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Health monitoring status of corals in Gulf of Mannar and Palk Bay (India) with special reference to coral bleaching event

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Abstract. *Sadhukhan K, Chatragadda E, Shunmugaraj T, Murthy MVR. 2022. Health monitoring status of corals in Gulf of Mannar and Palk Bay (India) with special reference to coral bleaching event. Indo Pac J Ocean Life 6: 61-73.* Coral reef ecosystems are highly important regarding ecological, cultural, and economic values. Unfortunately, these ecosystems are declining rapidly due to climate change and local anthropogenic threats. The present study assessed the coral reef health status in the Gulf of Mannar (GoM) and Palk Bay (PB), India, to understand the diversity and abundance of corals and the bleaching vulnerability of the reef areas. Extensive underwater surveys were conducted from August 2018 to August 2020. Line intercept transect (LIT) methods were employed in triplicates and estimated the bleaching-mediated reef threats. As a result, the average live coral cover of the Gulf of Mannar was 39.55±15.45% (Mean±SD), and Palk Bay was 28.40±14.60%, of which Mandapam Group of Islands has maximum live coral coverage (51.80±15.10%). Severe coral bleaching was also observed in the Gulf of Mannar and Palk Bay during the summer of two the consecutive year, 2019 and 2020, triggered by increased sea surface temperature (SST) of 4°C-5°C than the average temperature (28°C-31°C). The current study highlights the detailed distribution of the coral community with comparative analysis since 2000 and the adaptive response of native coral species to bleaching events that will help to implement management interventions like coral restoration of those native species to strengthen the reef resilience in the Gulf of Mannar and Palk Bay.

Keywords: Bleaching, coral cover, health monitoring, reef threats, Sea Surface Temperature (SST)

INTRODUCTION

Coral reefs, considered rainforests of the sea, occupy less than 1% of the ocean floor but significantly provide shelter to 25% of all marine organisms. In addition, millions of the coastal population depend on reef fish resources for food, medicine, and tourism (Burke et al. 2015; Zhao et al. 2019; Machendiranathan et al. 2020). The reef ecosystem also protects the shoreline and coastal habitats. But unfortunately, over the past few decades, the world's tropical reef ecosystem, especially reef-building corals and the dependent coastal populations, are rapidly declined due to global climate change and anthropogenic stressors (Spalding and Brown 2015; Heron et al. 2016; Eakin et al. 2016; Hughes et al. 2017; Camp et al. 2018). As a result, many reef-building corals and reef habitats in Indo-Pacific regions are disappearing. Therefore, the collapses of these ecosystems contribute to shifts or changes in reef habitats, species distribution, and species interactions (de Vantier et al. 2020).

Furthermore, to encounter the positive and negative drive of the reef ecosystem, monitoring and assessment are the key components that provide essential information on the current health status and trend of increasing threats in the ecosystem. The reef monitoring method is essential to answer the following important questions - what is on our reefs (abundance, biodiversity), what species are special or important for the region, what changes are being seen over time, what is causing the decline of the reef health, and what is the current health status of the reef. Therefore, Ecosystem monitoring is a fundamental technique to increase coral reef resilience that delivers a detailed account of ecosystem states with an emphasis on the abundance of important biological species (Mumby and Steneck 2008; Lindenmayer and Likens 2010; Kupschus et al. 2016).

The sequential occurrence of mass global bleaching events from 1998, 2002, and then 2014-2017 due to global warming and thermal heat waves disrupt the physiological and symbiotic functions between corals and associated dinoflagellates (Skirving et al. 2019; Harrison et al. 2019; Bolanos et al. 2021). Ultimately this mass bleaching response is recognized as the primary global challenge to the existence of coral reefs as a prolonged condition of the bleached corals often leads to the mass mortality and permanent shifting of live reefs to macroalgal dominant dead reefs (Baker et al. 2008; Eakin et al. 2016, 2017; Darling and Cote 2018; Head et al. 2019). However, Coral reefs in the Gulf of Mannar (GoM) are comprised of 117 reef-building coral species distributed from Rameswaram to the Tuticorin coast. The region was declared as Gulf of Marine National Park in 1986 by Tamil Nadu Coast (Edward et al. 2007). Massive coral bleaching events in Indian coral reefs dramatically changed the reef ecology, species interactions, loss of shallow water reef-building corals, including live coral cover, habitat loss of reef fishes, and damaged shoreline operations (Edward et al. 2012; De et al. 2017). The health of coral reefs in the GoM and Palk Bay (PB) region is being declined to several natural and anthropogenic stressors, directly affecting the coastal population who depends on the reef resources (Ramesh et al. 2020). The primary cause of reef health damage in the GoM is coral bleaching, which now becomes an annual phenomenon due to increasing global warming. Post-bleaching stress in reefs is induced by the overgrowing macroalgal populations and increased microbial infections (Coral disease). This phase shift occurrence becomes a significant restraint for newly recruiting corals and may lead to coral species loss. Reef-building corals can tolerate the increase of 1°C - 2°C of their upper thermal threshold, but during summer in each year, SST range between 30°C-36° C in GoM, which eventually increase average of 3°C-4°C than its normal living temperature (Lough 2011; Edward et al. 2018). Therefore, to estimate the reef health condition of coral reefs in the GoM and PB, the present study assessed the total live and coral coverage, community structure of reef-building corals, abundant status of corals, anthropogenic interventions, the extent of annual bleaching vulnerability to coral species and emerging new threats to this ecosystem. This study also documented the bleaching resistance of coral species for reef management activities like reef restoration and artificial coral gardens.

MATERIALS AND METHODS

Extensive field surveys were conducted at reef flats of 21 islands of the GoM (India) from August 2018 to August 2020. Field data acquisition was made by snorkeling and SCUBA diving. Line Intercept Transect (LIT) (English et al.1997; Hill and Wilkinson 2004) was employed to assess the distribution, abundance, and species diversity of corals in all the survey sites and used the internationally accepted corals' live form categories as mentioned by English et al. (1997). During the survey, field observations were made at 165 locations in all the 21 islands of GoM and 5 locations in PB (Figure 1). Locations were recorded using GARMIN e-Trex®30X handheld GPS device.

For detailed reef health assessment, a 20-meter-long flexible underwater tape was laid on selected reef areas, roughly parallel to the shoreline, with three replicates at each site in between 2-6 m depths, and every change in the benthic category is noted in underwater data sheets or underwater slates as described in English et al. (1997). Photographs and videos of benthic data in each transect were recorded as proof of underwater survey assessment in all the study areas. The identification of corals was made using standard coral identification keys (Veron, 2000; Huang et al. 2014). Observation of the sedimentation, coral disease, macroalgal proliferation, animal invasion, ghost nets, and anchor damage were considered to study the threats to the reefs. Sea Surface Temperature (SST), Dissolved oxygen, pH, and Salinity were estimated using Manta 2 water-quality multiprobe gadget. Furthermore, to evaluate the extent of bleaching, it has been categorized into partially bleached, completely bleached, and non-bleached (Sakai et al. 2019).

The descriptive statistical analysis measures the Relative Abundance (RA), linear regression curve, standard mean estimation, ANOVA, and Box Whisker analysis, calculated using SPSS software and MS Excel. Depending on the RA values, coral species are categorized into not recorded (RA=0), rare (0<RA<0.1), uncommon (RA=0.1-1), Common (RA=1-10), Abundant (RA=10-20), and dominant (RA>20) (Sukumaran and George 2012).

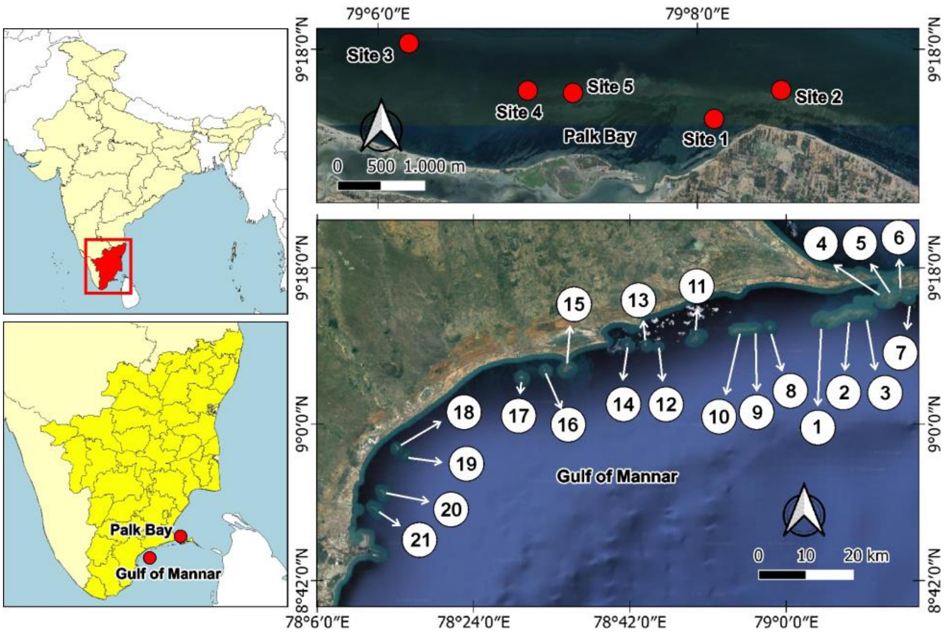

Figure 1. Study area Map – showing different islands of GoM and PB (India) [1. Hare Island (HAI); 2. Manoli Island (MAI); 3. Manoliputti Island (MPI); 4. Poomarichan Island (PCI); 5. Pullivasal Island (PVI); 6. Krusadai Island (KI); 7. Shingle Island (SHI); 8. Mulli Island (MUI); 9. Thalairi Island (THI);10. Valai Island (VAI); 11. Appa Island (API); 12. Poovarasanpatti Island (POI); 13. Anaipar Island (ANI); 14. Valimunai Island (VMI); 15. Nallathanni Island (NTI); 16. Pullivinichalli Island (PUI); 17. Upputhanni Island (UTI); 18. Karaichalli Island (KRI); 19. Vilanguchalli Islnd (VLI); 20. Kasuwar Island (KWI); 21. Vann Island (VNI)]

RESULTS AND DISCUSSION

Community structure

Community structure analysis revealed 75 species of hard corals and four species of soft corals belonging to 13 families and 22 genera of class Anthozoa. The family Acroporidae has the maximum representation of coral species (25), followed by Merulinidae (22) (Table 1). Mean live coral coverage in GoM was 39.55±15.45% and in PB was 28.40±14.60%. Among GoM, the Mandapam group of Islands has maximum live coral coverage, with 51.80±15.10%, followed by 48.60±15.30% in the Keezhakarai group of Islands, 26.30±14.20% in the Vembar group of islands and the live coral status found to be least in the Tuticorin group of Islands (26.30±14.20%) (Figure 2). The relative abundance of the investigated species was also categorized based on their abundance score as rare, uncommon, common, abundant, and dominant. Very few coral species were common, and *Montipora digitata* (10.66%) was the abundant coral species in GoM. *Acropora digitifera* (4.07%), *Acropora muricata* (5.03%), *Acropora hyacinthus* (4.19%), *Echinopora lamellose* (5.17%), and *Porites lutea* (7.30%) were commonly distributed in GoM and PB reefs (Table 1). Reefs of PB are abundant with massive and sub-massive corals, especially *P. lutea, P. solida, Dipsastraea speciosa, Dipsastraea favus,* and *Favites halicora*. Based on the relative abundance value, most coral species are uncommon to all islands of GoM. Few coral species, such as *Montipora tuberculosa* (0.05%), *Siderastrea savignyana* (0.05%), *Platygyra daedalea* (0.07%), *Pavona explanulata* (0.07%), *Goniopora columna* (0.05%) and *Porites nodifera* (0.02%) were rarely occurring in 21 islands of GoM (Table 1).

As compared to the earlier data of 2001 and 2015, it has been concluded that most of the islands have a significant recovery (F-7.14;df- 2; P<0.01) than the reef health condition existed 19 years back (Figure 3). The mean percentage of live coverage in the islands of Mandapam and Keezhakarai group increased substantially over time, while the live coral coverage in Vembar group of islands was found to be as degraded as 20 years back (Figure 3). Live coral coverage in Appa Island and Karaichalli Island has shown the highest increase in live coral coverage from 2% and 4% in 2001 to 54.5% and 48.4% in 2020 respectively (Figure 3). Island wise data on the different live and dead form categories has also been revealed during the study (Figure 4). Among the live form categories, branching *Acropora* corals (ACD, ACB & ACT) were found to be abundant in the islands of Mandapam Group and Appa Island of Keezhakarai range, whereas the live form CB found to be dominant in Tuticorin group of islands. Live-form categories called massive corals (CM) are generally found abundant at all islands of GoM and PB (Figure 4). Other live-form categories such as CS, CE, and CF are recorded from GoM and PB. Islands such as Poovarasanpatti, Valimunai, and Anaipar are the major contributor to the macroalgal assemblage (MA) in the reef. Among the dead form categories, DCA, R, RCK, and S has been revealed from both GoM and PB (Figure 4). The Vilanguchali island of the Tuticorin group of islands was found to be the most degraded coral coverage (11.7%) among all islands in which dead form categories were as follows - DCA - 57.9%, MA- 19.3%, R-3.2%, S-6.9%.

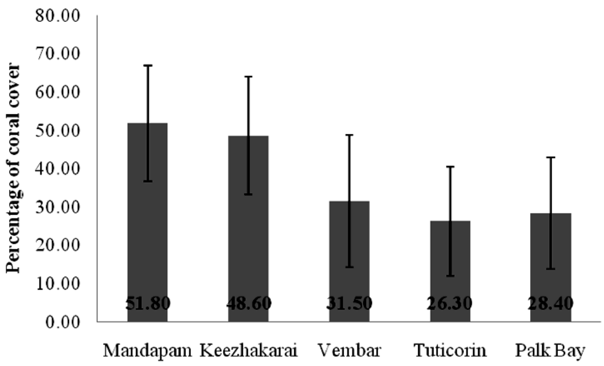

Figure 2. Average percentages of live coral cover in different areas of GoM and PB (India)

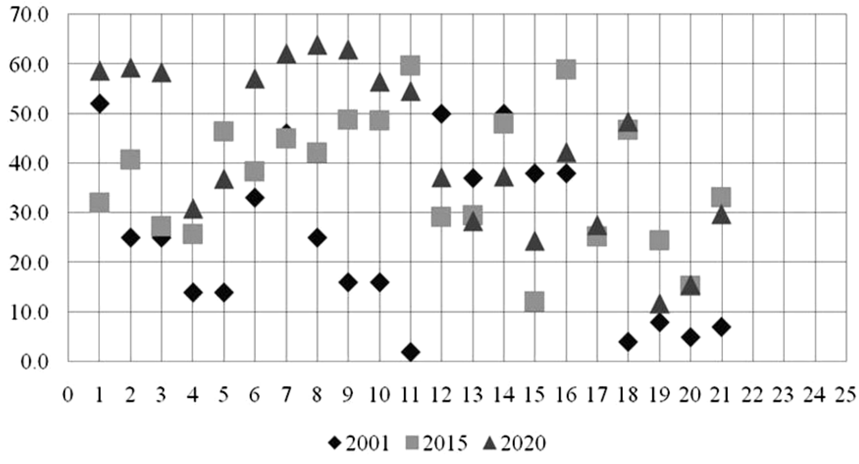

Figure 3. Comparative analysis of live coral coverage since 2001. Source: Shanmugaraj et al. (2013) and ENVIS (2015). [1-HAI; 2-MAI; 3-MPI; 4-PCI; 5-PVI; 6-KI; 7-SHI; 8-MUI; 9- THI;10- VAI; 11-API; 12-POI; 13-ANI; 14-VMI; 15-NTI; 16-PUI; 17-UTI; 18-KRI; 19-VLI; 20-KWI; 21-VNI]

Figure 4. Percentage value of different live form categories at all sites of GoM and PB (India)

Table 1. Relative abundance and status of corals in GoM and PB (India)

Hard coral species	RA	Status
Acropora digitifera (Dana, 1846)	4.07	C
Acropora muricata (Dana, 1846)	5.73	C
Acropora millepora (Ehrenberg, 1834)	0.24	UC
Acropora gemmifera (Brook, 1892)	3.14	C
Acropora nasuta (Dana, 1846)	0.45	UC
Acropora tenuis (Dana, 1846)	1.21	C
Acropora nobilis (Dana, 1846)	0.50	UC
Acropora cyhterea (Dana, 1846)	1.76	C
Acropora hyacinthus (Dana, 1846)	4.19	C
Acropora humilis (Dana, 1846)	0.79	UC
Acropora microphthalma (Verrill, 1869)	0.64	C
Acropora intermedia (Brook, 1891)	0.50	UC
Acropora abrolhosensis (Veron, 1985)	0.98	UC
Acropora cervicornis (Lamarck, 1816)	0.29	UC
Acropora valenciennesi (Milne Edwards, 1860)	0.21	UC
Acropora valida (Dana, 1846)	0.29	UC
Montipora digitata (Dana, 1846)	10.66	A
Montipora foliosa (Pallas, 1766)	2.28	C
Montipora aequituberculata (Bernard, 1897)	1.52	C
Montipora verrilii (Vaghan, 1907)	1.48	C
Montipora hispida (Dana, 1846)	0.45	UC
Montipora tuberculosa (Lamarck, 1816)	0.05	R
Montipora verrucossa (Lmarck, 1816)	0.40	UC
Montipora sp. (Unidentified, Blainville 1830)	0.05	R
Montipora sp. (Unidentified, Blainville 1830)	0.05	R
Pocillopora damicornis (Linneaus, 1758)	3.52	C
Siderastrea savignyana (Milne Edwards & Haime, 1850)	0.05	R
Goniastrea edwardsi (Chevalier, 1971)	0.14	UC
Goniastrea retiformis (Lamarck, 1816)	3.59	C
Goniastrea pectinata (Ehrenberg, 1834)	0.98	UC
Favites abdita (Ellis & Solander, 1786)	0.88	UC
Favites halicora (Ehrenberg, 1834)	3.35	C
Favites flexuosa (Dana, 1846)	0.57	UC
Favites pentagona (Esper, 1795)	0.62	UC
Favites complanata (Ehrenberg, 1834)	0.98	UC
Favites colemani (Veron, 2000)	0.12	UC
Favites spinosa (Klunzinger, 1879)	0.17	UC
Phymastrea valenciennesi (Milne Edwards & Haime, 1850)	0.24	UC
Dipsastraea favus (Forskal, 1775)	3.90	C
Dipsastraea speciosa (Dana, 1846)	1.76	C
Dipsastraea pallida (Dana, 1846)	1.26	C
Dipsastrae astelligera (Dana, 1846)	0.38	UC
Astreosmilia maxima (Veron, Pichon &Wijsman-Best 1977)	0.05	R
Cyphastrea serailia (Forskal, 1775)	0.43	UC
Cyphastrea microphthalma (Lamarck, 1816)	0.38	UC
Cyphastrea japonica (Yabe & Sugiyama 1932)	0.14	UC
Leptastrea purpurea (Dana, 1846)	1.14	C
Leptastrea transversa (Klunzinger, 1879)	0.86	UC
Merulina ampliata (Ellis & Solander, 1786)	0.38	UC
Platygyra daedalea (Ellis & Solander, 1786)	0.05	R
Platygyra lamellina (Ehrenberg, 1834)	0.48	UC
Platygyra sinensis (Milne Edwards & Haime, 1849)	0.29	UC
Leptoria phrygia (Ellis & Solander, 1786)	0.71	UC
Hydnophora microconos (Lamarck, 1816)	2.26	C
Hydnophora exesa (Pallas, 1766)	0.17	UC
Echinopora lamellosa (Esper, 1795)	5.14	C
Plesiastrea versipora (Lamarck, 1816)	0.07	R
Turbinaria peltata (Esper, 1794)	0.95	UC
Turbinaria mesenterina (Lmarck, 1816)	0.88	UC
Lobophyllia radians (Milne Edwards and Haime, 1849)	0.21	UC
Lobophyllia recta (Dana, 1846)	0.71	UC
Pavona varians (Verrill, 1846)	0.19	UC
Pavona decussata (Dana, 1846)	0.76	UC
Pavona explanulata (Lamarck, 1816)	0.07	R
Pavona duerdeni (Vaghan, 1907)	0.45	UC
Goniopora planulata (Ehrenberg, 1834)	0.83	UC
Goniopora minor (Crossland, 1952)	0.69	UC
Goniopora columna (Dana, 1846)	0.05	R
Porites solida (Forskal, 1775)	3.35	C
Porites lutea (Milne & Edwards, 1860)	7.30	C
Porites lichen (Dana, 1846)	0.93	UC
Porites nodifera (Klunzinger, 1879)	0.02	R
Porites compressa (Dana, 1846)	0.43	UC
Galaxea fascicularis (Linneaus, 1767)	1.09	UC
Galaxea astreata (Lamarck, 1816)	0.21	UC
Lobophytum crassum (Von Marenzeller, 1886)	0.14	UC
Sinularia sp. (May, 1898)	1.90	C
Sarcophyton sp. (Lesson, 1834)	0.81	UC
Lobophytum sp. (Marenzeller, 1886)	0.07	R

Table 2. Species wise data of bleached corals in GoM and PB (India)

	Number of bleached corals			
Species name	Mean	N	SD	Variance
Acropora cytherea	12.00	2	.000	.000
Acropora digitifera	13.00	1	.	.
Acropora muricata	36.50	6	14.829	219.900
Acropora humilis	8.00	1	.	.
Acropora hyacinthus	24.50	6	8.712	75.900
Cyphastrea japonica	10.00	2	.000	.000
Dipsastraea favus	22.57	8	8.284	68.619
Dipsastraea pallida	6.00	1	.	.
Dipsastraea speciosa	15.86	7	4.413	19.476
Favites abdita	6.00	2	1.414	2.000
Favites complanata	14.20	5	4.970	24.700
Favites flexuosa	6.00	2	5.657	32.000
Favites halicora	16.25	8	7.942	63.071
Goniastrea pectinata	6.67	3	4.163	17.333
Goniastrea retiformis	15.33	6	4.676	21.867
Hydnophora exesa	4.00	2	2.828	8.000
Leptastrea purpurea	5.00	2	2.828	8.000
Leptastrea transversa	3.00	1	.	.
Montipora aequituberculata	6.50	4	5.066	25.667
Montipora digitata	54.33	3	34.933	1220.333
Montiporafoliosa	14.25	4	5.909	34.917
Montipora verrucosa	5.00	1	.	.
Merulina ampliata	4.67	3	2.309	5.333
Montipora sp.	4.00	1	.	.
Porites lichen	18.00	1	.	.
Porites lutea	46.56	9	26.703	713.028
Porites solida	27.80	5	25.084	629.200
Platygyra daedalea	13.00	2	8.485	72.000
Platygyra lamellina	6.75	4	3.500	12.250
Plesiastrea versipora	3.00	1	.	.
Pocillopora damicornis	17.50	4	4.655	21.667
Turbinaria mesenterina	3.00	1	.	.
Turbinaria peltata	9.00	6	2.828	8.000
Total	18.34	116	17.158	294.402

Table 3. Descriptive statistics of different reef threats found in GoM (India)

Study area		Sedimentation	Coral disease	Algal proliferation	Animal invasion	Ghost nets	Anchor damage
Keezhakarai	Mean	2.00	3.83	13.77	2.70	1.63	0.73
	N	30	30	30	30	30	30
	SD	1.819	2.306	4.166	2.120	1.426	0.785
	SE of Mean	0.332	0.421	0.761	0.387	0.260	0.143
	Kurtosis	-0.875	0.567	-0.073	-0.238	-0.710	-1.153
	Skewness	0.405	0.163	0.345	0.377	0.323	0.524
	Variance	3.310	5.316	17.357	4.493	2.033	0.616
Mandapam	Mean	11.67	5.03	8.47	1.50	0.77	0.97
	N	30	30	30	30	30	30
	SD	3.962	2.684	4.091	1.280	1.006	1.159
	SE of Mean	0.723	0.490	0.747	0.234	0.184	0.212
	Kurtosis	-0.120	-0.142	0.614	0.171	1.988	-1.215
	Skewness	0.586	-0.107	0.270	0.529	1.375	0.638
	Variance	15.698	7.206	16.740	1.638	1.013	1.344
Tuticorin	Mean	14.33	5.17	13.07	3.03	1.10	1.10
	N	30	30	30	30	30	30
	SD	3.871	2.291	4.315	2.092	1.094	0.960
	SE of Mean	0.707	0.418	0.788	0.382	0.200	0.175
	Kurtosis	-0.291	-0.381	0.857	-0.530	0.144	-1.005
	Skewness	0.355	-0.348	0.810	0.292	0.806	0.291
	Variance	14.989	5.247	18.616	4.378	1.197	0.921
Vembar	Mean	12.83	2.13	3.70	1.37	0.67	0.70
	N	30	30	30	30	30	30
	SD	4.735	1.676	2.322	1.326	0.802	0.794
	SE of Mean	0.864	0.306	0.424	0.242	0.146	0.145
	Kurtosis	-0.684	-1.287	0.817	-1.030	-1.062	-1.120
	Skewness	0.078	0.058	0.409	0.404	0.700	0.610
	Variance	22.420	2.809	5.390	1.757	0.644	0.631
Total	Mean	10.21	4.04	9.75	2.15	1.04	0.88
	N	120	120	120	120	120	120
	SD	6.108	2.552	5.536	1.877	1.155	0.940
	SE of Mean	0.558	0.233	0.505	0.171	0.105	0.086
	Kurtosis	-0.889	-0.437	-0.349	0.213	0.362	-0.818
	Skewness	-0.071	0.169	0.309	0.732	0.949	0.624
	Variance	37.302	6.511	30.643	3.524	1.334	0.883

The physicochemical parameters of water were also measured to monitor water quality changes through time in GoM. Dissolved oxygen, temperature, salinity, and pH have ranged between 5.70-7.20 mg/L, 28.80-33.00°C, 34.00-37.80 mg/L and 6.8-8.20, respectively. Among water quality parameters, Sea Surface Temperature (SST) was found to be higher (33.40-36.00°C) than the average temperature (30.0°C) from March 2019 to May 2019 (Table 3). The increased sea surface temperature during summer led to coral bleaching in GoM and PB. Regression analysis revealed that no other parameters influence the increase or decrease of coral cover except sea surface temperature. SST positively correlates with the bleached coral cover during environmental stress (Figure 7).

Bleaching severity

Bleaching assessment in GoM and PB revealed species and site-specific bleaching patterns in corals, where branching corals displayed adaptive resistance to bleaching, while massive corals were highly affected (Tables 2 and 3). A total of 2,128 individuals belonging to 33 species of hard corals have been documented as bleached in GoM and PB regions. A species-wise assessment revealed that massive corals were completely bleached, of which *P. lutea* was 46.56±26.70%, *P. solida* 27.80±25.08%, *D. favus* 22.57±±8.28% and *F. halicora* 16.25±7.94 (Table 3). Among the branching corals, *M. digitata* (54.33±34.93%) was bleached maximum, followed by *A. muricata* 36.50±14.82% and *A. hyacinthus* 24.50±8.71%. Bleaching of other coral species ranged between 3-18% in both GoM and PB. Cumulative occurrence on the number of bleached corals revealed that Tuticorin Island (30.44±26.06%) and PB (26.07±21.89%) have the highest affected region among all the study sites. In contrast, the coral colonies in Mandapam, Keezhakarai, and Vembar are moderately bleached. Based on the pattern of distribution on the number of bleached corals, Mandapam, Tuticorin and PB have the highest distribution value to measure the intensity of bleaching during the study (Figure 5). Present study also recorded the unconditional distribution of completely bleached corals (CB) and partially bleached corals (PB) to understand the effect of bleaching on corals (Figure 6). Mean value of completely bleached corals (23.79±18.96) are higher than that of partially bleached corals (8.39±4.92). Histogram plot of descriptive statistics value showed a higher occurrence of completely bleached corals than partially bleached corals (Figure 6). There is no sign of coral mortality due to bleaching observed during the survey. But regular monitoring is underway to check the prevalence of bleaching and changes in SST. Water quality parameters highly influence the responsive variable called bleaching vulnerability (R^2=0.918). ANOVA results revealed that the bleaching vulnerability is significantly different (F-36.224, P<0.001) from the predicted variables. Regression analysis curve concluded that pH (t= -2.396, P=0.032, R^2=0.306) and salinity (t=1.101, P=0.291, R^2=0.086) are weakly correlated to the occurrence of bleaching in coral colonies, whereas SST (t=7.570, P<0.001, R^2=0.815) is strongly correlated to the bleaching vulnerability (Figure 7). Average SST was varied from 29.40°C in January 2019 to 34.60°C in May 2019, which indicated that average SST rises 5°C more than the optimum temperature (23°-29°C) required for coral survival. In 2020, SST (35.40°C) remained 1°C higher in May than in 2019, which induced the bleaching severity up to 85% in PB and 46.20% in GoM. Among coral species, *M. digitata*, *A. muricata*, *P. solida*, *P. lutea*, *D. favus*, *D. speciosa*, *F. halicora*, *Favites complanata*, *Goniastrea retiformis*, and *Sinularia* sp. were completely bleached at all islands (Figure 8).

Threats to the reefs

The present study documented six categories of threats (sedimentation, coral disease, algal proliferation, animal invasion, ghost nets, and anchor damage) from GoM reefs. Sedimentation (10.21±6.10) and algal proliferation (9.75±5.53) were the most dominant threats to the reefs of GoM. The average frequency of algal proliferation in Keezhakarai (13.77±4.16) and Tuticorin (13.07±4.31) were found to be higher than that of the Mandapam and Vembar group of islands (Table 3). Reefs damaged by sedimentation were found to be higher in Tuticorin (14.33±3.87), followed by Vembar (12.83±4.75), Mandapam (11.67±3.96), and Keezhakarai (2.00±1.81) group of islands. Threats such as animal invasion, ghost nets, and anchor damage were found to have occurred in the least number than sedimentation, algal proliferation, and coral disease (Table 3). F-test results revealed that reefs damaged by boat anchors (F=1.250, P=0.295, >0.05) do not significantly distribute within the study area, while other threats are significantly distributed within the study area (Table 4).

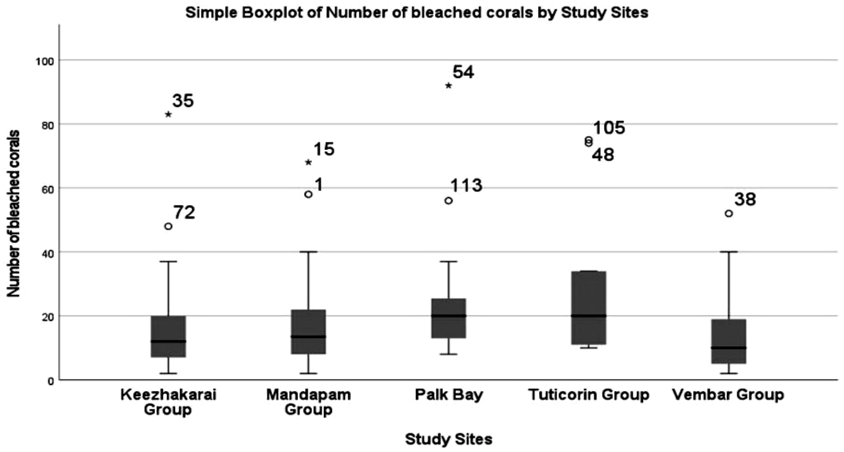

Figure 5. Box-plot diagram showed the number of bleached corals correspondence to study sites

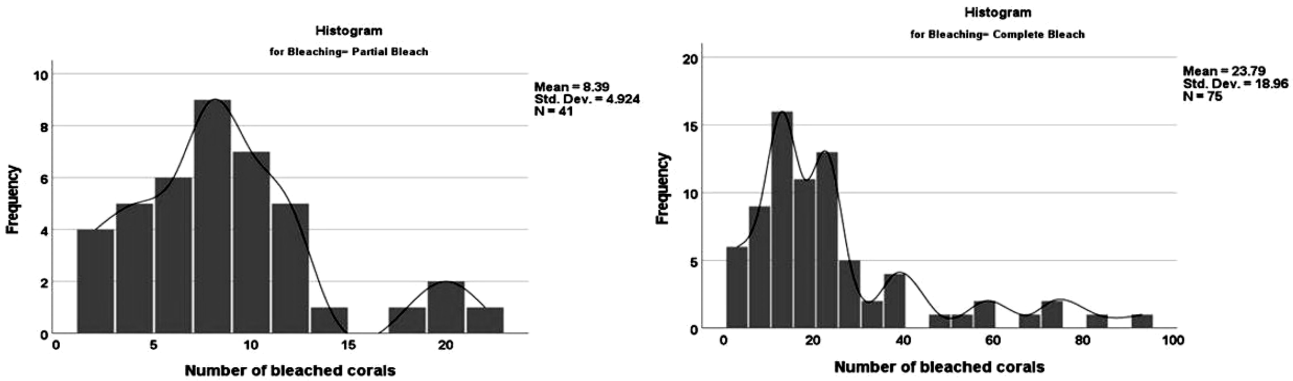

Figure 6. Histogram showing the details of partial and bleached coral status during the study

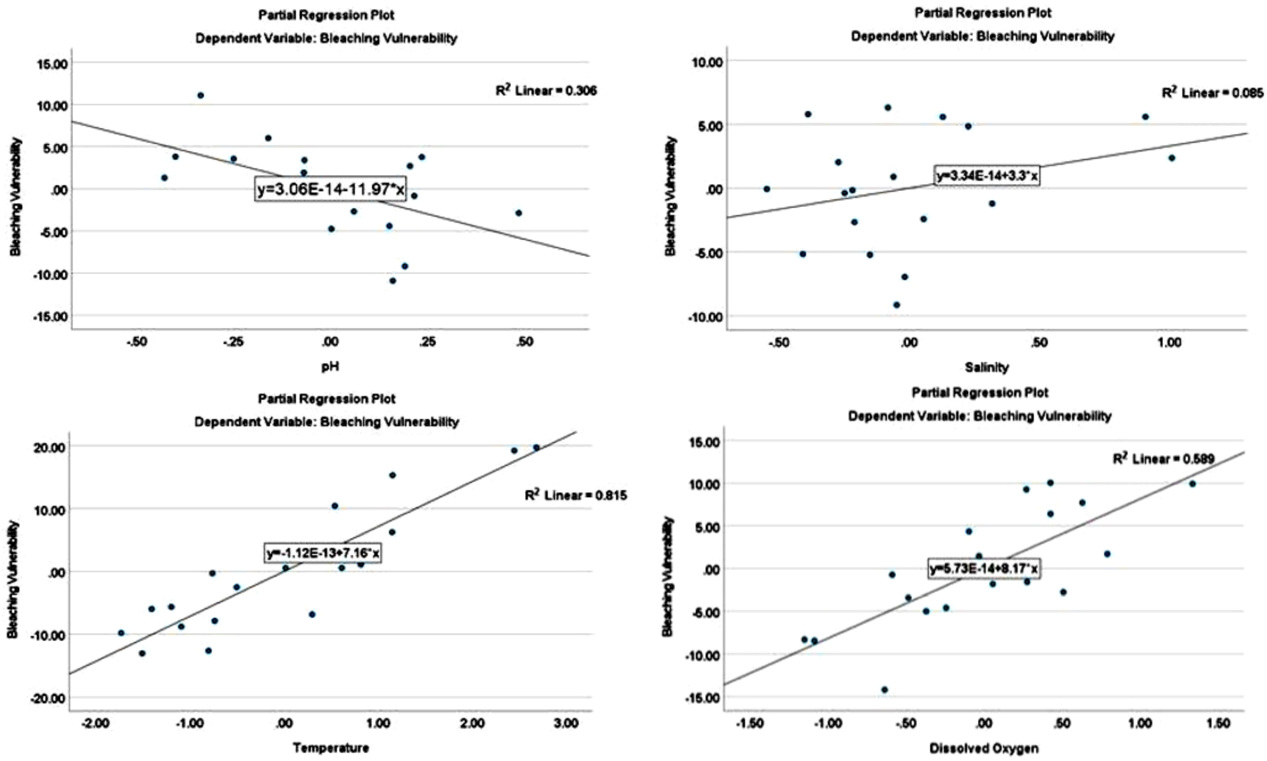

Figure 7. Linear regression analysis of bleaching severity (Dependent variables) with WQ parameters (Independent variables)

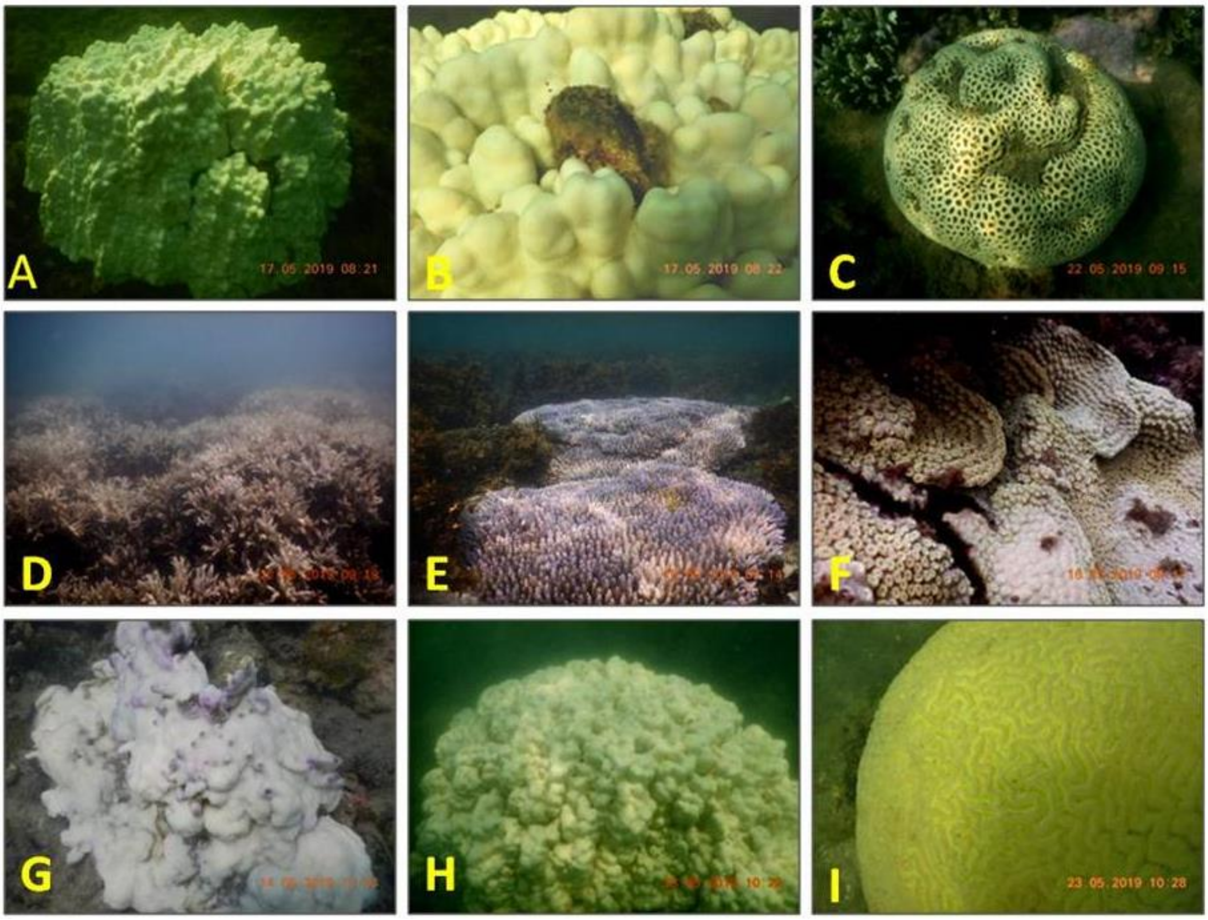

Figure 8. Bleaching in coral species – A-B Massive corals (*Porites* sp.) in PB; C-D. *Goniastrea* sp. in Tuticorin group; *Montipora digitata* reef in Tutitcorin group; *E. Acropora* reef in Keezhakarai group; F. *Turbinariapeltata* in Keezhakarai group; G-H. *Porites lichen* and *Porites lutea* in Mandapam group; I. *Leptoria Phrygia* in Vembar group

The normality distribution of different threats at islands of GoM has also been represented by the Boxplot diagrams, which showed a normal and symmetrical distribution of sedimentation and coral disease threats to the reefs. Algal proliferations were found to be extremely distributed, whereas animal invasion, ghost nets, and anchor damage were weakly distributed to the islands of GoM (Figure 9).

Discussion

This study documented some important reef health details of the coral communities, the relative abundance of coral species, the bleaching status of corals, and threats to the reefs that exist in GoM and PB. Coral reefs are fragile and highly virulent to natural and anthropogenic disturbances, including climate change, sedimentation, destructive fishing, shoreline operations, and tangling ghost nets (Krishnan et al. 2018). Therefore, community structure is highly variant through time; hence, the percentage of live coral coverage also significantly varied compared to the earlier data of 2001 and 2015 (Shanmugaraj et al. 2013; ENVIS 2015). Based on the statistical data, it is inferred that non-Acropora corals (massive corals, foliose corals, sub-massive and branching non-Acropora) are more abundant than Acropora branching corals (Figure 4). Only in the Mandapam group of Island *Acropora hyacynthes, Acropora digitifera, Acropora gemmifera,* and *A. muricata* commonly distributed and abundant. Detail live form categories are recorded from each island of GoM and sites of PB during the reef monitoring. Earlier studies reported that live coral coverage in the reef of GoM increased from 25.30±8.43% in 2000 to 36.98±13.12% in 2005, 42.85±10.74% in 2009, and 37.31±10.38% in 2012 (Edward et al. 2012), whereas present study reported 39.55±15.45%. In PB, the percentage of live coral coverage increased from 9.89±8.73% in 2010 to 5.82±8.43% in 2013 (Venkataraman and Rajan 2013; Azzez et al. 2016) to 28.40±14.60% in the current study. These data are the key factor in defining this ecosystem's coral reef resilience, which is highly influenced by resistant coral species, coral diversity, herbivore biomass, coral disease, and macroalgae cover (McClanahan et al. 2012; Maynard et al. 2015). Within a limited time of massive natural stress, species abundance also responds to changes in habitat variation, distribution pattern, and species interaction (Karlson et al. 2004, 2007; Done et al. 2015). In the present study, we reported 79 species of corals from August 2018 to August 2020, while 117 coral species were documented from GoM (ENVIS, 2015). The occurrence of abundant species in the reefs of GoM is found for *M. digitata* (Table 1), which might be due to space competition.

Among the physicochemical parameters, low pH or increased CO_2 and Sea surface temperature (SST) are the important factors affecting corals' community structure. Accumulation of huge amount of CO_2 can lower the pH (<7.0) in marine water, which in turn reduce the growth, physical integrity, and calcification ability of marine invertebrates like corals and foraminifera (Kroeker et al. 2013; Guinotte and Fabry 2008). In the present study, pH varied between 6.80 and 8.20, which found well-maintained water quality in GoM and PB. However, due to rainfall, the pH levels become lower than 7 during July 2019. Therefore, SST is one of the intrinsic factors affecting the reef environment severely.

Table 4. ANOVA result of different threats observed in GoM, India

		Sum of Squares	df	Mean Square	F	Sig.
Sedimentation * Study Area	Between Groups (Combined)	2802.876	3	934.292	66.243	0.000
	Within Groups	1636.072	116	14.104		
	Total	4438.948	119			
Coral DIsease * Study Area	Between Groups (Combined)	178.025	3	59.342	11.535	0.000
	Within Groups	596.767	116	5.145		
	Total	774.792	119			
Algal Proliferation * Study Area	Between Groups (Combined)	1961.500	3	653.833	45.012	0.000
	Within Groups	1685.000	116	14.526		
	Total	3646.500	119			
Animal invasion * Study Area	Between Groups (Combined)	63.567	3	21.189	6.909	0.000
	Within Groups	355.733	116	3.067		
	Total	419.300	119			
Ghost Nets * Study Area	Between Groups (Combined)	17.092	3	5.697	4.664	0.004
	Within Groups	141.700	116	1.222		
	Total	158.792	119			
Anchor damage * Study Area	Between Groups (Combined)	3.292	3	1.097	1.250	0.295
	Within Groups	101.833	116	0.878		
	Total	105.125	119			

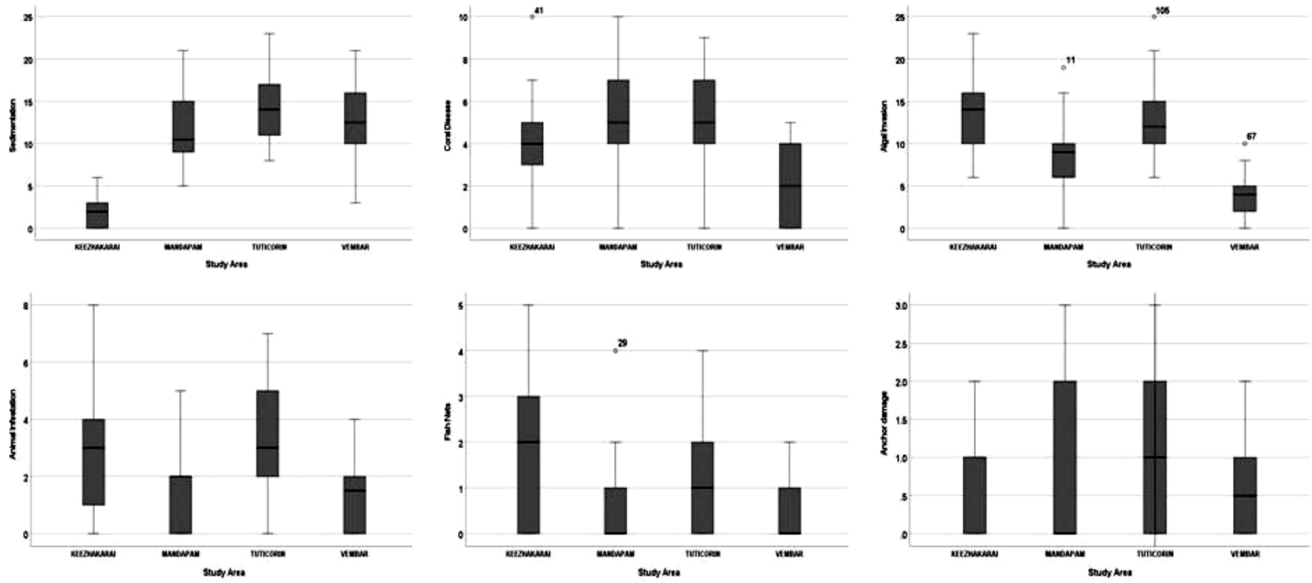

Figure 9. Box-Whisker analysis showing the status of each threat assessed in different sites of GoM and PB, India

The ocean temperature in the Indo-Pacific region is crossing the bleaching threshold quickly during the summer due to global warming (Hughes et al. 2017). As per the report of IPCC, the warming of coral reef waters in general increased globally (0.10-0.12 °C/decade, 1971-2010) and regionally (0.02-0.13 °C/decade, 1950-2009) (Hartmann et al. 2013; Rhein et al. 2013). For the last 24 years, GoM documented a thermal threshold of 30.23±0.39 and a bleaching threshold of 30.73 (Arora et al. 2010), indicating the vulnerability of corals to the bleaching threshold. The coral bleaching phenomenon has declined global coral reef status by 30%, and 60% 0f the remaining corals could be damaged by 2030 (Camp et al. 2018). This thermal-induced coral bleaching during 2014 and 2016 in the Indian and other tropical regions surpassed the previous bleaching event in intensity and duration (Oliver et al. 2018). In the present study, SST ranges between 29.00°C-35.80°C during January and May, causing severe coral bleaching during summer (Figure 7). During 2016 coral bleaching, the temperature ranged between 30°C-34°C which caused 71.48% of corals to bleach in PB and 46.04% of coral bleached in GoM (Krishnan et al. 2018). However, a similar result was found in the present study, where the Tuticorin group of Islands represents a high number of bleached corals than other areas of GoM, followed by PB (Figure 5). Earlier studies documented that branching corals were more tolerant to increased SST than massive corals, which is a sign of prolonging adaptive bleaching patterns found in GoM (Krishnan et al. 2018; Ramesh et al. 2020). In the current study, species-specific evaluation of bleaching revealed the same pattern of bleaching in which massive corals such as *P. lutea*, *P. solida*, *D. favus*, *D. speciosa*, *F. halicora* are bleached intensively, whereas, bleaching among branching corals limited mainly to *A. muricata*, *A. hyacinthus*, and *M. digitata*. During 2019-2020, there was no report of mass bleaching events from global coral reef data, which could be predicted that this bleaching was at a local level and can be mentioned as an annual phenomenon for GoM and PB. The species-specific bleaching pattern might be developed from the condition to past exposure to acute or chronic thermal stress on coral species. Different coral species have distinct abilities to respond to increased thermal stress through their symbionts *Symbiodinium* spp. (ENVIS 2015; Guest et al. 2016). Coral reef species have diverse Symbiodinium clade (Genetic variation) that brings coral resistance to the host corals (Guest et al. 2016). Therefore, in GoM and PB, it can be assumed that branching corals may have adapted with a more resistant clade of *Symbiodinium* than massive corals. Other encrusting coral species, *Hydnophora* sp., *Lobophyllia* sp., *Leptastrea* sp., and *Platygyra* sp. were partially bleached and may recover soon from this local bleaching event.

Threats to the coral reefs of GoM and PB are prevalent. Earlier studies documented reefs are highly disturbed by sedimentation, coral mining, macroalgal proliferation, coral disease, destructive fishing, and domestic sewage (Edward et al. 2012; George and Jasmine 2015). The present study investigated six categories of more acute threats in recent times: sedimentation, coral disease, macroalgal proliferation, animal invasion, ghost nets, and anchor damage (Table 3). Among the six categories of threats, macroalgal proliferation is abundant at all the sites of GoM, which could be considered the potential competitor to the reef-building corals, whereas sedimentation is found prevalent in the Mandapam and Tuticorin group of islands (Table 3). Though several earlier studies reported a high proliferation of macroalgae *Kappaphycus alvarezii* causes severe damage to the reefs of GoM and PB, the current study doesn't reveal any trace of these macroalgae in GoM (Mandal et al. 2010; Kamalakannan et al. 2014; Edward et al. 2015). Earlier studies also documented that the macroalgal genus *Caulerpa* sp. and *Turbinaria* sp. were the most dominant species at the reef of GoM (Manikandan and Ravindran 2017; Ramesh et al. 2019b). However, the present study recorded that *Caulerpa taxifolia*, *C. racemosa*, *Ulva reticulata*, *Padina gymnospora*, *Turbinaria* sp., *Sargassum* sp., and *Halimeda* sp. were found to be the most abundant in the GoM reefs (Figure 10).

The abundance of macroalgae reduces the chance of post-larval settlement of the coral species and also replace the live reef to macroalgae dominated reef. The coral disease was also found abundant in Mandapam and Tuticorin groups which were assumed to be spread faster after the macroalgal proliferation and frequent bleaching events (Figure 9). Pink line disease, Pink spot disease, Black band, and white band disease have been recorded from the reef of GoM (Ramesh et al. 2019a). The animal invasion has also recently been an increasing threat to the reefs of GoM (Thangaradjou et al. 2016; Raj et al. 2018). The present study recorded a higher occurrence of animal invasion in the Tuticorin and Keezhakarai group of Islands than in another region of GoM (Table 3). Another two stress factors that affect the reefs are ghost nets and anchor damage which is entirely raised by anthropogenic disturbances from the local fishermen communities. The fisher communities of GoM are characterized by low literacy rates, lack of awareness of environmental issues, and low income to take up livelihood options other than fishing. Therefore, fishers often forcefully involve themselves in more effective but illegal, destructive, and unsustainable fishing practices (Edward et al. 2007). The present study depicted that the consequences of these two factors are minimal, and possible mitigation could improve the health of the reefs. Coral colonies of the Keezhakarai group of islands are frequently disturbed (Figure 9) by the entangling of ghost nets and by the boat anchor, which breaks the big coral colonies while fishermen anchor the boat near the reef for fishing. Based on the investigations by the current study, it is inferred that corals in GoM are heading toward destruction by increased stress factors of algal assemblages, coral disease, and animal invasion.

Figure 10. Field observation on threats to coral reefs: A-B: Algal growth on live corals; C-D: Sedimentation slowly kills the corals; E: Coral disease (Pink line disease); F. Fishing gears retarded the growth of young coral colonies

Health monitoring studies of reef-building corals in GoM and PB revealed that only increased live coral cover could not improve the overall health of the reefs. It is a complex ecosystem; thus, controlling coral disease and macroalgal proliferation could improve the macrozoobenthic diversity in the islands. Thus, the substrate becomes resourceful by accumulating more reef fish in GoM and PB. Natural threats such as bleaching become a frequent phenomenon in GoM, which influence the additional threats to the reefs, such as Macroalgal proliferation and coral disease. The bleaching resistance capacity of *Acropora* sp. could be an advantage in targeting the coral recovery process as an alternative management program. Coral transplantation of *Acropora* sp. can also improve the natural recruitment process in degraded reef areas. NCCR has already initiated a coral reef restoration program in the Mandapam group of islands. Despite all such remedial actions taken up by management interventions, the future of coral reefs critically depends on their ability to respond to the rapid environmental changes with new adaptive strategies.

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