate communities in the coral reef ecosystem (**Table 6**). The proposed RBI index is expressed as follows (Equation (2)):

$$RBI = (Beco) + (Bealef + Bede + Becasc + Besyfe) \quad (2)$$

where: Beco = coral-vorous organisms (crown-of-thorns starfish, *Acanthaster cf. solaris/planci*); Bealef = algal and epibenthic feeders (sea urchins, including long-spined black sea urchins (*Diadema* spp.) and collector sea urchins); Bede = detritivores (sea cucumbers); Becasc = carnivorous species (Triton’s trumpet, spiny lobsters, and cleaner shrimps); Besyfe = symbiotic and filter-feeding organisms (giant clams and fluted giant clams).

Table 5. Proposed criteria for coral reef assessment under the conditions of Phu Quoc, Vietnam.

No.	Percent Live Coral Cover (%)	Assessment Scale	Current Status in Phu Quoc, Vietnam (%)	Assessment Score (0.0–1.0)
1	>50–100	Good	56	Good
2	25–50	Medium		
3	<25	Poor		

Table 6. Proposed Assessment Scale for Coral Reef Invertebrates in Phu Quoc, Vietnam.

No.	Corallivorous Invertebrates (%)	Current Status of Non-Corallivorous Invertebrates (%)	Assessment Scale	Coral Reef Invertebrates in Phu Quoc, Vietnam (%)	Assessment Score of Phu Quoc, Vietnam
1	<10	>90	Good	<10	Good
2	10–30	70–90	Medium		
3	>30	<70	Poor		

Based on the Reef Health Index (RHI) framework and previous ecological studies, the benthic invertebrate community was classified according to the proportion of corallivorous invertebrates as follows: Good (<10%), Moderate (10–30%), and Poor or Outbreak Condition (>30%). This classification is proposed specifically for the assessment of coral reef ecosystems in Phu Quoc.

This index was designed to integrate the major functional groups of benthic invertebrates and to provide an ecological assessment of coral reef condition in Phu Quoc, Vietnam.

2. Proposed Reef Fish Assemblage Index for Coral Reefs in Phu Quoc, Vietnam (Proposed by Luom Thanh Thai)

Based on reef fish survey data collected during 2014–2023, a reef fish assemblage index (Fcore) was developed to assess the ecological status of coral reef fish communities in Phu Quoc, Vietnam.

The proposed reef fish assemblage index is expressed as follows (Equation (3)) (**Table 7**):

Table 7. Table of Proposed Assessment Scale for Coral Reef Fish in Phu Quoc, Vietnam.

No.	Status of Corallivorous Fish (%)	Status of Non-Corallivorous Fish (%)	Assessment Scale	Coral Reef Fish in Phu Quoc, Vietnam (%)	Assessment Score of Phu Quoc VN (0.0–1.0)
1	5–10	95	Good		
2	15–40	85	Medium		
3	>50	<50	Poor	<50	Poor

Based on the Reef Health Index framework for reef fish and previous studies, this study proposes a site-specific classification for the proportion of corallivorous fishes in Phu Quoc reefs. Specifically, values of <10% are classified as good, 10–30% as moderate, and >30% as poor or indicative of an outbreak condition [42].

$$RFI = (Ocf + Fcf) + (Her + Scr + Bro + Inv + Pis + Det + Fil) \quad (3)$$

where: Ofc and Fcf represent living benthic components, whereas Her, Scr, Bro, Inv, Pís, Det and Fil represent non-living substrate components.

Where: the coral-feeding group comprises obligate coral feeders (Ocf) and facultative coral feeders (Fcf). The non-coral-feeding group comprises herbivores (Her), scrapers/excavators (Scr), browsers (Bro), invertivores (Inv), piscivores (Pis), detritivores (Det), and filter feeders (Fil). These trophic groups are used to characterize the functional composition of reef fish communities and to assess the condition of coral reef ecosystem.

where:

RFI = overall status of the reef fish assemblage;

Ocf + Fcf = corallivorous fishes, including butterflyfishes, angelfishes, parrotfishes, and humpback parrotfishes.

Her + Scr + Bro + Inv + Pis + Det + Fil = Her (herbivores), Scr (scrapers/excavators), Bro (browsers), Inv (invertivores), Pis (piscivores), Det (detritivores), Fil (filter feeders), including non-corallivorous fish species recorded during the monitoring surveys in Phu Quoc.

3. Index of Sponge Impacts on Coral Reef Health

Sponges function as filter feeders, nutrient recyclers and habitat-forming organisms under normal conditions. However, excessive sponge cover, particularly by bioeroding or competitive species, may negatively affect coral reef health.

Sponges can be classified into several functional groups: filter feeders (Ff), symbiotic sponges (Ssp), bioeroding (boring) sponges (Bosp), which are capable of eroding calcareous substrates, space competitors (Spc), habitat-forming sponges (Hfsp), and nutrient recyclers (Nure).

Sponge covers play a dual ecological role in coral reef ecosystems. At low abundance, sponges contribute positively to reef health by filtering seawater, recycling nutrients, and providing habitat for reef-associated organisms. However, excessive sponge cover, particularly by bioeroding and competitive species, may inhibit coral growth, increase bioerosion, and reduce the resilience of coral reef ecosystems.

In this study, the sponge cover (SP) classification proposed for the coral reefs of Phu Quoc is as follows: Good (<5% sponge cover), Moderate (5–10%), and Poor (>10%).

In the case of Phu Quoc, sponge cover was 3.0% in 2023, with a mean value of 2.12% during the 2014–2023 period (**Table 3**). According to the sponge assessment criteria proposed in this study, these values indicate that the impact of sponges on the coral reef ecosystem is classified as good (**Table 8**).

Table 8. Scoring Scale for Sponge Impacts on Coral Reefs.

No	Spong Cover (%)	Impact Level	SPI of Phu Quoc, Vietnam
1	>5%	Good	Good
2	5–10%	Medium	
3	<10%	Poor	

4. Algal Impact Index on the Health of Phu Quoc Coral Reefs

Calcareous algae (CA) are considered the most beneficial algal group for coral reefs because they contribute to reef formation and structural stabilization while providing suitable settlement substrates for coral larvae. Turf algae (TA) represent an intermediate functional group. At low cover, they are a natural component of coral reef ecosystems and serve as an important food source for herbivorous organisms. However, when they become overly abundant, they compete with corals for space and other resources. Fleshy macroalgae (FS) pose the greatest potential threat to coral reefs. An increase in macroalgal cover is widely recognized as an indicator of coral reef degradation and a sign of a coral-to-algae phase shift, in which macroalgae become the dominant benthic component.

Overall, turf algae and fleshy macroalgae exert direct effects on coral growth and development, with fleshy macroalgae representing the greatest threat when they proliferate and dominate the reef.

In the case of the Phu Quoc coral reefs, fleshy macroalgal cover was 1% in 2023 and averaged 2% during the 2014–2023 period. Based on the algal impact assessment criteria proposed in this study, the Algal Cover Index (ACI) for the Phu Quoc coral reefs is classified as Good (**Table 9**).

Table 9. Proposed Assessment Scale for Algal Impacts on the Health of Phu Quoc Coral Reefs.

No	Algal Cover (%)	Impact Level	ACI of Phu Quoc, Vietnam
1	>20%	Good	Good
2	20–40%	Medium	
3	<40%	Poor	

5. Integrated Assessment of Coral Reef Ecosystem Health Based on Coral Condition, Benthic Invertebrates, Reef Fish, Sponges, and Algae (Developed and Proposed by Luom Thanh Thai)

$$SPI = Ff + Ssp + Bosp + Spc + Hfsp + Nure \quad (4)$$

$$ACI = CA + TA + FS \quad (5)$$

$$CREC = LCCI + RBI + RFI + SPI + ACI \quad (6)$$

Equations (1)–(6) constitute the coral reef ecosystem health assessment framework developed by the author based on field survey data and ecological evaluations (**Table 3**).

The Comprehensive Reef Ecosystem Condition (CREC) is assessed by integrating the major biological components that directly influence coral reef health, including: (1) Live Coral Cover Index (LCCI), representing the status of living corals; (2) Reef Benthic Invertebrate Index (RBI), representing the status of large benthic invertebrates affecting coral reefs; (3) Reef Fish Index (RFI), representing the functional composition of reef fish communities that directly influence coral reef ecosystems; (4) Sponge Impact Index (SPI), representing the percentage cover of sponges affecting coral growth and reef development; and (5) Algal Cover Index (ACI), representing the proportion of calcareous algae, turf algae, and fleshy macroalgae that influence coral growth and reef condition.

The overall coral reef ecosystem health index (CREC) is determined by integrating the assessment results of the five component indices described in Equations (1)–(5) to produce the comprehensive index presented in Equation (6). This integrated index reflects the temporal variation in the biological condition of the coral reefs of Phu Quoc based on the principal biological components influencing reef health.

The integrated assessment of the Phu Quoc coral reef ecosystem during the period 2014–2023 indicates that the coral reefs remain in good ecological condition according to the proposed assessment framework. Nevertheless, the results also suggest that the reef ecosystem is subject to potential environmental pressures. In particular, increases in BOD, COD, and $N\text{-}NO_2^-$ concentrations beyond the established environmental thresholds may adversely affect coral reef health. These environmental impacts are evaluated separately within the environmental assessment component of the framework. Therefore, strengthened conservation measures, effective management strategies, and ecological restoration programs are recommended to enhance ecosystem resilience and ensure the long-term sustainability of the Phu Quoc coral reef ecosystem (**Table 10**).

Table 10. Proposed Scoring Scale for Coral Reef Assessment Based on the Living Biological Components of the Phu Quoc Coral Reef Ecosystem.

No.	Level	LCCI	RBI	RFI	SPI	ACI	Assessment Score of Phu Quoc VN
1	Good	Good	Good		Good	Good	Good
2	Medium			Medium			
3	Poor						

3.5. Validation of the Proposed Assessment Index (CREC)

To evaluate the applicability of the proposed Comprehensive Reef Ecosystem Condition (CREC) index, its performance was assessed using ecological indicators measured during the long-term monitoring program, including live coral cover, reef fish assemblages (RFI), and large benthic macroinvertebrate communities (RBI). These biological variables are widely recognized as reliable indicators of coral reef condition and ecosystem resilience [42,43].

Regression analysis showed that benthic macroinvertebrate assemblages were moderately associated with live coral cover ($R^2 = 0.244$, $R = 0.487$), whereas reef fish assemblages exhibited only a weak relationship ($R^2 = 0.0436$, $R = 0.209$). Multiple regression incorporating both ecological components provided a similar level of explanation ($R^2 = 0.244$, $R = 0.490$), as described by the following equation:

$$Y_{CREC} = 35.93144 + 0.135623_{XRBI} + 0.026171_{XRFI}$$

These results indicate that benthic macroinvertebrate communities are more closely associated with coral condition than reef fish assemblages, although the moderate explanatory power suggests that additional environmental factors also contribute to temporal variation in reef ecosystem condition.

The observed relationships are consistent with established coral reef ecological theory. Reefs with high live coral cover generally supported stable benthic communities, lower abundances of coral-damaging invertebrates, and relatively balanced reef fish assemblages. In contrast, degraded reefs were characterized by reduced coral cover, increased proportions of dead substrate or algal dominance, and altered biological communities, consistent with previous studies [44,45].

Comparison among representative reef conditions further demonstrated the effectiveness of the CREC framework. Reefs with live coral cover exceeding approximately 50% generally exhibited limited biological disturbance and were classified as good. Reefs with intermediate coral cover (30–50%) produced intermediate CREC values, whereas degraded reefs (<30% live coral cover), characterized by greater proportions of rubble or dead substrate and stronger biological disturbance, consistently received the lowest CREC scores and were classified as moderate or poor.

The validation also indicated that CREC was primarily influenced by the Live Coral Cover Index (LCCI), highlighting the dominant contribution of live coral cover and benthic substrate composition to overall reef condition. In comparison, the RBI and RFI components showed positive but weaker relationships with the integrated index, suggesting that they provide complementary ecological information rather than serving as the principal drivers of reef condition.

The proposed CREC framework effectively distinguished reefs in good ecological condition from those exhibiting different levels of degradation by integrating coral condition, benthic macroinvertebrates, reef fish assemblages, sponge cover, and algal communities into a single ecological assessment metric.

Nevertheless, the present evaluation should be regarded as an initial internal validation because the biological variables used for validation also constitute components of the CREC framework. Consequently, the current results primarily demonstrate the internal consistency of the index rather than its independent predictive capability. Furthermore, several important ecological indicators, including coral recruitment, reef fish biomass, structural complexity, and long-term biodiversity metrics, were not consistently available throughout the monitoring period. In addition, CREC has so far been developed and evaluated only within the Phu Quoc Marine Protected Area, while modifications to survey locations limited strict temporal comparisons.

Future studies should strengthen the validation of the proposed framework by incorporating independent datasets from other coral reef monitoring programs together with statistical cross-validation approaches, such as k-fold or leave-one-out cross-validation, to evaluate its predictive performance and robustness. Comparisons with internationally recognized coral reef assessment frameworks, including Reef Check, the Global Coral Reef Monitoring Network (GCRMN), the Atlantic and Gulf Rapid Reef Assessment (AGRRA), and the International Union for Conservation of Nature (IUCN) Red List of Ecosystems framework, would provide independent benchmarks for assessing CREC's ecological sensitivity and classification accuracy. Validation across multiple reef systems with different environmental conditions and disturbance histories will further improve the general applicability, reliability, and transferability of the proposed framework for long-term coral reef ecosystem assessment and management.

3.6. Water Quality Dynamics

3.6.1. Dry Season

During 2014–2023 (**Tables 11** and **12**), seawater temperature (27.5–30.2 °C), salinity (31.0–33.5‰), chloride (13,188–15,500 mg/L), pH (7.85–7.95), DO (5.19–6.27 mg/L), phosphate (0.045–0.060 mg/L), and dissolved Fe^{2+} (0.0126–0.0160 mg/L) remained relatively stable, indicating consistent environmental conditions in the Phu Quoc Marine Protected Area. TSS ranged from 19.0 to 29.0 mg/L, while BOD (7.5–12.5 mg/L) and COD (18.9–43.3 mg/L) showed greater interannual variation. Nitrite, nitrate, and ammonia remained at relatively low concentrations throughout the monitoring period.

Table 11. Assessment of chemical water quality and nutrient pollution indicators in the marine protected area of Phu Quoc, Vietnam (March in dry season).

Years	T °C	Salinity (‰)	TSS (mg/L)	BOD (mg/L)	Cl^- (mg/L)	Coliform (MPN/100 mL)	pH	DO (mg/L)	COD (mg/L)	N-NO_2^- (mg/L)	N-NO_3^- (mg/L)	N-NH_3 (mg/L)	PO_4^{3-} (mg/L)	Fe^{2+} (mg/L)
2014	30	32	19	7.5	14,319	620	7.95	5.29	34.05	0.03	0.03	0.04	0.045	0.016
2015	30	31.5	19.5	8	13,542	650	7.92	5.19	43.3	0.018	0.014	0.045	0.05	0.013
2016	27.5	31	29	9	14,436	710	7.90	6.27	25.35	0.024	0.09	0.042	0.048	0.0157
2017	27.5	31	25.25	8.5	13,188	750	7.88	5.88	30.62	0.01	0.08	0.043	0.046	0.014
2018	29.5	32	24.5	9.2	14,000	820	7.89	5.70	24.2	0.018	0.11	0.051	0.047	0.013
2019	29	31	27	10	14,800	860	7.91	5.78	23.35	0.02	0.08	0.06	0.05	0.014
2020	29	32	25.2	11	15,500	970	7.93	5.87	18.9	0.02	0.09	0.07	0.055	0.0126
2021	30.2	33.5	27.8	11	14,800	1,150	7.85	5.86	20	0.025	0.10	0.065	0.06	0.016
2022	29.4	32	27.7	12.5	14,200	960	7.90	5.86	27.7	0.021	0.09	0.055	0.055	0.015
2023	29.2	31	26	10.8	14,300	1,100	7.92	5.88	21.8	0.02	0.12	0.058	0.052	0.016
SE	0.302	0.25	1.07	0.50	207.34	57.90	0.009	0.98	2.34	0.0016	0.0106	0.003	0.0015	0.0004

Table 12. Assessment of chemical water quality and nutrient pollution indicators in the marine protected area of Phu Quoc, Vietnam (September in rainy season).

Years	T °C	Salinity (‰)	TSS (mg/L)	BOD (mg/L)	Cl^- (mg/L)	Coliform (MPN/100 mL)	pH	DO (mg/L)	COD (mg/L)	N-NO_2^- (mg/L)	N-NO_3^- (mg/L)	N-NH_3 (mg/L)	PO_4^{3-} (mg/L)	Fe^{2+} (mg/L)
2014	29.4	23	29	6.5	13,219	1,200	7.25	5.09	29.05	0.04	0.06	0.169	0.08	0.012
2015	26.6	22	29.5	7.5	12,542	1,300	7.22	5.02	38.3	0.05	0.064	0.16	0.07	0.011

Table 12. *Cont.*

Years	T °C	Salinity (‰)	TSS (mg/L)	BOD (mg/L)	Cl^- (mg/L)	Coliform (MPN/100 mL)	pH	DO (mg/L)	COD (mg/L)	$N\text{-}NO_2^-$ (mg/L)	$N\text{-}NO_3^-$ (mg/L)	$N\text{-}NH_3$ (mg/L)	PO_4^{3-} (mg/L)	Fe^{2+} (mg/L)
2016	28.5	23	29	7.5	12,436	1,400	7.40	5.27	20.35	0.04	0.09	0.17	0.09	0.013
2017	28.1	21.5	26.5	7.5	12,188	1,500	7.33	5.38	25.62	0.055	0.09	0.13	0.088	0.012
2018	29.5	23.5	25.5	8	13,265	1,400	7.39	5.20	19.2	0.05	0.11	0.095	0.09	0.011
2019	29.8	24	27	9.2	13,480	1,600	7.31	5.28	18.35	0.06	0.18	0.11	0.092	0.012
2020	29	23.5	25.5	9.8	13,460	2,100	7.33	5.27	20.9	0.07	0.21	0.16	0.055	0.0122
2021	29.5	21.5	29.8	9.2	12,400	2,600	7.35	5.36	20	0.08	0.12	0.15	0.086	0.013
2022	29.6	23	29.7	10.5	12,200	2,300	7.40	5.28	22.7	0.061	0.09	0.12	0.075	0.013
2023	28.5	24	28	9.8	12,300	2,100	7.42	5.38	20.8	0.058	0.12	0.12	0.11	0.012
SE	0.307	0.296	0.538	0.416	170.208	152.93	0.021	0.038	1.93	0.0039	0.015	0.0085	0.005	0.0002

3.6.2. Rainy Season

During 2014–2023 (**Tables 11** and **12**), temperature ranged from 26.6 to 29.8 °C, while salinity decreased to 21.5–24.0‰ because of seasonal freshwater inputs. pH, DO, and dissolved Fe^{2+} remained relatively stable, whereas BOD, COD, and coliform abundance exhibited greater temporal variability. Nutrient concentrations ($N–NO_2^-$, $N–NO_3^-$, $N–NH_3$, and PO_4^{3-}) were generally higher than in the dry season but fluctuated within moderate ranges.

Overall, coral reefs in Phu Quoc exhibit signs of ecological recovery but have not yet reached a near-pristine condition, which is typically characterized by live coral cover exceeding 75%, dominance of reef-building corals, low macroalgal cover (<15%), and limited coral mortality or bleaching (<10–20%) [46–48].

Across both seasons (**Tables 11** and **12**), BOD and COD consistently exceeded the limits of the Vietnamese National Technical Regulation on Marine Water Quality (QCVN 10-MT:2015/BTNMT), indicating persistent organic matter inputs into coastal waters. Nitrite ($N–NO_2^-$) exceeded the regulatory threshold only during the rainy season from 2017 onward, suggesting an increasing influence from surface runoff and land-based pollution. In contrast, pH, DO, TSS, nitrate, ammonia, phosphate, Fe^{2+}, and coliform generally remained within national standards, although nutrient and coliform concentrations tended to increase during the rainy season. These results indicate that water quality in the Phu Quoc Marine Protected Area remains generally suitable for coral reef development, while elevated BOD, COD, and seasonal nitrite enrichment should remain priorities for long-term monitoring and management.

3.6.3. Statistical Analysis of Water Quality Trends

Long-term monitoring from 2014 to 2023 indicated generally stable water quality in the Phu Quoc Marine Protected Area, although clear seasonal differences were observed. Concentrations of $N–NO_3^-$, $N–NH_3$, PO_4^{3-}, $N–NO_2^-$, and coliform were consistently higher during the rainy season, reflecting increased terrestrial runoff and nutrient inputs. Despite interannual fluctuations, nitrate (0.014–0.120 mg/L in the dry season; 0.060–0.210 mg/L in the rainy season) and phosphate (0.045–0.060 mg/L; 0.055–0.120 mg/L, respectively) showed no persistent increasing trend. In contrast, BOD and coliform gradually increased after 2019, suggesting enhanced organic and microbial inputs, although no evidence of severe or persistent eutrophication was detected.

Comparison with benthic monitoring demonstrated that live coral cover increased from 38.59% in 2014 to more than 50% during 2021–2023, while macroalgal cover remained below 5%. These observations indicate that the nutrient levels recorded during the study period did not promote widespread algal proliferation or prevent coral recovery. The continued increase in coral cover despite moderate increases in BOD and coliform suggests that reef resilience, herbivory, and effective management may have mitigated potential impacts of declining water quality.

Among the monitored environmental variables, only BOD, COD, and $N–NO_2^-$ consistently exceeded the Vietnamese regulatory limits and were therefore selected for correlation analysis with live coral cover. Linear regression showed a strong positive relationship between live coral cover and BOD during the dry season (R^2 = 0.473, R =

0.687), whereas correlations with COD ($R^2 = 0.0416$, R = 0.204) and rainy-season $N–NO_2^-$ ($R^2 = 0.0104$, R = 0.102) were weak.

Paired-sample *t*-tests further confirmed significant seasonal differences for most water quality variables. Salinity and chloride were significantly lower during the rainy season ($p < 0.001$) owing to freshwater dilution, whereas BOD, COD, coliform, DO, pH, Fe^{2+}, $N–NO_2^-$, $N–NO_3^-$, $N–NH_3$, and PO_4^{3-} were significantly higher ($p < 0.05$). Water temperature ($p = 0.424$) and TSS ($p = 0.053$) did not differ significantly between seasons.

The statistical analyses indicate that seasonal runoff substantially influences nutrient dynamics in the Phu Quoc Marine Protected Area. However, among the pollutants exceeding environmental standards, only BOD exhibited a relatively strong relationship with live coral cover, suggesting that organic pollution represents the principal water-quality concern for coral reef conservation in the study area. The weak relationships observed for COD and $N–NO_2^-$ further indicate that the current levels of nutrient enrichment have not yet translated into measurable declines in coral cover. Future studies should incorporate longer time series, repeated-measures analyses, and additional ecological indicators, including coral recruitment, fish biomass, and benthic community composition, to better quantify the influence of water-quality dynamics on coral reef resilience.

4. Discussion

Long-term monitoring demonstrated an overall improvement in coral reef condition in the Phu Quoc Marine Protected Area during 2014–2023. Mean live coral cover increased from 38.59% in 2014 to 58.0% in 2023, although a temporary decline was observed during 2019–2020. The subsequent recovery to more than 50% by 2022–2023 suggests that the reef ecosystem retained a relatively high capacity for recovery following disturbance rather than experiencing continuous degradation. Similar recovery trajectories have been reported for coral reef ecosystems where disturbances remain limited and ecological resilience is maintained [42,43].

Most physicochemical parameters remained relatively stable throughout the monitoring period, while seasonal increases in nutrients, BOD, and coliform were not accompanied by persistent declines in live coral cover or substantial increases in macroalgal dominance. Filamentous and fleshy macroalgae consistently accounted for less than 5% of benthic cover. These observations suggest that the recorded environmental variation was not associated with an obvious coral–macroalgal phase shift during the study period. However, the present study does not demonstrate a direct causal relationship between water quality and coral recovery, because coral reef responses are influenced by the magnitude, duration, and interaction of multiple environmental and ecological stressors [44,45]. Similarly, the relatively stable abundance of coral-associated butterflyfishes is consistent with the persistence of suitable coral habitat, although this relationship should be interpreted as an ecological association rather than direct evidence of causation [46].

The recovery pattern observed in Phu Quoc is broadly consistent with those reported from coral reef ecosystems across the Indo-Pacific region. As observed on parts of the Great Barrier Reef and reefs in Indonesia and the Philippines, improvements in reef condition may occur where local disturbances remain limited and management measures reduce chronic anthropogenic pressures. Nevertheless, reef recovery is inherently a multifactorial process. In addition to local environmental conditions, recovery may be influenced by interactions among fishing pressure, sedimentation, nutrient inputs, coral recruitment, regional oceanographic processes, climate variability, and the frequency or severity of coral bleaching events. The relative importance of these factors could not be quantified in the present study, and therefore the observed temporal trends should be interpreted as ecological patterns rather than evidence of direct causal mechanisms [49–53].

These findings highlight the importance of continued management within the Phu Quoc Marine Protected Area. The relatively good ecological condition of less-disturbed reefs suggests that reducing local anthropogenic pressures may contribute to maintaining reef resilience. Nevertheless, effective conservation should continue to emphasize law enforcement, long-term ecological monitoring, watershed management to reduce land-based nutrient inputs and sedimentation, protection of key functional fish groups, and community participation to support adaptive ecosystem management.

Several limitations should be acknowledged. Coral recruitment, juvenile coral survival, reef fish biomass, structural complexity, and bleaching history were not consistently quantified throughout the monitoring period, limiting the ability to evaluate the mechanisms underlying reef recovery. In addition, some ecological indicators were based partly on semi-quantitative assessments, while several potentially important drivers, including regional hydrodynamic connectivity, fisheries pressure, and climate variability, were not explicitly incorporated into the analyses. Consequently, the present findings should be interpreted as describing ecological trends and associations rather than establishing direct cause-and-effect relationships.

Future studies should integrate long-term coral demographic surveys, quantitative reef fish biomass, structural complexity, hydrodynamic connectivity, fisheries information, bleaching records, climate data, and independent environmental datasets to better evaluate the interacting mechanisms regulating coral reef recovery and resilience. Such information would improve understanding of coral reef dynamics in the Phu Quoc Marine Protected Area and strengthen ecosystem-based management and long-term conservation planning for coral reefs in Vietnam and across the Indo-Pacific region.

5. Conclusions

Long-term monitoring of coral reefs in the Phu Quoc Marine Protected Area from 2014 to 2023 showed an overall improvement in reef condition, although temporal variations were observed throughout the monitoring period. Mean live coral cover increased from 38.59% in 2014 to 58.0% in 2023. According to the proposed assessment criteria, most surveyed reefs were classified as being in good condition. However, localized coral mortality and differences among monitoring sites indicate that reef condition varied both spatially and temporally.

The benthic macroinvertebrate community exhibited relatively low species diversity and was dominated by long-spined sea urchins (*Diadema* spp.), while crown-of-thorns starfish (*Acanthaster cf. solaris/planci*) were not recorded throughout the study period. These observations suggest that no significant outbreaks of crown-of-thorns starfish occurred during the monitoring period. However, the ecological role of *Diadema* spp., as well as the absence of crown-of-thorns starfish, should not be regarded as direct causes of the observed changes in coral reef condition, as the present study does not provide sufficient analytical evidence to support such causal relationships.

Reef fish assemblages were dominated by corallivorous butterflyfishes, whereas several ecologically important functional groups, particularly large herbivorous fishes and top predators, were recorded at relatively low abundances at many survey sites. This pattern suggests that, although live coral cover improved during most of the study period, the recovery of reef fish assemblages may still be incomplete.

The integrated assessment framework proposed in this study, comprising the Living Coral Cover Index (LCCI), Reef Benthic Invertebrate Index (RBI), Reef Fish Index (RFI), Sponge Index (SPI), Algal Cover Index (ACI), and the Comprehensive Reef Ecosystem Condition (CREC) index, provides a practical approach for integrating multiple biological indicators into a single ecological assessment. Application of the framework indicated that the surveyed coral reefs generally maintained good ecological condition throughout the study period. However, the framework has so far been developed and validated only within the Phu Quoc Marine Protected Area. Therefore, further validation using independent datasets, application across different coral reef regions, and comparisons with internationally recognized coral reef assessment frameworks are required before broader implementation.

Water quality in the study area generally remained within ranges considered suitable for coral reef ecosystems during both the dry and rainy seasons, although several nutrient and organic matter parameters exhibited seasonal increases. The present study does not demonstrate a direct causal relationship between water quality and changes in coral reef condition. Nevertheless, the observed environmental trends highlight the importance of continued water-quality monitoring, strengthened management of land-based sources of pollution, and long-term ecological monitoring to improve understanding of the factors influencing the condition and resilience of coral reef ecosystems in the Phu Quoc Marine Protected Area.

Author Contributions

Conceptualization, L.T.T.; methodology, L.T.T. (proposal equations); software, Q.T.L., L.T.T., M.D. and G.H.P.; validation, Q.T.L., L.T.T., M.D. and G.H.P.; formal analysis, Q.T.L., L.T.T., M.D., G.H.P., A.H.N., T.T.P.H. and L.T.P.P.; investigation, Q.T.L., L.T.T., M.D., G.H.P., A.H.N., T.T.P.H. and L.T.P.P.; resources, Q.T.L., L.T.T., M.D., G.H.P., A.H.N., T.T.P.H. and L.T.P.P.; data curation, Q.T.L., L.T.T., M.D., G.H.P., A.H.N., T.T.P.H. and L.T.P.P.; writing—original draft preparation, Q.T.L., L.T.T., M.D. and G.H.P.; writing—review and editing, L.T.T., M.D. and G.H.P.; visualization, L.T.T., M.D. and G.H.P.; supervision, L.T.T.; project administration, L.T.T.; funding acquisition, Q.T.L. and L.T.T. All authors have read and agreed to the published version of the manuscript.

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Data Availability Statement

Data are available from the corresponding author upon reasonable request. In Kien Giang University, the Protected Marine Area of the Department of Agriculture and Environment in An Giang province.

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Conflicts of Interest

The authors declare no conflict of interest.

AI Use Statement

The authors certify that this manuscript was prepared entirely through their own scientific work and expertise, without the use of artificial intelligence (AI) tools for writing, data analysis, interpretation, or content generation.

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