The Bioscan
AN INTERNATIONAL QUARTERLY JOURNAL OF LIFE SCIENCES
20(3): S.I(3). 1455-1473, 2025 www.thebioscan.com

ECOLOGICAL ASSESSMENT OF CORAL–ALGAL PHASE SHIFTS IN PALK BAY, SOUTHEASTERN INDIA

Vijay Krishanan[*1], Devasena, B [2], Nafisa Farheen [3], Shobana, S [4] and Geetha, C[5]

[*1,2]Peri college of physiotherapy, Chennai -48, TN, India
[3]Peri college of Pharmacy, Chennai -48, TN, India
[4]Peri Institute of Technology, Chennai - 48, TN, India
[5]Peri college of Nursing, Chennai -48, TN, India

Corresponding Email: publications@peri.ac.in

DOI: 10.63001/tbs.2025.v20.i03.S.I(3).pp1455-1473

KEYWORDS:
Coral Reefs, Palk Bay, Seaweed, Algal Blooms, Macroalgal Dominance

Received on:
01-09-2025
Accepted on:
06-10-2025
Published on:
11-11-2025

ABSTRACT

Coral reef ecosystems are undergoing significant degradation worldwide due to a combination of natural and anthropogenic stressors. Key threats include climate change-induced bleaching, coral diseases, pollution, overfishing, and destructive fishing practices. One of the most critical consequences of these stressors is the phenomenon of coral–algal phase shifts, wherein macroalgae replace live corals. While extensively reported in regions like the Caribbean and the Great Barrier Reef, documentation from Indian coastal waters remains limited. This study investigates the occurrence and extent of coral–algal phase shifts along the Palk Bay coast, southeastern India. Using field surveys across three sites—Munaikadu, Thonithurai, and Olaikuda—benthic cover data and biodiversity indices were assessed, alongside nutrient analysis. Our results indicate a significant increase in macroalgal dominance, particularly post-bleaching events, with Munaikadu and Thonithurai exhibiting the highest stress indicators. The findings underscore the role of nutrient enrichment, fishing pressure, and reef zone depth in influencing coral resilience. This study highlights the urgent need for targeted conservation strategies to prevent irreversible reef phase shifts in Indian waters.

1. INTRODUCTION

Coral reefs are experiencing a rapid global decline due to a range of natural and anthropogenic stressors. Among the most pressing threats are climate change-induced coral bleaching, coral diseases resulting from pollution and natural outbreaks, overfishing, destructive boating practices, and increased storm frequency. These stressors have significantly reduced coral recruitment, resilience, and recovery capacity. One notable ecological consequence is the coral–algal phase shift, where coral-dominated communities are gradually replaced by macroalgae.

This shift has been widely documented in various parts of the world, especially in the Caribbean and the Great Barrier Reef, and is now recognized as a significant ecological transition. The phenomenon is often driven by the loss of key herbivores, eutrophication from nutrient enrichment, and alternative successional trajectories (hysteresis). As McManus et al. (2000) observed, the loss of three-dimensional habitat complexity also exacerbates coral vulnerability and delays recovery.

Several studies emphasize that anthropogenic pressures—including sedimentation, overfishing, and nutrient loading—play a dominant role in coral degradation. For example, the removal of herbivorous fishes disrupts natural algal control, while nutrient inputs from terrestrial runoff enhance macroalgal growth. Szmant (2002) proposed a reciprocal relationship between nutrient availability and dominance of either corals or macroalgae, highlighting that coral communities tend to outcompete macroalgae under oligotrophic (nutrient-limited) conditions.

Other ecological interactions further influence coral health. Coral-scraping fish, such as *Bolbometopon muricatum* and *Sparisoma viride*, as well as invertebrates like coral-eating mollusks and *Hermodice carunculata* (fireworms), contribute to coral mortality. Notably, outbreaks of the crown-of-thorns starfish (*Acanthaster planci*), especially following predator depletion (e.g., *Lethrinus* spp.), can lead to large-scale coral loss and facilitate macroalgal dominance.

While coral–algal phase shifts have been extensively documented in other parts of the world, limited attention has been given to this phenomenon in Indian waters. Palk Bay, located on the southeast coast of India, was selected for this study due to its diverse yet vulnerable coral assemblages and the proximity of human settlements, which contribute to pollution through domestic and industrial effluents. Additionally, intense fishing activity poses further ecological stress.

Despite its biological richness, Palk Bay has not received the same level of conservation attention as the adjacent Gulf of Mannar Marine National Park. Therefore, this study aims to investigate the presence and persistence of coral–algal phase shifts in Palk Bay and identify the primary causative factors, with a focus on nutrient levels, herbivore depletion, and historical coral health trends. The findings will help determine whether this region is undergoing a similar ecological transition as observed globally.

2. PERCENT COVER OF REEF IN DIFFERENT REEF ZONATION

REEF FLAT

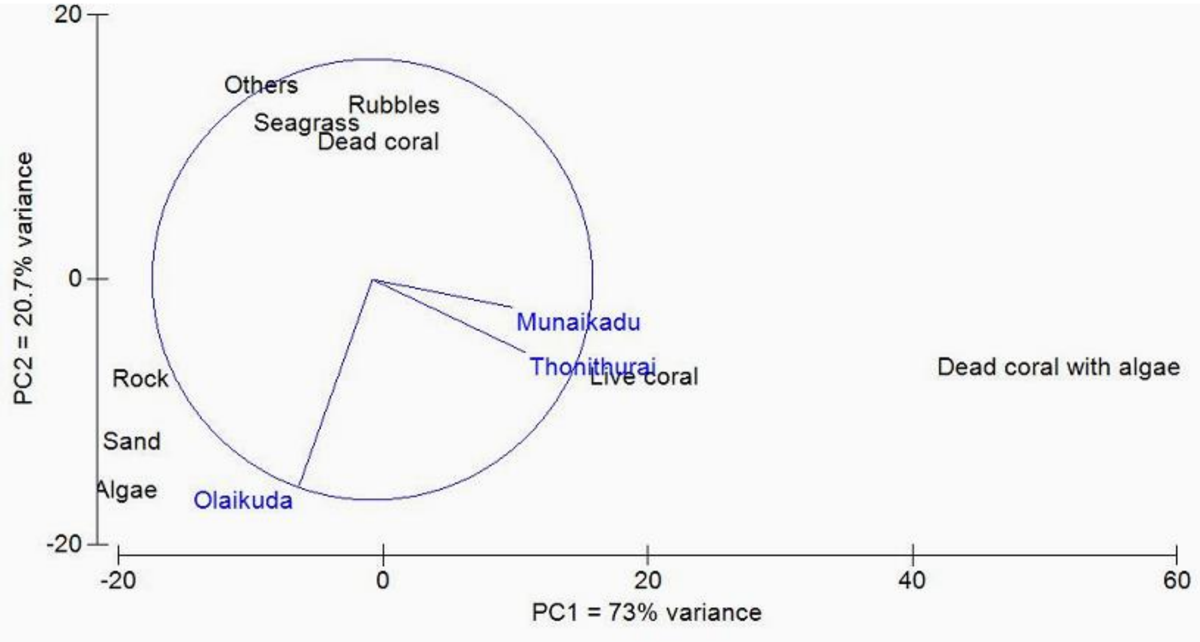
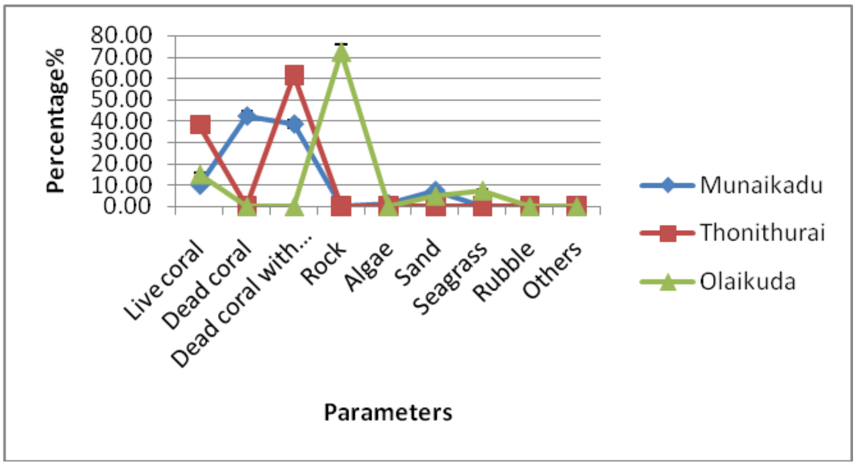


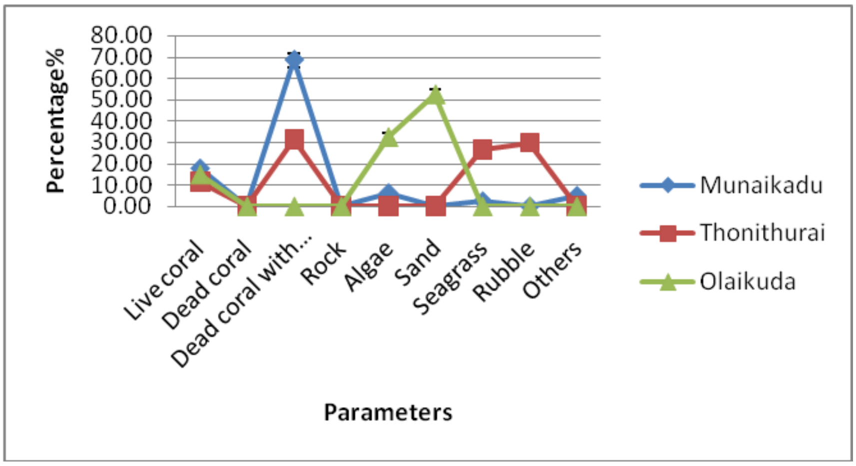
Fig: 1 Principal component analysis (PCA) of reef communities of Munaikadu, Thonithurai and Olaikuda.



Graph: 2. Percentage variation of reef flat parameters in between the sites

In the reef flat zone, the highest live coral cover was recorded at Thonithurai (38.33%). The maximum dead coral cover was observed at Munaikadu (42.5%), while no dead coral was found at the other two sites. The highest percentage of dead coral with algae was also observed at Thonithurai (61.67%). Algal presence was minimal at Munaikadu (1.25%), and completely absent at both Thonithurai and Olaikuda. No rubble was observed across all three sites in this zone. Statistical analysis indicated no significant differences among the sites in terms of reef flat parameters (ANOVA, p = 0.95; see Graph 2)

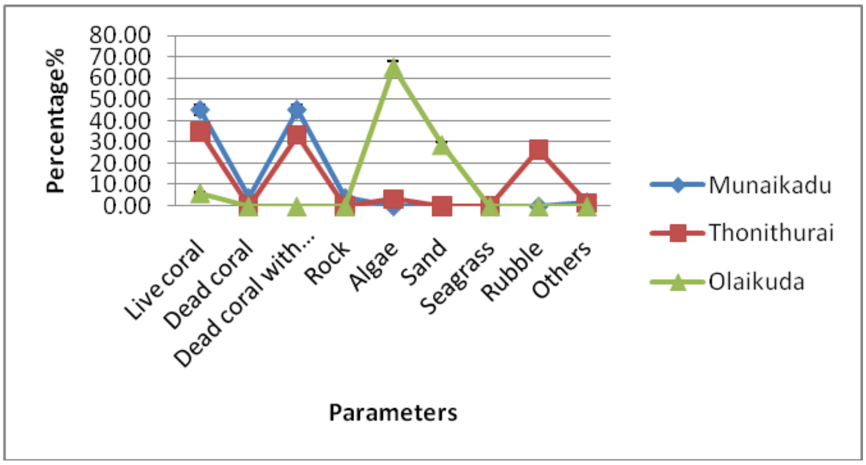
REEF FRONT



Graph: 3. Percentage variation of reef front parameters in between the sites

Live coral cover in the reef front zone was relatively evenly distributed, with Munaikadu showing the highest cover at 17.75%, followed by Olaikuda (15.0%) and Thonithurai (11.67%). Dead coral was absent at all three sites in this zone. However, dead coral with algae (DCA) was predominant at Munaikadu (68.5%), with a moderate level at Thonithurai (31.67%), and absent at Olaikuda. Algal cover was highest at Olaikuda, moderate at Munaikadu, and not observed at Thonithurai (Graph 3).

REEF SLOPE



Graph: 4. Percentage variation of reef slope parameters in between the sites

In the reef slope zone, live coral cover was highest at Munaikadu (45%), followed by Thonithurai (35%), and lowest at Olaikuda (6.25%). Dead coral was only recorded at Munaikadu (4%) and was absent at the other two sites. The dead coral with algae cover was greatest at Munaikadu (45%), moderate at Thonithurai (33.33%), and again, absent at Olaikuda. The highest algal cover was observed at Olaikuda (65%), compared to Thonithurai (3.33%), and no algae were recorded at Munaikadu. Rubble cover was only observed at Thonithurai (26.67%), while Munaikadu and Olaikuda showed no rubble presence (Graph 4).

BRAY-CURTIS CLUSTER ANALYSIS OF REEF ZONATION.

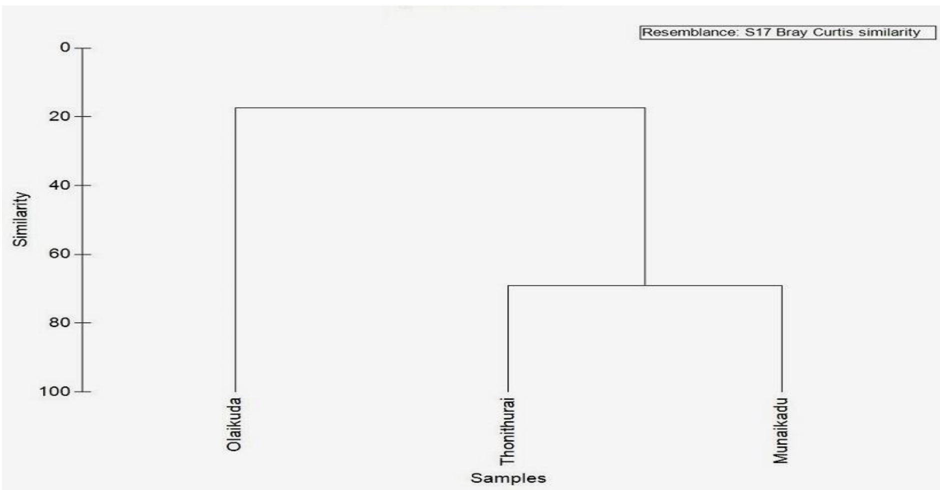


Fig: 2 Bray-Curtis cluster analysis of study sites. The sites Thonithurai and Munaikadu well-grouped together were similar in their community structure.

The Bray–Curtis cluster analysis revealed that the reef zonations across the study sites formed four well-defined groups (Fig. 3). The site Olaikuda exhibited less than 20% similarity with the zonations of the other two sites, indicating distinct community structures. In contrast, Munaikadu and Thonithurai shared over 40% similarity, suggesting comparable benthic compositions. Notably, the reef flat zones across all three sites showed considerable dissimilarity among themselves, likely due to their exposure to high-energy wave action and anthropogenic disturbances, such as coastal activities and boat anchoring.

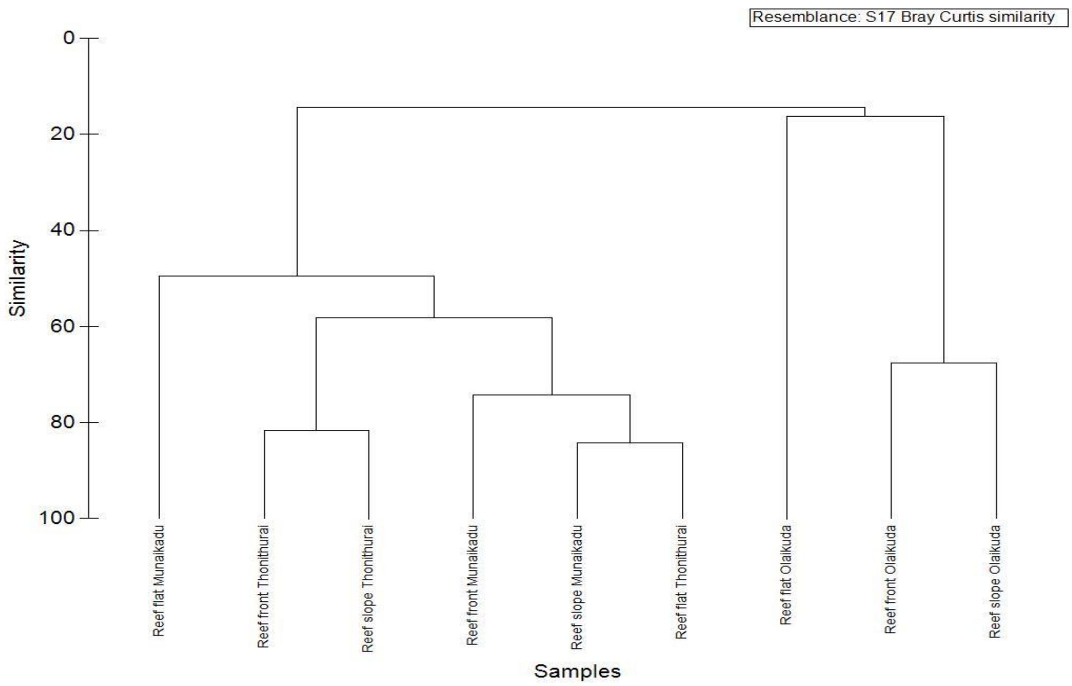
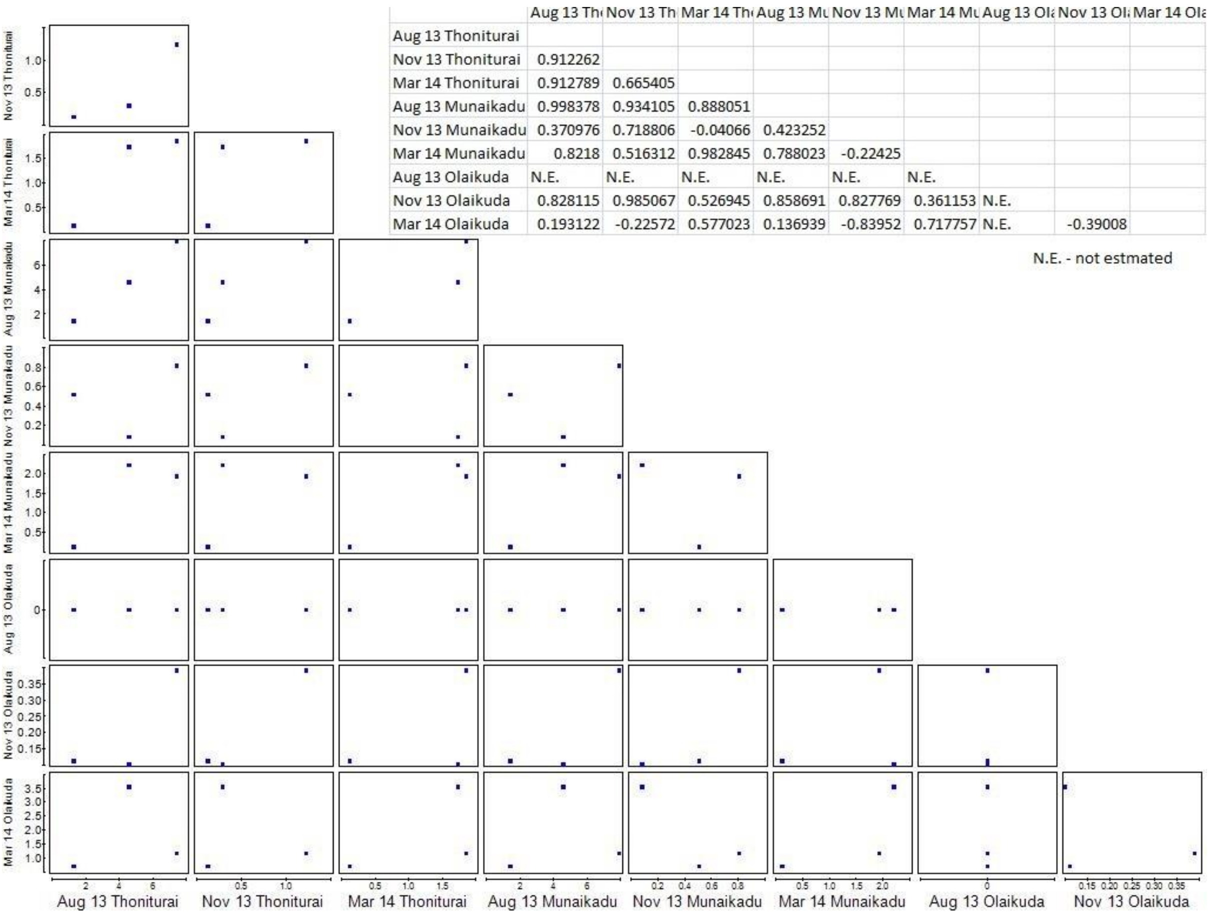


Fig: 3 Bray-Curtis cluster analysis of reef zonation (reef flat, reef front and reef slope). The reef zonations of Thonithurai and Munaikadu well-grouped together were similar in their community structure than Olaikuda. The reef flat had showed less similarity within their sites suggests the reef flat had perturbation by different artificial and natural disturbances.

ASSESSMENT OF NUTRIENTS

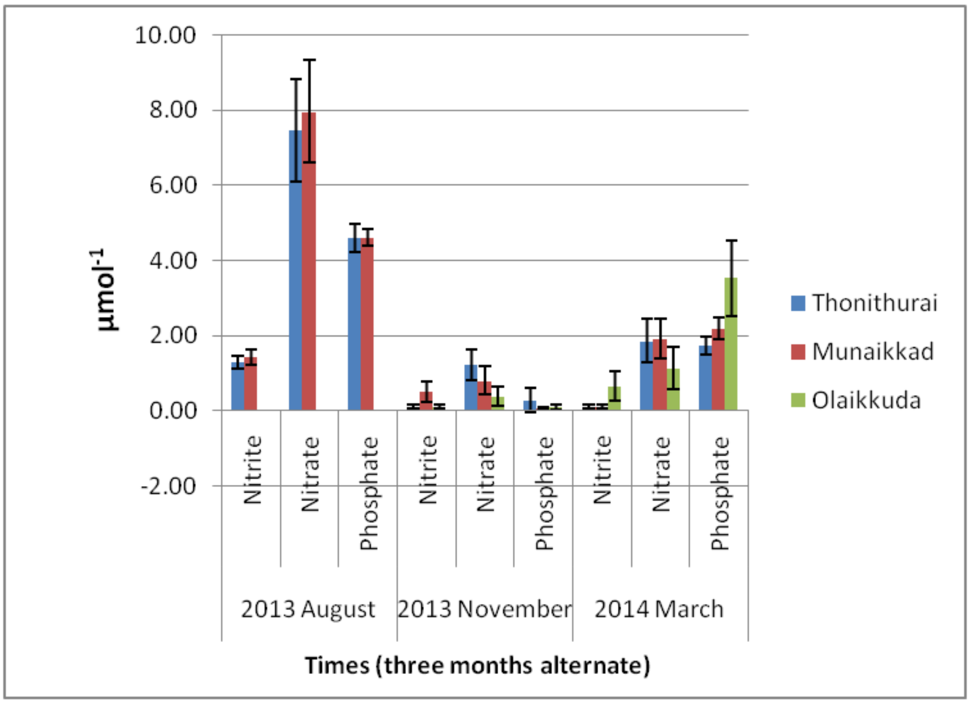
The Bioscan
AN INTERNATIONAL QUARTERLY JOURNAL OF LIFE SCIENCES
20(3): S.I(3). 1455-1473, 2025 www.thebioscan.com



	Aug 13 Th	Nov 13 Th	Mar 14 Th	Aug 13 Mu	Nov 13 Mu	Mar 14 Mu	Aug 13 Ola	Nov 13 Ola	Mar 14 Ola
Aug 13 Thoniturai									
Nov 13 Thoniturai	0.912262								
Mar 14 Thoniturai	0.912789	0.665405							
Aug 13 Munaikadu	0.998378	0.934105	0.888051						
Nov 13 Munaikadu	0.370976	0.718806	-0.04066	0.423252					
Mar 14 Munaikadu	0.8218	0.516312	0.982845	0.788023	-0.22425				
Aug 13 Olaikuda	N.E.	N.E.	N.E.	N.E.	N.E.	N.E.			
Nov 13 Olaikuda	0.828115	0.985067	0.526945	0.858691	0.827769	0.361153	N.E.		
Mar 14 Olaikuda	0.193122	-0.22572	0.577023	0.136939	-0.83952	0.717757	N.E.	-0.39008	

Fig. 4. Draftsman plot (all possible pairwise scatter plots) for the nutrients collected at three different locations and different intervals of time period. Olaikuda site had showed mostly negative correlation in March 2014 and positive correlation in November 2013 with Munaikadu and Thonithurai.

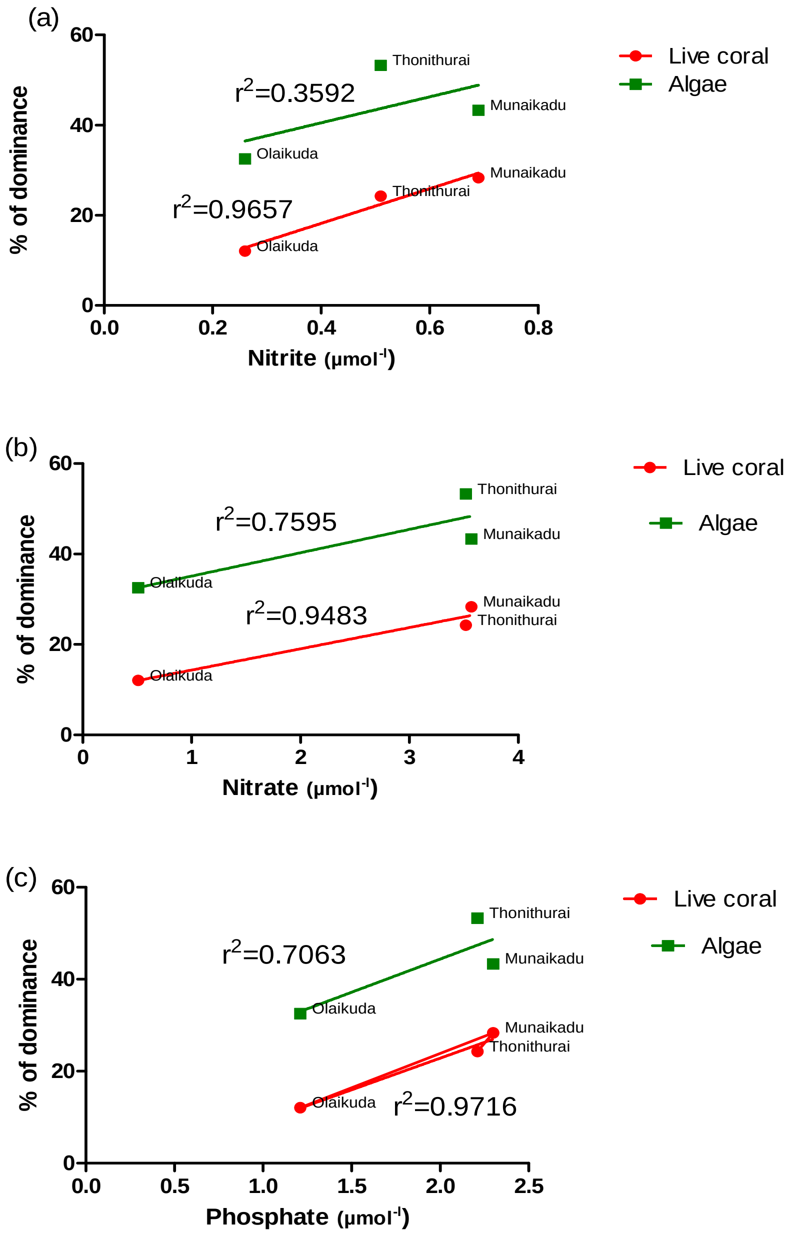
The concentrations of nitrite, nitrate, and phosphate varied significantly across the three sampling periods (August 2013, November 2013, and March 2014). The highest nutrient levels were recorded in August 2013, with notable declines in the subsequent sampling months (Graph 5).



Graph. 5. Nutrient concentrations of the study sites for different time periods. Nutrient concentrations had been elevated in between the time periods.

The draftsman plot analysis revealed strong mutual correlations among nutrient parameters, particularly between the sites Munaikadu and Thonithurai, which had an average correlation coefficient of approximately 0.90 (Fig. 4). In contrast, Olaikuda displayed positive correlations in November 2013 and negative correlations in March 2014, indicating fluctuating environmental conditions.

Regression analysis showed that nitrite had a strong positive correlation with coral dominance ($r^2 = 0.966$), but a relatively low influence on macroalgal growth ($r^2 = 0.359$). On the other hand, both nitrate ($r^2 = 0.760$) and phosphate ($r^2 = 0.706$) were found to positively influence macroalgal proliferation, while having a negative effect on coral cover ($r^2 = 0.948$ and $r^2 = 0.977$, respectively; Graph 6). These findings highlight the significant role of nutrient enrichment in driving coral–algal phase shifts in Palk Bay.

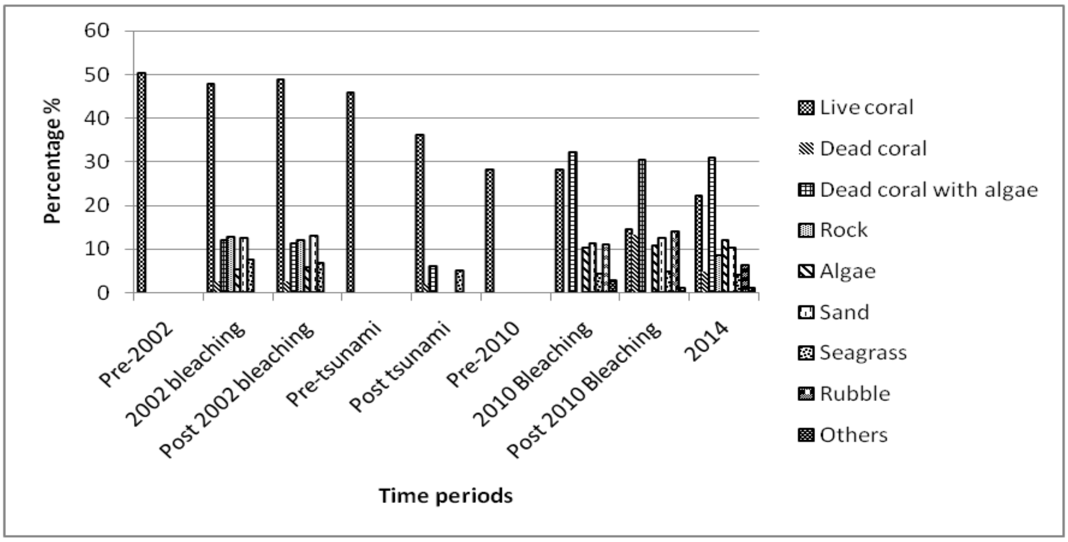


Graph: 6. the linear regression result illustrates the relationship between nitrite, nitrate and Phosphates concentration (influence) and dominance percentage (percent cover) for live coral and Macroalgae. These nutrients negatively influence the live coral and

positively influence the macroalgal dominance but nitrite moderately effects the macroalgae than other nutrients in Palk Bay coast

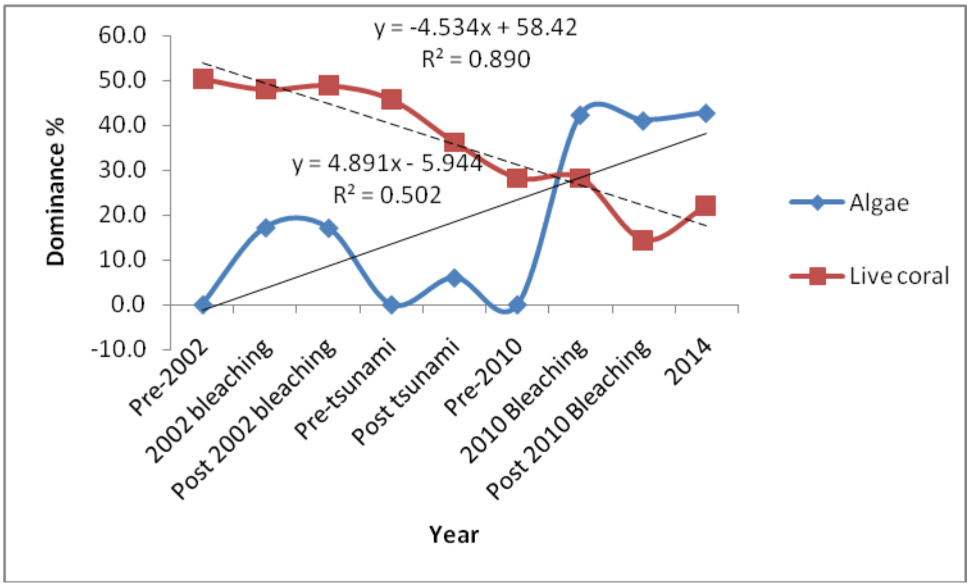
3. HISTORICAL CORAL REEF BASELINES AND RECENT CHANGES

Historical reef data were compiled and categorized into key periods: pre-2002, 2002 bleaching, post-2002 bleaching, pre-Tsunami, post-Tsunami, pre-2010, 2010 bleaching, post-2010 bleaching, and the current study period (2014). A clear downward trend was observed in live coral cover, decreasing from 50.3% in pre-2002 to 22.1% in 2014. The lowest coral cover (14.4%) occurred following the 2010 bleaching event, coinciding with poor coral recruitment and facilitating the onset of macroalgal dominance.



Graph: 7 Relative differences of coral community structure between historic and present statuses for the Palk Bay coast.

In contrast, the highest dead coral cover (13.2%) and dead coral with algae (32.2%) were observed during the 2010 bleaching and remained high in the 2014 observations, signifying ongoing ecosystem degradation (Graph 7).



Graph: 8. illustrates the macroalgae showing the dominance against live coral in Palk Bay in a different period of time.

Regression analysis further confirmed that macroalgal dominance has steadily increased, significantly inhibiting coral recovery. The relationship between macroalgae and coral cover showed a strong inverse correlation, with macroalgal dominance explaining 89% of the decline in coral cover (r^2 = 0.890) over the last decade (Graph 8).

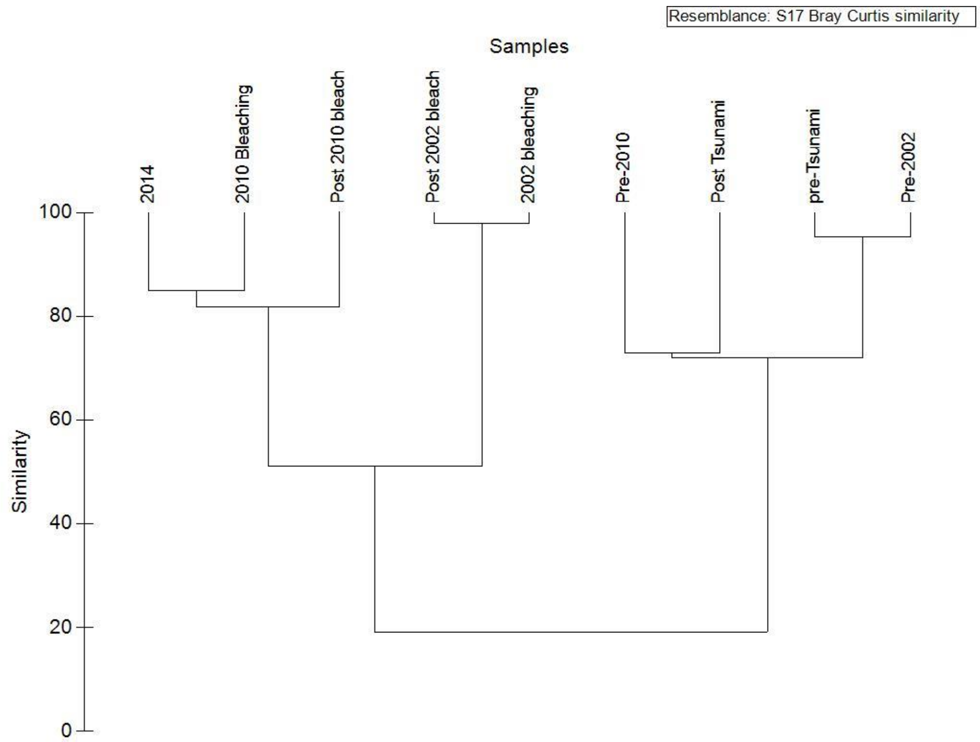


Fig: 5 Bray-Curtis cluster analysis for comparison of historic data with the present data. The different time periods well-grouped together were similar in their live coral structure. The present study and 2010 bleaching had showed less similarity with other time periods, suggests the coral resilience was limited in a decade due to poor coral reef conservation management along Palk Bay coast.

A Bray–Curtis similarity analysis comparing historical and current data grouped the time periods into three major clusters, with 2010 and 2014 data showing over 80% similarity. These recent periods were least similar to earlier baseline conditions, indicating a marked and persistent decline in coral resilience due to inadequate reef management in the Palk Bay region (Fig. 5)

Table: 1. Univariate community parameters for Munaikadu, Thonithurai and Olaikuda.

BIODIVERSITY INDICES	MUNAIKADU	THONITHURAI	OLAIKUDA
Simpsons index (D)	0.25	0.38	0.41

Simpsons index of diversity (1-D)	0.75	0.62	0.59
Shannon weiner diversity Index (H)	1.59	1.16	1.29
Coral mortality Index	0.39	0.00	0.00

4. DISCUSSION

The results of this study clearly indicate that macroalgae are more resilient to environmental disturbances compared to corals, a trend that is increasingly evident in coral reef ecosystems globally. Chronic stressors—such as overfishing of herbivores, nutrient enrichment, organic pollution, and coral bleaching—have been repeatedly linked to coral decline and algal proliferation. As reported by McCook et al. (2001), corals and algae engage in competitive interactions that shape reef community structures. A shift from coral to algal dominance can significantly disrupt reef ecosystem functions and biodiversity.

Bruno et al. defined macroalgal dominance as occurring when macroalgae occupy more than 50% of the reef surface, which is widely accepted as a threshold for coral–algal phase shifts. Our findings align with this definition, as macroalgal cover in Palk Bay has exceeded 50% in recent years, especially following the 2010 bleaching event. The highest algal proliferation was observed in association with dead coral substrata, suggesting that the degradation of live coral directly facilitates algal colonization.

A recent study also reported that more than 90% of live corals in heavily fished zones are under severe threat from mechanical damage caused by fishing activities. Our study supports this observation, as the coral–algal phase shift in Palk Bay appears directly related to coral health, relative abundance, and anthropogenic stressors. Based on ecological indices, Munaikadu and Thonithurai were categorized under Conservation Class 1 (CC-1) as per Edinger and Risk (2000), characterized by low spatial complexity, low live coral cover, and high coral mortality (Mortality Index > 0.39). Although Thonithurai had a lower recorded mortality index, its ecological condition was comparable or worse than Munaikadu.

Sites under CC-1 exhibited low species diversity, absence of rare species, and were severely impacted by both natural and human-induced disturbances, confirming previous assertions (Edinger et al., 1998; Done, 1997). Interestingly, Olaikuda was categorized as CC-3, yet it did not conform to expectations. Despite this classification, Olaikuda had lower coral cover and species richness than the CC-1 sites. This anomaly may be explained by historically limited coral growth in Olaikuda and the presence of large sand patches, which inhibit coral settlement and promote macroalgal colonization.

While all three sites exhibited macroalgal dominance, the substrates supporting algal growth varied. In CC-1 sites, macroalgae predominantly colonized dead coral structures, whereas in CC-3 (Olaikuda), algae thrived on sandy substrates. This suggests two possible scenarios: either historical coral cover in CC-3 was always low, or macroalgae in sand-dominated areas outcompete coral recruits, preventing reef recovery. Additionally, nutrient enrichment and sedimentation, especially from coastal upwelling, likely further degrade coral health and promote algal growth.

Thus, the application of reef classification based on coral morphology and ecological indices, as suggested by Edinger and Risk (2000), proves effective in identifying phase shifts from coral to algae-dominated systems.

The analysis of reef zonation (reef flat, reef front, and reef slope) further revealed important spatial patterns. Among these, the reef slope showed the highest live coral cover and lowest algal proliferation, indicating lower exposure to anthropogenic disturbances such as fishing and pollution. The reef flat and reef front zones, being more accessible and shallower, experienced higher levels of degradation, consistent with observations of increased dead coral and algal overgrowth.

Depth-related differences further support the notion that reef slopes serve as refugia for coral communities due to reduced mechanical damage and sedimentation. Ravindran et al. (2014) also reported that coral reefs in Palk Bay were frequently damaged by artisanal fishing gear. Our results suggest that reef slopes experience minimal fishing pressure, thereby maintaining higher coral integrity. Jayaraj et al. (2016) and Uthappa & Ananth (2013) reference climate-driven algal phase shifts in this area, but don’t provide specific nutrient concentrations. Historical hydrological records (e.g., Jayaraman 1954) for Mandapam exist, but these are more generalized descriptions of seasonal nutrient variations—not tied to phase-shift events.

5. HIGHER NUTRIENT LEVELS IN THE STUDY AREAS:

Elevated nitrogen and phosphorus levels—particularly nitrate and phosphate—have been linked to enhanced macroalgal growth and coral decline in coral reef systems. McCook (1999) highlights the critical thresholds of nutrient enrichment that can trigger phase shifts in the Great Barrier Reef. Similarly, Burkepile and Hay (2012) demonstrated through field experiments that nutrient loading, combined with reduced herbivory, significantly enhances macroalgal dominance. In Pacific lagoon reefs, Reynolds et al. (2020) correlated nitrogen enrichment from sewage and agricultural runoff with rapid increases in macroalgal cover

Elevated nitrate ($r^2 = 0.760$) and phosphate ($r^2 = 0.706$) concentrations in our study negatively correlated with coral dominance and positively with macroalgal cover—mirroring observations by McCook [1] and Burkepile and Hay [3], where nutrient enrichment combined with diminished herbivory facilitated macroalgal proliferation. In lagoon systems, Reynolds et al. [2] also confirmed that anthropogenic nitrogen inputs drove macroalgal blooms. Elevated nitrogen and phosphorus levels—particularly nitrate and phosphate—have been linked to enhanced macroalgal growth and coral decline in coral reef systems. McCook (1999) highlights the critical thresholds of nutrient enrichment that can trigger phase shifts in the Great Barrier Reef. Similarly, Burkepile and Hay (2012) demonstrated through field experiments that nutrient loading, combined with reduced herbivory, significantly enhances macroalgal dominance. In Pacific lagoon reefs, Reynolds *et al.* (2020) correlated nitrogen enrichment from sewage and agricultural runoff with rapid increases in macroalgal cover.

Elevated nutrient levels have long been implicated in coral–algal phase shifts worldwide. For example, McManus and Polsenberg [10] highlight the combined role of nutrient enrichment and reduced herbivory in advancing macroalgal dominance. Field studies by Jayaraj *et al.* [6] and Uthappa & Ananth [7] confirm similar trends in the Mandapam and Gulf of Mannar reefs, where increasing nitrogen and phosphorus levels coincided with pronounced macroalgal proliferation. Additionally, Sotka and Hay [11] experimentally demonstrated how nutrient enrichment, together with herbivore loss, accelerates algal expansion, suppressing coral growth.

6. COMPARISON TO HISTORICAL DATA

This study compares historical data with recent observations to confirm that Palk Bay is experiencing a significant coral–algal phase shift, consistent with similar phenomena reported globally. Over the past decade (2002–2013), macroalgal colonization in Palk Bay increased approximately fourfold, rising from 17% to 45%. In contrast, live coral cover declined sharply from 50.3% to 22.1%, and dead coral cover rose more than tenfold, from 2.4% to 13.2%.

These changes indicate a marked decline in coral reef resilience, likely driven by macroalgal overgrowth that suppresses coral recruitment and regeneration. The availability of dead coral substrata following the 2010 bleaching event provided ideal conditions for macroalgal settlement, thereby accelerating the phase shift. As macroalgae proliferate, they occupy more space, limiting the areas available for coral larval settlement, increasing post-settlement mortality, and intensifying competition for resources.

The low coral recruitment rates observed after the 2010 bleaching, compared to previous events such as in 2002, highlight the beginning of a persistent macroalgal dominance in the region. Although baseline data on earlier algal cover are limited, available observations suggest that algal proliferation has become progressively more pronounced in recent years.

This trend aligns with global reports, where coral cover is declining at alarming rates. For instance, coral reef cover in the Caribbean and Indo-Pacific has dropped by 20% and 5% per decade, respectively. Similarly, our study shows a reduction in coral cover by more than 50% over the last decade in Palk Bay, reflecting a regional manifestation of this global decline.

A major factor contributing to this shift is the reduction in herbivorous fish populations, which play a critical role in controlling macroalgal growth through grazing. The loss of herbivores allows algae to overgrow coral recruits, obstruct sunlight, and alter microbial communities, all of which undermine coral health and resilience.

Recent field surveys in Palk Bay report severe coral reef degradation due to colonization by algal turfs and macroalgae such as Caulerpa racemosa, Padina spp., and Sargassum spp. Overfishing, particularly targeting herbivorous and carnivorous reef fishes, exacerbates the situation. On average, 414 kg of herbivorous fish and 135 kg of carnivorous fish are harvested monthly by local fishers. Key herbivorous species such as Scarus spp. and Siganus spp., which are vital for regulating algal growth, are among the most heavily exploited.

The overharvesting of these functional groups diminishes the natural grazing pressure on algae, contributing significantly to coral degradation. This study concludes that Palk Bay is approaching a critical ecological threshold, similar to other reef systems undergoing coral–algal phase shifts. Immediate attention and enhanced reef management and conservation strategies are urgently required to prevent irreversible damage to one of India's most biodiverse reef systems.

7. REFERENCES:

[1] L. J. McCook, “Macroalgae, nutrients and phase shifts on coral reefs: scientific issues and management consequences for the Great Barrier Reef,” Coral Reefs, vol. 18, no. 4, pp. 357–367, Dec. 1999.

[2] R. G. Reynolds et al., “Landscape-scale patterns of nutrient enrichment in a coral reef ecosystem: implications for coral to algae phase shifts,” Ecol. Society Amer., 2020.

[3] P. S. Burkepile and M. E. Hay, “Effects of herbivory, nutrients, and reef protection on algal proliferation and coral growth on a tropical reef,” PLoS ONE, 2012.

[4] A. Reef, J. M. Pandolfi, and C. E. Lovelock, “The effect of nutrient enrichment on the growth, nucleic acid concentrations, and elemental stoichiometry of coral reef macroalgae,” Ecol. Evol., vol. 2, no. 8, pp. 1985–1995, 2012.

[5] T. Precht et al., “Assessing evidence of phase shifts from coral to macroalgal dominance on coral reefs,” Advances in Marine Biology, 2020.

[6] S. K. Jayaraj, R. K. Harikrishnan, and M. A. Prasad, “Trend in coral–algal phase shift in the Mandapam

group of islands, Gulf of Mannar Marine Biosphere Reserve, India," J. Ocean Univ. China, vol. 15, pp. 1080–1086, Nov. 2016.

[7] P. S. Uthappa and A. P. Ananth, "Climate-change-induced coral bleaching and algal phase shift in reefs of the Gulf of Mannar, India," in Climate Change Impacts—Adaptation and Mitigation, 2013, pp. 87–94.

[8] S. K. Edward and J. R. Bhatt, "Impacts of cultivation of Kappaphycus alvarezii on coral reef environs of the Gulf of Mannar and Palk Bay, Southeastern India," Mar. Res. Inst., Dec. 2011.

[9] R. R. Das et al., "Evidence of coral diseases, phase shift, and stressors in the atolls of Lakshadweep Islands, Arabian Sea—with geographical notes on their occurrence within the Indian EEZ," Diversity, vol. 15, no. 3, Art. 382, Mar. 2023.

[10] J. W. McManus and J. F. Polsenberg, "Coral–algal phase shifts on coral reefs: ecological and environmental aspects," Prog. Oceanogr., vol. 60, pp. 263–279, Feb. 2004.

[11] E. E. Sotka and M. E. Hay, "Effects of herbivores, nutrient enrichment, and their interactions on macroalgal proliferation and coral growth," Coral Reefs, vol. 28, pp. 555–568, 2009.

[12] J. W. McManus and J. F. Polsenberg, "Coral–algal phase shifts on coral reefs: ecological and environmental aspects," Prog. Oceanogr., vol. 60, pp. 263–279, Feb. 2004.

[13] L. J. McCook, "Macroalgae, nutrients and phase shifts on coral reefs: scientific issues and management consequences for the Great Barrier Reef," Coral Reefs, vol. 18, no. 4, pp. 357–367, Dec. 1999.

[14] P. S. Burkepile and M. E. Hay, "Effects of herbivory, nutrients, and reef protection on algal proliferation and coral growth on a tropical reef," PLoS ONE, vol. 7, no. 1, Jan. 2012.

[15] S. K. Jayaraj, R. K. Harikrishnan, and M. A. Prasad,

"Trend in coral–algal phase shift in the Mandapam group of islands, Gulf of Mannar Marine Biosphere Reserve, India," J. Ocean Univ. China, vol. 15, pp. 1080–1086, Nov. 2016.

[16] P. S. Uthappa and A. P. Ananth, "Climate-change-induced coral bleaching and algal phase shift in reefs of the Gulf of Mannar, India," in Climate Change Impacts—Adaptation and Mitigation, 2013, pp. 87–94.

[17] E. E. Sotka and M. E. Hay, "Effects of herbivores, nutrient enrichment, and their interactions on macroalgal proliferation and coral growth," Coral Reefs, vol. 28, pp. 555–568, Nov. 2009.

[18] T. Precht et al., "Assessing evidence of phase shifts from coral to macroalgal dominance on coral reefs," Adv. Mar. Biol., vol. 87, 2020.

[19] S. K. Edward and J. R. Bhatt, "Impacts of cultivation of Kappaphycus alvarezii on coral reef environs of the Gulf of Mannar and Palk Bay, Southeastern India," Mar. Res. Inst., Dec. 2011.

[20] R. R. Das *et al., "Evidence of coral diseases, phase shift, and stressors in the atolls of Lakshadweep Islands, Arabian Sea," Diversity, vol. 15, no. 3, Art. 382, Mar. 2023.

[21] J. W. McManus and J. F. Polsenberg, "Coral–algal phase shifts on coral reefs: ecological and environmental aspects," Prog. Oceanogr., vol. 60, pp. 263–279, Feb. 2004.

[22] E. D'Angelo and F. Wiedenmann, "Impacts of nutrient enrichment on coral reefs: new perspectives and implications for coastal management and reef survival," Sci. Total Environ., vol. 468–469, pp. S14–S23, 2014.

[23] M. Fox, "Differential resistance and acclimation of two coral species to chronic nutrient enrichment," Funct. Ecol., 2021.

[24] E. J. Tomascik and F. Sander, "Competition between corals and algae on coral reefs: a review of evidence and mechanisms," Coral Reefs, vol. 19, no. 1, pp. 500–505, 2001.

[25] P. S. Lapointe, "Eutrophication on coral reefs: nutrient enhancement of macroalgae and its detrimental effects," Limnol. Oceanogr., vol. 44, no. 3, pp. 1583–1586, May 1999.

[26] R. A. Hughes et al., "Eutrophication, herbivory, and phase shifts on coral reefs," Science, vol. 301, no. 5635, pp. 929–932, Aug. 2003.