



Associations Between Algae, Substrate Characteristics, and Herbivorous Fish in Coral Reef Ecosystems of Pari Island, DKI Jakarta

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ABSTRACT

Coral reefs around Pari Island, DKI Jakarta, provide vital habitats supporting corals, algae, and reef fish. This study examined the associations between algal cover, bottom substrates, and herbivorous fish abundance at four sites (South, West, East, and North Pari) during July 2020, October 2020, and January 2021. Using the line intercept transect (LIT) method at depths of 3 and 10m, data on substrate composition, algal types, herbivorous fish, and water quality were collected. Algal cover ranged from 7.23 to 31.48%, with the highest at shallow depths (3m) and during the transitional season (October). Turf algae dominated on dead coral substrates, while macroalgae such as *Padina*, *Sargassum*, and *Halimeda* were common on sandy areas. Correlation analysis showed strong positive relationships between algae and dead hard coral ($r = 0.823$, $P < 0.01$) and sand ($r = 0.765$, $P < 0.05$), but a weak link with herbivorous fish ($r = -0.267$, $P > 0.05$). Principal component analysis indicated that macroalgae, herbivorous fish, and dead coral contributed most to ecosystem variation (55.97%). Elevated nitrate levels (0.124 mg. L^{-1}) exceeded national standards, promoting algal growth. Nutrient enrichment and substrate conditions, rather than herbivory, were identified as the main drivers of algal proliferation on Pari Island reefs.

INTRODUCTION

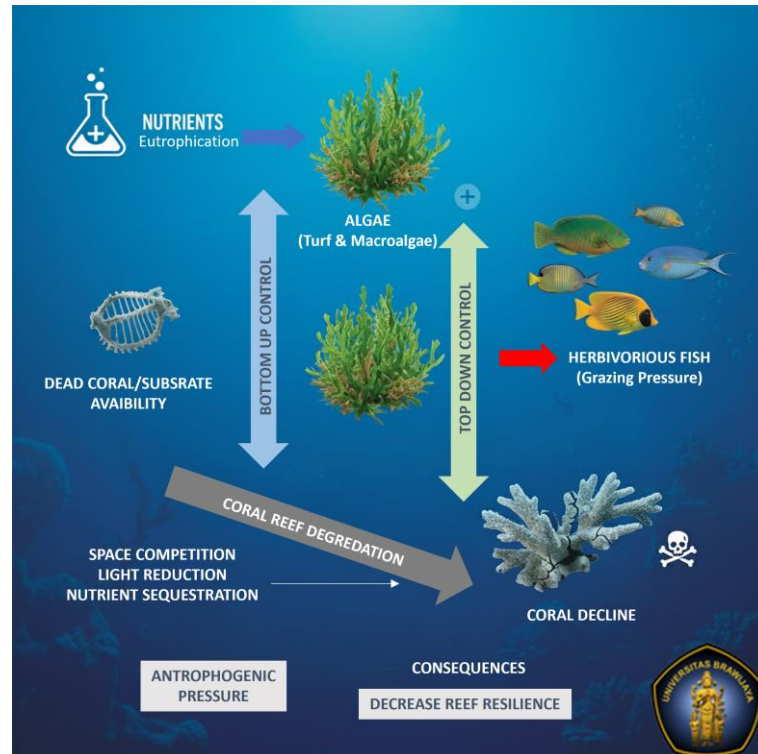
Coral reefs are crucial global ecosystems sustained by the delicate balance between corals, algae, and consumers. The dynamics of algal communities particularly turf and

macroalgae are central to ecosystem health, as they can rapidly shift community structure. Following stressors like coral mortality or nutrient loading, algae act as powerful competitors, suppressing coral recruitment and recovery by monopolizing space, light, and nutrients (**Clements & Hay, 2023; Cornwall *et al.*, 2023**). This process of ecological phase shift, where algal proliferation leads to coral decline, is a primary driver of reef degradation worldwide (**Inagaki & Longo, 2024**).

The health of reefs, therefore, is fundamentally dependent on the mechanisms that regulate algal growth. Algal distribution and biomass are mediated by three critical factors: substrate type (e.g., dead coral availability), nutrient supply (bottom-up control), and grazing intensity from herbivorous fish (top-down control) (**Teichert *et al.*, 2020**). However, anthropogenic pressures, particularly eutrophication and overfishing, often disrupt this balance. The resultant increase in nutrient availability, coupled with the decline in grazer populations, diminishes the reef's natural resilience, allowing unchecked algal expansion (**Wei *et al.*, 2025**).

Pari Island, located near the heavily urbanized Jakarta Bay, is a key reef ecosystem exposed to significant nutrient influx and wastewater discharge (**Herandarudewi & Yusuf, 2014; Shadrina *et al.*, 2023**). While the area's coral diversity has been studied, there is a critical gap in the quantitative understanding of the specific ecological interactions driving the observed degradation. Previous studies lack the concurrent analysis of local factors, leaving the complex interrelationships among algae, specific bottom substrate types (e.g., dead coral), and the effectiveness of the herbivorous fish abundance in this nutrient-enriched environment largely underexplored.

To address this gap, this study aims to investigate the relationships between algae, substrate composition, and herbivorous fish abundance on Pari Island's coral reefs. Specifically, the study seeks to: (i) determine the spatial and temporal distribution of algae, (ii) assess the relationship between algal cover and substrate types, and (iii) evaluate the role of herbivorous fish in regulating algal growth. By examining these interactions, this research will contribute to a deeper understanding of reef ecosystem dynamics, particularly in nutrient-enriched tropical environments, and provide insights for more effective coral reef management and conservation strategies on the Thousand Islands.



Conceptual framework

MATERIALS AND METHODS

Environmental permit

This research was conducted in full adherence to established ethical guidelines and institutional regulations concerning both field research and animal welfare. The study protocol involving observation and handling of fish species was reviewed and approved by the Animal Care and Use Committee (ACUC) of IPB University under the ethics registration number ACUC 03_2020 IPB as well as under supervised LIPI.

Study area

This study was conducted around Pari Island (5°52'40" S, 106°36'55" E), located within the southern part of the Thousand Islands group (Kepulauan Seribu), DKI Jakarta, Indonesia. Four reef sites were selected: South Pari, West Pari, East Pari, and North Pari, representing different exposure conditions to coastal currents and anthropogenic inputs. The western site faces the open sea, the southern site lies within a Marine Protected Area, while the eastern site is influenced by effluents from Jakarta Bay, and the northern site faces the Java Sea.

Sampling design

Field observations were carried out during three sampling periods, July 2020 (dry season), October 2020 (transitional season), and January 2021 (rainy season) to capture

temporal variability. At each site, data were collected at two depth strata: shallow (3 m) and deep (10 m). Three replicate transects (20 m each) were established per depth, yielding a total of 24 transects per sampling period. (Fig. 1).

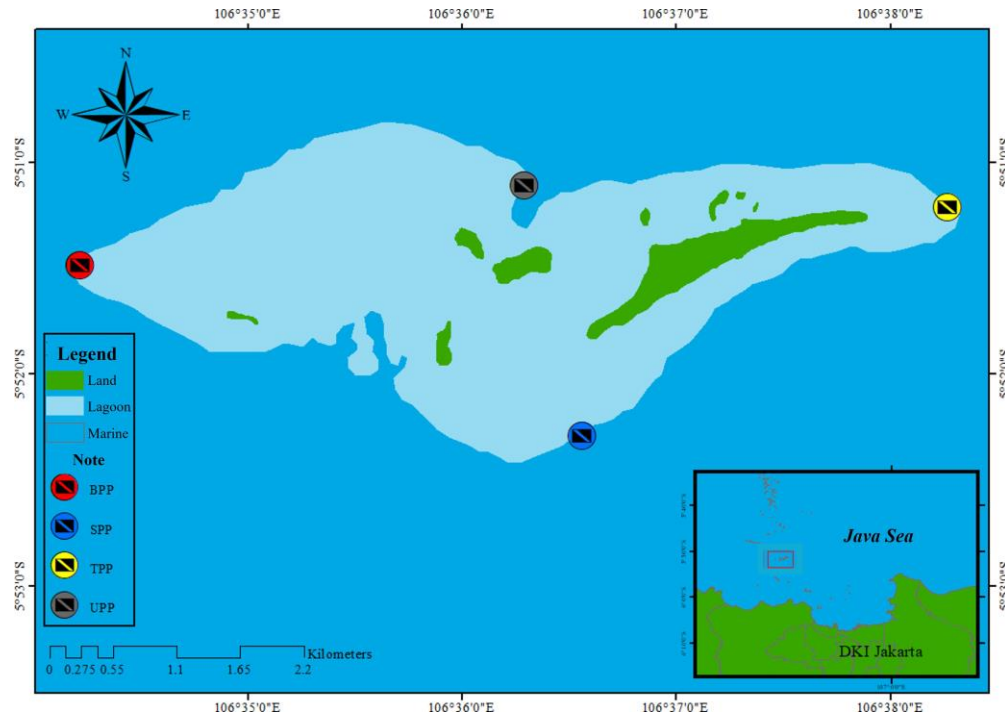


Fig. 1. Study area of the current status assessment across the Pari Island (The map shows the distribution of the sampling sites included in this study)

Data collection

Algal and substrate observation

The line intercept transect (LIT) method was used to quantify algal and substrate composition (Urbina-Barreto *et al.*, 2021). Along each transect line (20m), every benthic component intercepted beneath the measuring tape was recorded. Categories included live coral, dead coral, coral rubble, sand, and rock. Algae were identified morphologically to genus level following published method (Herandarudewi & Yusuf, 2014) and classified into turf algae and macroalgae (Islamy *et al.*, 2024a, b, 2025c) (e.g., *Padina*, *Gracilaria*, *Sargassum*, *Turbinaria*, *Caulerpa*, and *Halimeda*).

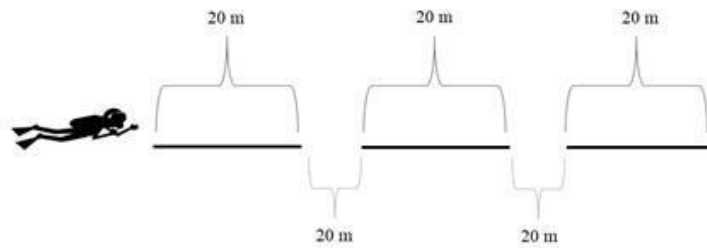


Fig. 2. Illustration of coral reef and algae data collection

Herbivorous fish census

Herbivorous fish were surveyed using the underwater visual census (UVC) technique along each LIT transect with a 2.5 m belt width on both sides, covering 100m² per transect (Urbina-Barreto *et al.*, 2021). Individuals were identified to genus level, and the total number per transect was recorded.

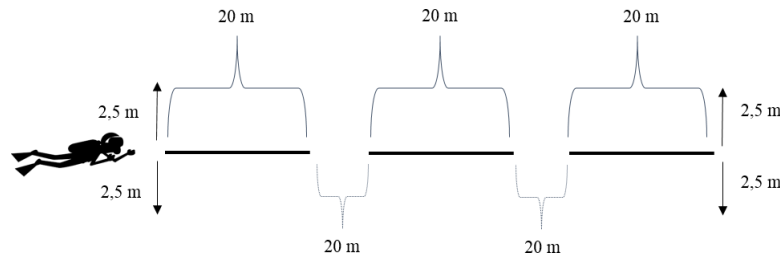


Fig. 3. Illustration of reef fish data collection

Water quality measurement

In situ measurements of temperature, salinity, and dissolved oxygen (DO) were taken using portable meters. Water samples for nitrate (NO₃-N) and phosphate (PO₄-P) analyses were collected in 500mL polyethylene bottles, stored on ice, and analyzed in the laboratory using spectrophotometry (Islamy *et al.*, 2024). Measured values were compared with Indonesian marine water quality standards (Islamy *et al.*, 2025a, b, c).

Table 1. Physic-chemical parameters of observed waters

Parameter	Unit	Measuring Instrument
Depth	M	Deep gauge
Temperature	°C	Thermometer
Salinity	Psu	Refractometer
Dissolved oxygen	mg/L	Winkler titration
Nitrate (NO ₃ -N)	mg/L	Spectrophotometer
Phosphate (PO ₄ -P)	mg/L	Spectrophotometer

Data analysis

Percentage cover (%) of algal cover

Percentage cover was employed as a means of evaluating the condition of algal cover in an aquatic environment through the utilisation of the line intercept transect method. The identification of algal cover was achieved through the delineation of a transect line (Urbina-Barreto *et al.*, 2021; Masithah & Islamy, 2023).

Algae cover (%)

Algae cover (%) is a key metric in aquaculture used to quantify the daily percentage increase in an organism's weight over a given period. It provides insights into growth efficiency under varying environmental and dietary conditions. The SGR is calculated using the following equation:

$$\text{Algae cover (\%)} = \frac{A}{B} \times 100$$

Description:

A : Total length of algae category (cm)

B : Transect length (cm) observed (6000cm)

Composition of algae species

The analyses were conducted by examining and categorizing the identified algae types in the line transects at each observation location. The macroalgae species were identified at the genus level, as well as other types of algae, such as turf algae on the bottom substrate. This was done in accordance with the methodology described by (Herandarudewi & Yusuf, 2014; Masithah & Islamy, 2023). Based on the types of algae found, several types of algae that live in the coral reef ecosystem on Pari Island can be identified, as well as the percentage of each type of algae.

Length of substrate

The percentage of bottom substrate served to determine the condition of living coral reefs in waters and the composition of the bottom substrate, both biotic and abiotic. This condition had a relationship with live coral cover and diversity of benthic organisms. The method used was line intercept transect (Urbina-Barreto *et al.*, 2021), which was formulated as follows:

$$\text{Length of substrate (\%)} = \frac{A}{B} \times 100$$

Description:

A : Length of substrate parameter (cm)

B : Transect length (cm) observed (6000 cm)

Coral condition assessment was oriented towards the quality criteria for the percentage of coral reef cover, as set forth by the Minister of Environment Decree No. 4 Kep-04/MENLH/02/2001. The following criteria were used to assess the quality of coral reefs:

Table 2. Quality criteria for percentage coral reef cover

Percentage of live hard coral cover	Category per hard coral cover percentage
0-24.9%	Bad
25- 49.9%	Medium
50- 74.9%	Good
75- 100%	Very Good

Abundance of herbivorous fish

The term "herbivorous fish abundance" referred to the number of herbivorous fish observed at a given location, expressed as a ratio per unit area of observation transect. This metric was closely linked to the growth of algae, which play a crucial role in the dynamics of the surrounding coral reef ecosystem. The calculation of herbivorous fish abundance could be performed using the following formula:

$$D = \frac{N_i}{A}$$

Description:

D : Abundance (Ind/m²) N_i : Number of individuals

A : Observation transect area (300m²)

Relationship between algae, bottom substrate and herbivorous fish abundance

The correlation analysis employed in this study aimed to ascertain the interrelationships between multiple variables, including the percentage of algae, the diversity of algae species, the abundance of herbivorous fish, and the percentage of bottom substrate, comprising the percentage of dead hard coral, sand, broken coral, rocks, and live coral cover.

Statistical analysis

All statistical analyses were conducted using the R statistical environment (version 4.1.0), leveraging appropriate packages for assumption testing, correlation, and multivariate pattern analysis. The analytical approach was structured in three phases: assumption testing, bivariate analysis, and dimensionality reduction.

Assumption testing and data preparation

Prior to primary analyses, the distributional properties of the data were assessed:

- Normality Test: The normality of key continuous biological and environmental variables was assessed using the Shapiro-Wilk test. Variables exhibiting significant departure from normality ($P < 0.05$) were subjected to appropriate transformation (e.g., $\log_{10}$ or square root) to improve adherence to the assumptions of parametric tests.
- Data Standardization: For the subsequent principal component analysis (PCA), all data were standardized (Z-scored) to ensure that variables were equally weighted, regardless of their original measurement scale or magnitude.

Bivariate analysis: Pearson's correlation

To quantify the strength and direction of linear relationships among the substrate characteristics (e.g., dead coral, sand) and the biota parameters (e.g., total algal cover, live hard coral cover, herbivorous fish biomass), the Pearson's product-moment correlation coefficient (r) was calculated for all pairwise combinations.

- Interpretation of r : The coefficient ranges from -1 (perfect negative correlation) to +1 (perfect positive correlation), with 0 indicating the absence of a linear relationship.
- Significance Testing: The statistical significance of each correlation coefficient was determined using a two-tailed t-test, testing the null hypothesis ($H_0: r = 0$). A significance threshold was set at $P < 0.05$ for the rejection of the null hypothesis.

Dimensionality reduction: Principal component analysis (PCA)

PCA was applied to the standardized multivariate dataset to reduce dimensionality and identify the dominant underlying ecological gradients. The rigor of the analysis was established by confirming prerequisites:

- Suitability Assessment:
 - The Kaiser-Meyer-Olkin (KMO) measure of sampling adequacy was calculated; a value of $KMO > 0.5$ was required to confirm sufficient shared variance among variables.
 - Bartlett's Test of Sphericity was performed; a statistically significant result < 0.05 verified that the correlation matrix was significantly different from an identity matrix, thus justifying the reduction procedure.
- Component Extraction: Components were extracted using the Kaiser criterion, retaining only components with an eigenvalue ≥ 1 .
- Factor Loading Interpretation: The structure of the retained components was interpreted based on the factor loadings, with coefficients ≥ 0.6 considered highly influential in defining the ecological characteristics of the component.

Water conditions

The data on the condition of marine waters in the coral reef ecosystem on Pari Island was used as supporting evidence to demonstrate the impact of pollution on the water quality. The data were compared with the concentration of water quality parameters and class III quality standards for aquatic biota. The observations on the physical and chemical parameters of the waters were also compared with the water quality standards that refer to the Decree of the Minister of Environment No. 51 of 2004.

RESULTS

1. Percentage of algae cover

The total percentage of algal cover across all observation sites ranged from 7.23 to 31.48%. Spatially, algal cover was consistently higher at the shallow depth (3m) than at the deep depth (10m). The highest recorded cover was 31.48% at the West Pari site (3m), while the lowest was 7.23% at East Pari (10m) (Fig. 5). Temporally, algal growth peaked during the transitional season (October), with average cover percentages ranging from 27.58 to 35.98% (Fig. 4).

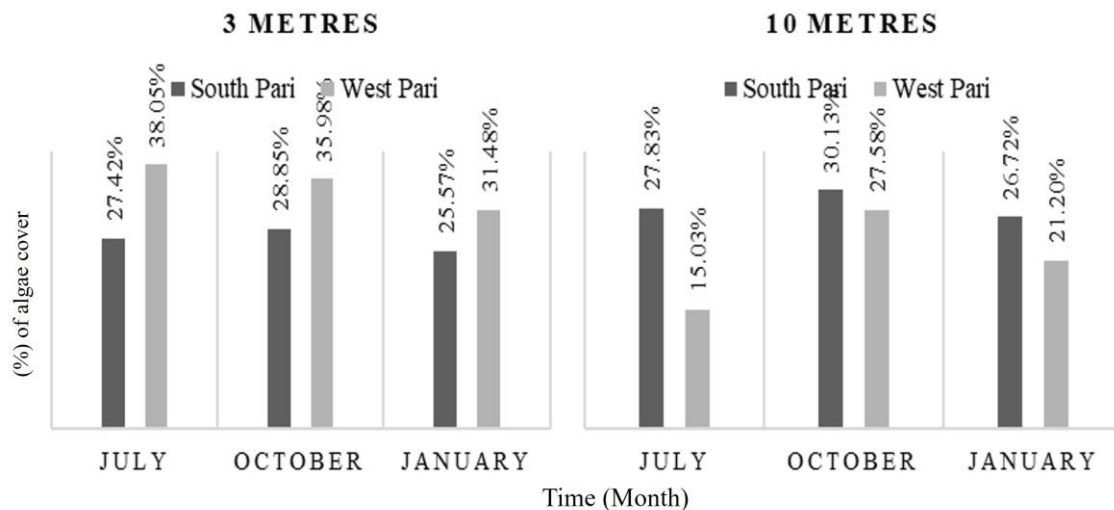


Fig. 4. Percentage of algal cover length (temporal)

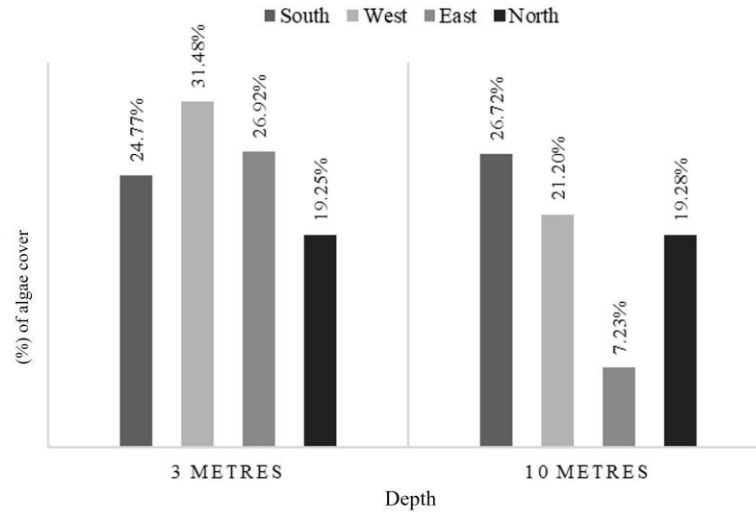


Fig. 5. Percentage of algal cover length (spatial)

2. Percentage cover (%) of algal turf and macroalgae cover

The percentage value of turf algae (Fig. 6) at the South Pari site at a depth of 3m ranged from 24.93 to 25.7%, and at a depth of 10m ranged from 20.06 to 26.33% for the West Pari site at a depth of 3m, with higher values observed. The values ranged from 28.91 to 37.85% for a depth of 10m, with the range for the West Pari site at a depth of 3m being 14.06 to 20.81% (Figs. 6- 9). For other species, the value was less than 8.76% of the total observations, which was the macroalgae category.



Fig. 6. Turf algae

The observations revealed the presence of six genera of macroalgae, including *Padina* sp. (Phaeophyceae), *Gracilaria* sp. (Rhodophyta), *Sargassum* sp. (Phaeophyceae), *Turbinaria* sp. (Phaeophyceae), *Caulerpa* sp. (Chlorophyta) and *Halimeda* sp. (Chlorophyta) (Fig. 7). The genus *Padina* sp. of macroalgae was

the most prevalent, with percentage cover length values ranging from 0 to 8.76%. In contrast, the lowest macroalgae species was *Caulerpa* sp. with percentage cover length values ranging from 0.7 to 0.83%.



Fig. 7. Types of macroalgae

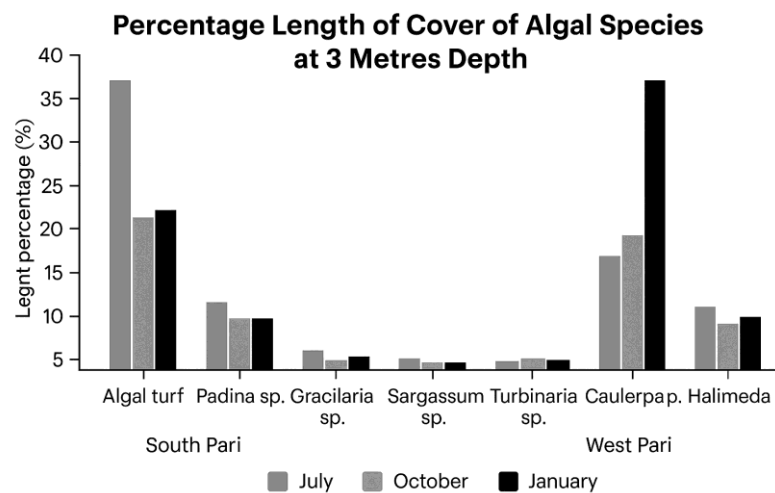


Fig. 8. Percentage cover (%) of cover of algal species at 3 meters depth

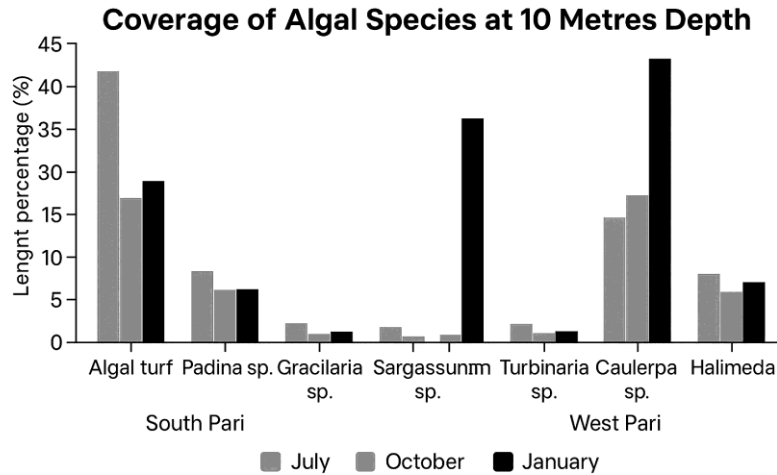


Fig. 9. Coverage of algal species at 10 meters depth

3. The abundance of herbivorous fish

The abundance of herbivorous fishes was found to be low, with a range of 1 to 24 individuals observed in a 300m² transect area. The highest recorded abundance of herbivorous fish at the South Pari site in July was 24 individuals. The most prevalent herbivorous fish were of the genera *Scarus* sp. and *Siganus* sp. The overall abundance of fish at each observation site in each month is illustrated in Fig. (10).

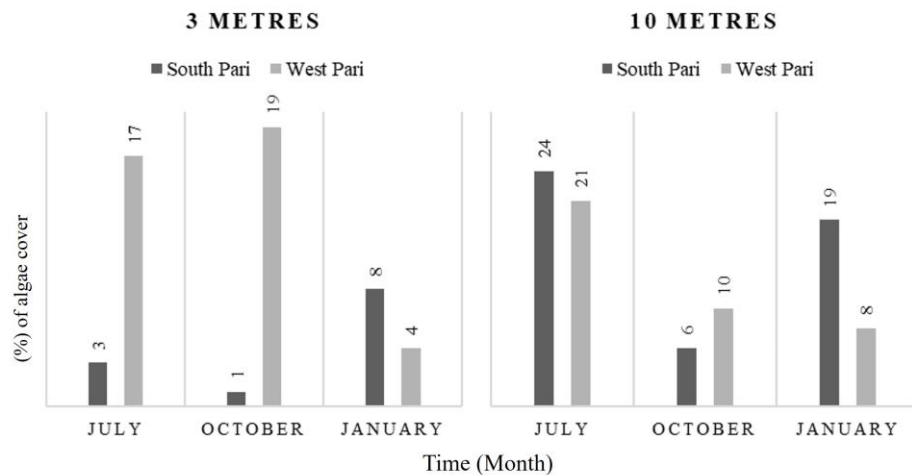


Fig. 10. Herbivorous fish abundance

4. Percentage cover (%) of live hard coral substrate

The observations revealed that the percentage of live hard coral cover at a depth of 3m exhibited considerable variation, with values ranging from 37.78 to 49.46%. Notably, the West Pari site exhibited the highest coral cover at this depth in July, reaching 49.46%. At a depth of 10m, the percentage cover ranged from 12.1 to

31.55%. The largest cover value at the West Pari location in October was 31.55%. The overall percentage value is illustrated in Fig. (11).

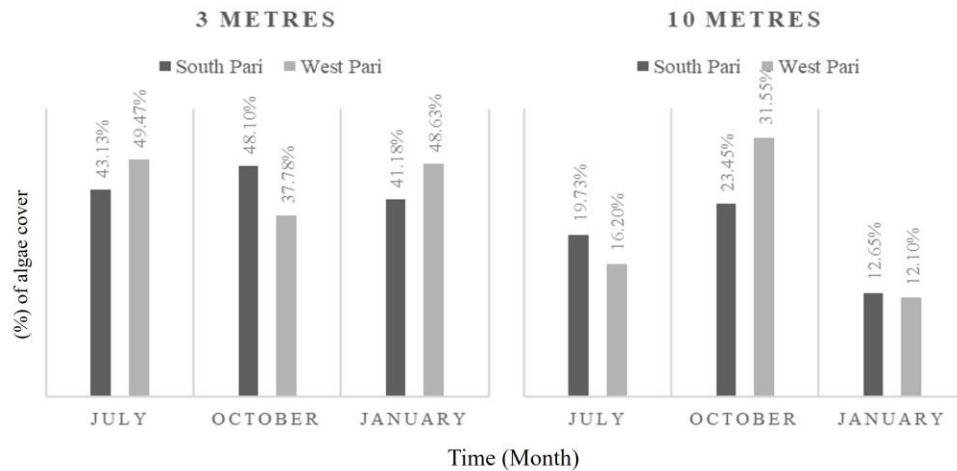


Fig. 11. Percentage of live hard coral cover length

5. Percentage cover (%) of dead hard coral substrate

The percentage values observed for the dead hard coral substrate ranged from 16.3 to 35.67% at a depth of 3m, exhibiting a higher percentage than at a depth of 10m. The percentage of dead coral substrate at the West Pari site at a depth of 3m was found to be higher than that observed at the South site, while at a depth of 10m it was lower (Fig. 12).

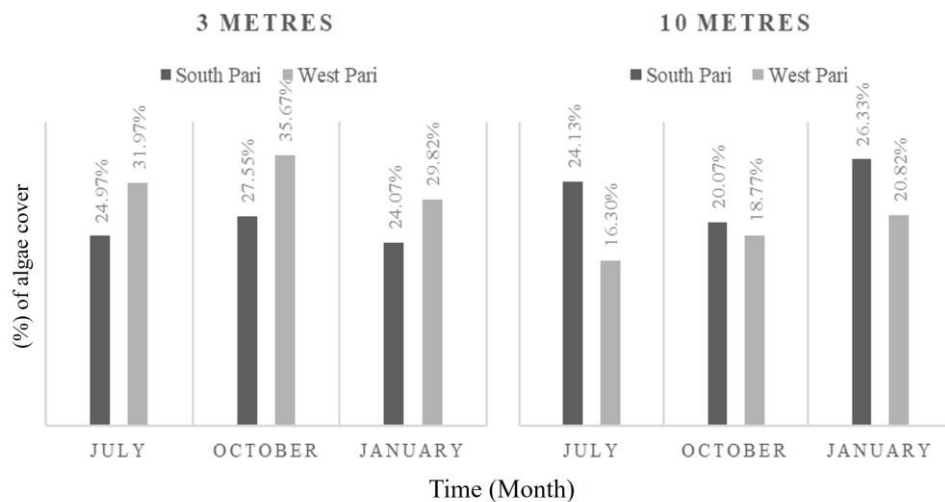


Fig. 12. Percentage of dead coral cover length

6. Percentage cover (%) of coral break substrate

The results of observations at the West and South Pari locations at a depth of 10m indicated a relatively high percentage of coral rubble in comparison to observations at a depth of 3m. The percentage value of coral rubble at a depth of 10m ranged between 18.33 and 20.55%, with a higher range of 12.15 to 43.87% observed at a depth of 3m.

The South Pari site exhibited a higher percentage of coral rubble than the West site. The overall percentage value of coral rubble is illustrated in Fig. (13).

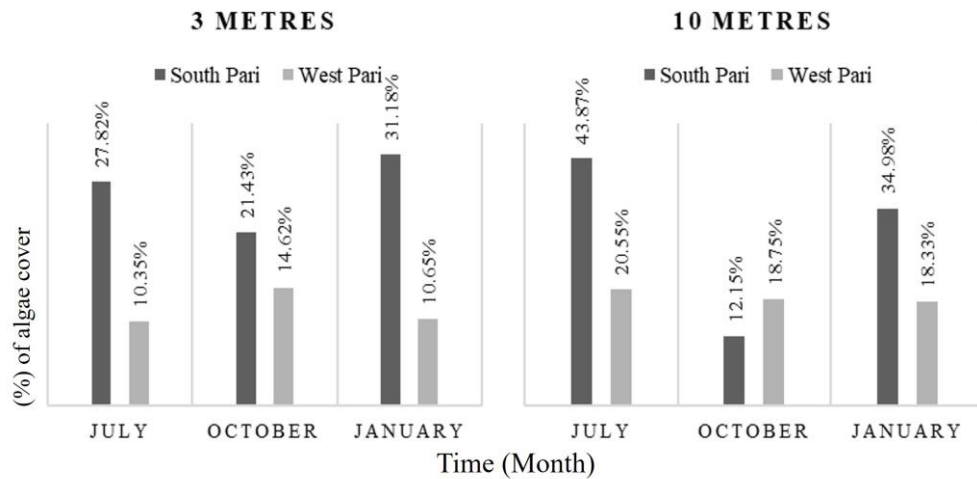


Fig. 13. Percentage of coral fault cover length

7. Percentage of the length of the sand substrate

The results of observations of the sand substrate exhibited a relatively low percentage, with values ranging from 1.03 to 8.05%. At the West Pari location, at a depth of 3 m, the percentage was relatively high in comparison with the South Pari location. Conversely, at a depth of 10m, the South Pari location exhibited a higher percentage than the West Pari location. The percentage of sand substrate may be reduced as a consequence of its closure by algae, coral fragments or water currents within the coral reef ecosystem. The overall percentage value of sand substrate is illustrated in Fig. (14).

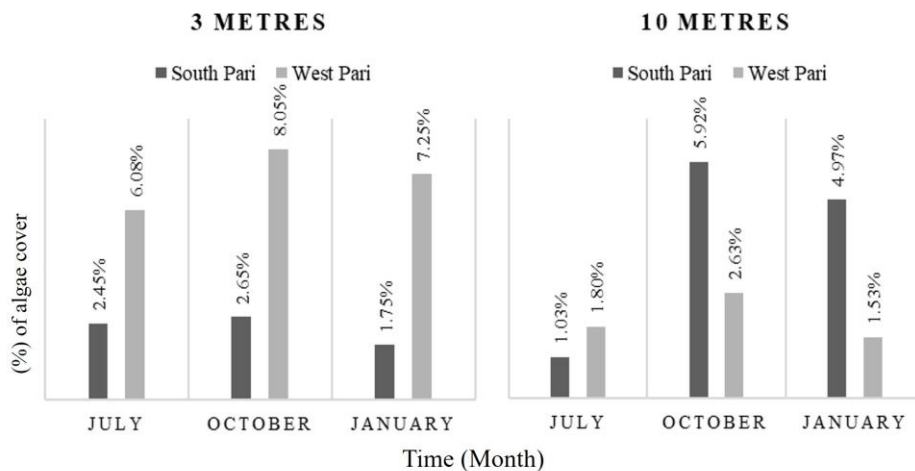


Fig. 14. Percentage of sand cover length

8. Percentage of the length of the rock substrate

The observations revealed that the percentage of rock substrate cover was predominantly dominant at a depth of 10m, with percentage values ranging from 0 to 37.87%. At a depth of 3m, the rocky substrate was observed to be relatively small in size, only present at the South location in January with a percentage of 0.65%. At a depth of 3m, the bottom substrate was found to be dominated by other substrates. The overall percentage value of rocks is presented in Fig. (15).

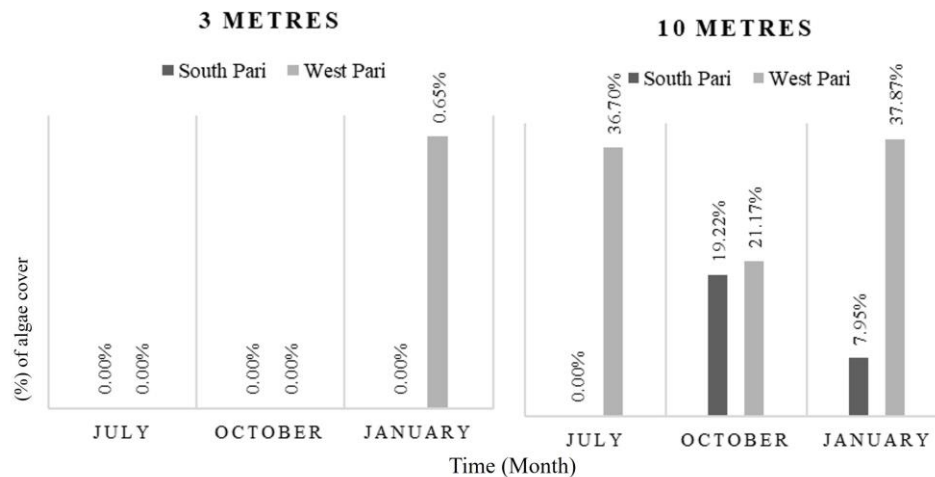


Fig. 15. Percentage of rock cover length

9. The sea water quality of Pari Island

The water quality values obtained in each observation location (Table 3) for temperature values exhibit minimal variation across months and observation locations, with a mean value of 28°C. The salinity values exhibited a decline from July to January, with the highest recorded value of 35psu observed in the South Pari location during July. The values of dissolved oxygen (DO) exhibited an increase over the course of the observation period, with the highest recorded value of 6.59mg/ L in both locations. The nitrate value exhibited fluctuations on a monthly basis, with the highest recorded value observed in July at both observation sites, namely 0.124mg/ L. The nitrate values exhibited a range between 0.08 and 0.124mg/ L. The range of phosphate values was 0.002 to 0.008mg/ L, with the highest value observed in July at 0.008mg/ L in the West Pari location.

Table 3. Observed water quality values of Pari Island

Location	Parameter	Unit	Quality Standard	July 2020	October 2020	January 2021
South	Temperature	°C	28-30	28	28	28
	Salinity	Psu	33-35	35	33	31
	DO	mg/L	>5	6,44	6,51	6,59
	Phosphate	mg/L	0.015	0.004	0.004	0.002
	Nitrate	mg/L	0.008	0.124	0.089	0.09
West	Temperature	°C	28-30	28	28	28
	Salinity	psu	33-35	34	32	31
	DO	mg/L	>5	6.48	6.55	6.59
	Phosphate	mg/L	0.015	0.008	0.007	0.005
	Nitrate	mg/L	0.008	0.124	0.121	0.087

10. Correlation analysis and principal component analysis (PCA)

PCA was applied to assess the underlying data structure. The analysis demonstrated that the first two principal components (F1 and F2) accounted for 55.97% of the total variance, with F1 contributing 34.52% and F2 contributing 21.42% (Fig. 16). The variables with the most significant contributions to these components were macroalgae, herbivorous fish, and dead coral (Tables 4, 5). Furthermore, the life form parameters (live corals and algae) alone explained 62.85% of the variance (F1: 34.84%; F2: 28.01%). The suitability of the data for PCA was confirmed by both the Kaiser-Meyer-Olkin (KMO) measure and Bartlett's Test of Sphericity ($P < 0.05$).

Table 4. Correlation value of algae with the aquatic bottom substrate and herbivorous fish

Variable	Alga	Hp	Dead coral	Rock	Rubble	Sand
Algae	1	0,020	0,853	-0,681	-0,359	0,768
Hp	0,020	1	0,054	0,090	0,351	0,011
Dead coral	0,853	0,054	1	-0,762	-0,199	0,683
Rock	-0,681	0,090	-0,762	1	-0,205	-0,353
Rubble	-0,359	0,351	-0,199	-0,205	1	-0,615
Sand	0,768	0,011	0,683	-0,353	-0,615	1

Table 5. Correlation value of the aquatic bottom substrate with types of algae

Variable	Alga	DC	Sand	AAP	APD	AGC	ASG	ATB	ACP	AHM
Algae	1	0,85	0,76	0,87	0,29	-0,01	0,30	0,06	0,02	0,51
DC	0,85	1	0,68	0,98	-0,19	-0,12	-0,03	0,20	-0,46	0,61
Sand	0,76	0,68	1	0,68	0,24	-0,29	0,44	-0,06	0,05	0,53
AAP	0,87	0,98	0,68	1	-0,16	-0,10	0,01	0,10	-0,40	0,68
APD	0,29	-0,19	0,24	-0,16	1	-0,02	0,42	-0,21	0,85	-0,32
AGC	-0,01	-0,12	-0,29	-0,10	-0,02	1	0,10	-0,14	0,01	-0,20
ASG	0,30	-0,03	0,44	0,01	0,42	0,10	1	-0,04	0,52	0,17
ATB	0,06	0,20	-0,06	0,10	-0,21	-0,14	-0,04	1	-0,16	-0,12
ACP	0,02	-0,46	0,05	-0,40	0,85	0,01	0,52	-0,16	1	-0,24
AHM	0,51	0,61	0,53	0,68	-0,32	-0,20	0,17	-0,12	-0,24	1

Note:

Alga – Percentage of Algae

AT – Percentage of Algal Turf

Hp – Abundance of Herbivorous Fish

APD– Percentage of Padina sp. (Macroalgae)

Dead Coral – Percentage of Dead Hard Coral

AGC– Percentage of Gracilaria sp. (Macroalgae)

Rock – Percentage of Rock

ASG–Percentage of Sargassum sp. (Macroalgae)

Rubble – Percentage of Coral Rubble

ATB– Percentage of Turbinaria sp. (Macroalgae)

Sand – Percentage of Sand

ACP – Percentage of Caulerpa sp. (Macroalgae)

Hc – Percentage of Live Hard Coral

AHM– Percentage of Halimeda sp. (Macroalgae)

CB – Non-Acropora Branching

ACB – Acropora Branching

CE – Non-Acropora Encrusting

CM – Non-Acropora Massive

CME – Non-Acropora Millepora

CF – Non-Acropora Foliose

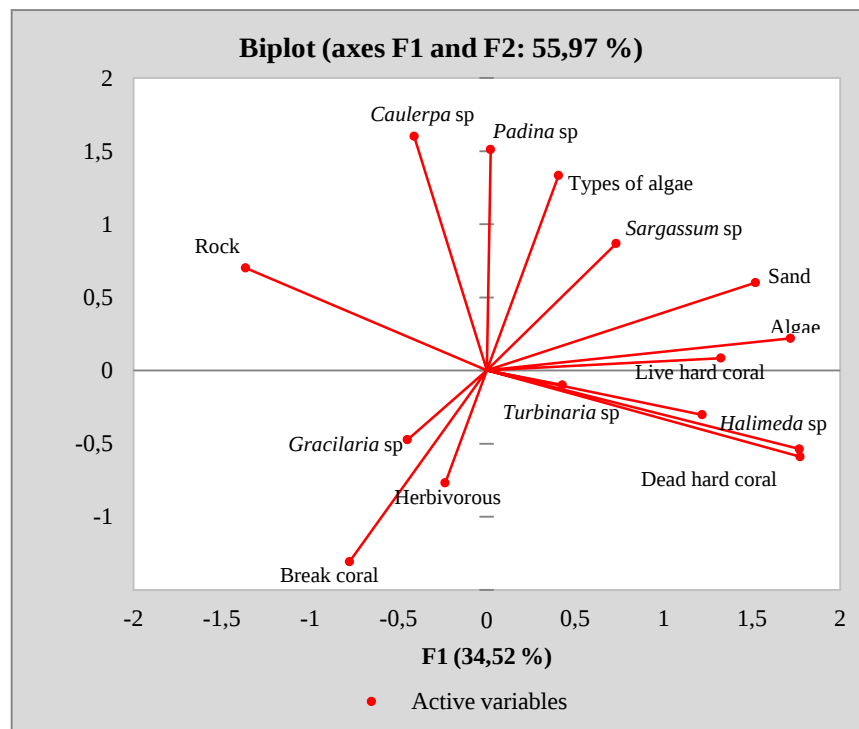
CS – Non-Acropora Submassive

CMR – Non-Acropora Mushroom

JJ – Number of Algae Species

CTU – Non-Acropora Tubipora

ACT – Acropora Tabulate



DISCUSSION

This study provided quantitative evidence that the phase shift on Pari Island's coral reefs characterized by substantial algal dominance was driven by a robust, synergistic interaction among three primary factors: chronic nutrient enrichment, habitat degradation (increased non-living substrate), and a critical failure of top-down grazing control. The current ecological state is a clear indicator of a transition away from a coral-dominated system, governed by local anthropogenic pressures.

The observed algal proliferation was enabled primarily by anthropogenic nutrient enrichment. The high level of nitrate concentration, which consistently exceeded established water quality standards, confirmed that the ecosystem was operating under

chronic eutrophication stress (**Islamy *et al.*, 2024, 2025a**). This nutrient loading, likely sourced from local coastal wastewater discharge (**Herandarudewi & Yusuf, 2014**), elevated bioavailable nitrogen (nitrate), strongly supporting the nutrient enrichment hypothesis. Under these chronic conditions, the growth kinetics of opportunistic algae are optimized, circumventing typical bottom-up resource limitations and driving a fundamental shift in primary production dynamics (**Fadjar *et al.*, 2025**).

Critically, the strong positive correlations between algal cover, dead hard coral ($r=0.853$) and sand ($r=0.768$) demonstrated that the algal community was primarily opportunistic, colonizing available degraded habitat rather than actively engaging in direct competition with established, healthy coral. This relationship was most pronounced with turf algae, which exhibited an extremely high correlation with dead hard coral ($r=0.986$). This confirmed a local, negative ecological feedback loop characteristic of stressed Indo-Pacific reefs: coral mortality creates the dead substrate necessary for rapid colonization by turf algae. These algal mats can then hinder coral recruitment and increase stress on surviving corals through localized hypoxia (**Tebbett *et al.*, 2019**), thereby accelerating the phase shift. Furthermore, the differential relationship between algae and live non-*Acropora* coral life forms suggested that coral morphology influences susceptibility, with massive forms providing a larger, structurally stable surface for creeping algal overgrowth.

A crucial ecological insight was the clear failure of top-down trophic control, evidenced by the statistically negligible correlation between the total biomass of key herbivorous fish and overall algal cover ($r=0.02$, $P>0.05$). This finding is pivotal because it contradicts the expected density-dependent grazing response, where functional herbivore guilds typically aggregate in and control areas of high primary production. This strongly suggests that the grazing pressure exerted by the current herbivore community is functionally insufficient to suppress chronic algal expansion. The low biomass and potential loss of key functional groups (e.g., large parrotfish scrapers) mean the reef lacks the necessary functional redundancy to counter the accelerated growth of algae driven by nutrient enrichment. This inability of grazers to contain algae in a nutrient-enriched environment is a hallmark of tropical reefs subjected to cascading effects from overfishing or habitat degradation (**Tebbett *et al.*, 2019**).

The principal component analysis (PCA) synthesized these factors, demonstrating that the primary axis of ecological variation (F1 and F2, explaining 55.97% of variance) was defined by macroalgae, dead coral, and herbivorous fish. This multivariate structure confirmed that the ecological status of Pari Island was governed by high substrate degradation and insufficient biotic control (grazing), a pattern characteristic of vulnerable nearshore reef environments worldwide.

In summary, this research advances current understanding by quantitatively validating the simultaneous, synergistic roles of chronic nutrient loading, substrate availability, and trophic control failure as the primary drivers of the observed phase shift.

The findings underscore that management interventions must adopt a dual-focus strategy: Source reduction of terrestrial nutrient inputs is necessary but insufficient; it must be coupled with robust protection measures aimed at functional recovery of the herbivorous grazing guild to successfully arrest the phase shift trajectory.

CONCLUSION

This study provides compelling evidence that the extensive algal proliferation and subsequent ecological phase shift observed on the coral reefs of Pari Island are driven by a synergy of localized stressors, primarily chronic nutrient enrichment and habitat degradation, exacerbated by inadequate trophic control. The analysis confirms that the algal dynamics are influenced by seasonal factors (peaking during the transitional season) and spatially controlled by depth (higher abundance at 3m). Crucially, the strong correlation of turf algae with dead hard coral and the persistent elevation of nitrate concentrations confirms that the ecosystem is under severe eutrophication stress. Furthermore, the negligible correlation between total algal cover and the abundance of herbivorous fish confirms a significant breakdown of top-down control. This collective evidence indicates that the Pari Island reef system has transitioned to an opportunistic, algae-dominated state, where local human activities (nutrient input and potentially fishing pressure) are the dominant ecological drivers, overwhelming the system's natural resilience. This research contributes to the understanding of nearshore reef decline in the Western Indo-Pacific by quantitatively linking the failure of biotic control mechanisms with chronic anthropogenic nutrient input and resulting substrate availability. Our findings are translated directly into critical priorities for reef management and monitoring at Pari Island, aimed at interrupting the positive feedback loops driving the phase shift. Given the severity of the eutrophication stress, the most urgent intervention is the Source Reduction of Nutrients through the immediate implementation of enhanced wastewater treatment and sanitation protocols. Simultaneously, due to the failure of top-down control, restrictions on fishing and the establishment of marine protected areas (MPAs) are necessary to promote the recovery of biomass and functional diversity within the herbivorous fish community, thereby restoring critical grazing pressure. Furthermore, Targeted Rehabilitation efforts, such as manual algal removal and coral transplantation, must prioritize the stabilization of live coral cover to reduce the abundance of dead coral substrate available for opportunistic algal colonization. To support adaptive management, future research should focus on quantifying the long-term dose-response relationship between ambient nutrient concentrations and rates of turf algal growth, and conducting caging experiments to definitively assess the current grazing capacity of the herbivorous fish assemblage and identify the target grazing levels needed for effective algal suppression.

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