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ARTICLE

Baseline Survey on Coral Diseases, Stress Factors and New Threats in Coral Reefs of Gulf of Mannar Marine Biosphere, India

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ABSTRACT

Gulf of Mannar Marine Biosphere Reserve (GOMMBRE) is the first marine biosphere reserve in India and Southeast Asia. It has a rich marine biodiversity including coral reefs, but now facing threats from different environmental factors and anthropogenic interferences. Particularly, coral reefs distributed in the 21 islands under the Gulf of Mannar (GoM) region are facing critical threats. Although several institutions and authors have studied various aspects on corals, direct and indirect influences of natural and anthropogenic catastrophes on corals have been poorly understood. Therefore, the main objective of this study was to identify the anthropogenic disturbances, biological stress factors and diseases on fringing reefs of GoM. The present study reveals that dead coral reefs are being replaced by assemblage of marine algae. Although several diseases were recorded during this study, pink line disease is wide spread in all the islands. *Porites sp. and Acropora sp*. were the more affected corals. This baseline data lays foundations to survey and to assess the rapid changes that occur over a period of time in coral reefs of GoM.

1. Introduction

Coral reefs are the rainforests of the marine environment. They provide protection, shelter, food and spawning ground to thousands of marine species. Currently, around 40 million people depend mostly on reef fishes for livelihood and food security [1]. However, these ecosystems are being damaged through extensive illegal fishing techniques like poisoning or dynamite fishing, causing coral reef damage greatly [2]. Several other natural threats and anthropogenic interventions that are destroying coral reefs worldwide are bleaching, sedimentation, earthquakes, hurricanes, raising temperatures, ocean acidification, seawater pollution (due to increased discharge of wastewater from domestic and industrial sources), land runoff, tourist and scuba divers behaviour. Among these threats, coral diseases have been extensively studied worldwide. Arnfried Antonius had first started coral disease research in 1973, and subsequently this topic has steadily gained more attention and led researchers towards etiology and microbiological aspects [3]. Since then, studies on the spread of coral diseases, causative patho-

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gens and mitigation plans are focused highly to conserve the coral reefs.

The GoM region in Tamil Nadu, India is one of the coral rich hotspot well known in Southeast Asia with 117 species of corals. Fringing coral reefs (patchy or continuous) distributed in all the 21 islands of GoM are found in shallow waters with a maximum depth of 2 to 5m. All the 21 islands are uninhabited and mostly covered with mangrove and coastal floral vegetation. However, these reefs are scarcely studied [4]. GOMMBRE was the first marine biosphere reserve identified in India and Southeast Asia by IUCN commission. It was set up on 1989 jointly by Government of India and Tamil Nadu state to protect marine biodiversity and its environment in the bay side (depths of 3.5 fathoms) and seaward side (depths of 5 fathoms) [5]. GOMMBRE extends from Rameswaram to Kanyakumari. It includes a total of 21 islands distributed in four regions namely Mandapam, Keelakarai, Vembar and Tuticorin. GoM was once considered as 'Paradise of marine Biologists' due to its rich biodiversity, including coral reefs, but now it is being known as 'ghost islands' [6]. Over the past few decades, as a consequence of climate change, coral reefs in GoM has been damaged severely by bleaching events [7], rapid growth of exotic invasive algae such as *Kappaphycus alvarezii* [8, 9], *Caulerpa* species [10], the invasive sponge *Terpios hoshinota* [11] and others sponge species [12]. In 2004, the live coral cover of 48.5% in GoM was reduced to 36% due to the tsunami of 26th December 2004 [13]. Significantly, coral reefs of GoM have been extensively faced severe bleaching events due to El-niño [14] and elevated temperatures of 30.5 ℃ to 34 ℃ [15], resulting loss of live coral cover up to 85.1% in 2010 [16], 67.55 ±12.32 in April–May 2016 [15] and 22.69±9.07% during October 2016 [17]. Coral diseases are also known damage reefs in GoM. Among the nine types of diseases recorded in GoM [4], black-band disease has a higher spread rate, and can kill a coral colony surface area of 3 cm in a month when the temperature and nutrient values are higher [4]. To determine the currently existing diseases and threats persistence in coral reef rich islands in Mandapam group region, surveys were conducted for developing scientific mitigation approaches.

2. Materials and Methods

2.1 Study Area

Mandapam group islands are located at the southeast coast of Tamil Nadu, India (Fig. 1). These islands are exposed to seasonally reversing open-ocean currents –the East and West India Coastal Current, which flows between the Arabian Sea, Laccadive Sea and Bay of Bengal, thus mixing of seawater by the entry of seawater from shallow waters Palk Bay to deep water GoM [18]. Mandapam group islands comprise rich coral diversity distributed in seven islands (Figure 1). Hare Island –also called Musal is the largest among these islands with 129.04^{2}area in hectares. An official permission has been obtained from the local government, Gulf of Mannar Forest Reserve Trust, Ramanthapuram (PCCF and CWLW letter WL 5(A)/18855/2017 Dt. 12.06.17) to conduct surveys on coral reefs in GoM.

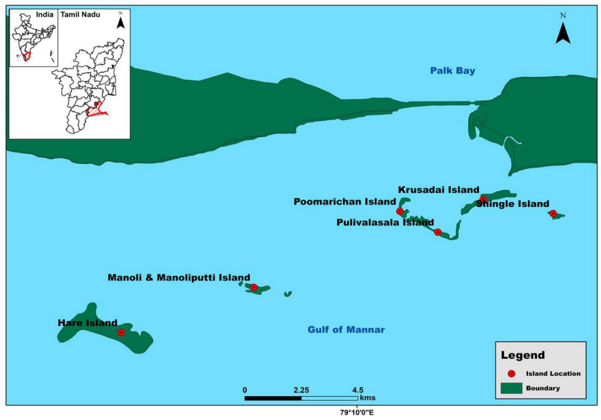

Figure 1. Study sites in Mandapam group of Islands in GoM

2.2 Underwater Surveys

Coral diseases, benthic algal assemblages on corals and other stress factors around the coral reefs of Mandapam group of Islands were investigated at 17 selected corals rich sites. Underwater surveys (Scuba diving and Snorkelling) were conducted between the months of August 2018 to February 2019. Along fringing reefs, the depth consistence is almost similar, roughly representing a maximum depth of 1 to 2m in reef flat, 1 to 6m in reef crest and 3 to >5 at reef slope. At each site, a line transect of 50 m length was laid and performed the Line Intercept Transect (LIT) method [19]. Along LIT, different diseases and other threats observed on different corals were recorded. Overall, 27 line transects were analysed (covering a total area of 1350 m^2) to assess the common health impairments and disease symptoms of corals as well as condition of benthic algal community in the reefs. Scleractinian and alcyonacean corals found across all transects were identified to genus or species level using standard identification keys [20]. Based on underwater observations, health status of corals and reef building crustose coralline algae were also determined by visualised color codes.

2.3 Water Parameter Measurements

The present features of each island beach topography and

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water quality parameters were recorded during field surveys using Manta+ Water Quality Sonde (Table 1). This data will be used as a reference for future studies to link with the changes happened in a reef flat over a period of time.

2.4 Diseases and Invasive Algae Identification

Coral diseases and bloom forming algal communities examined in underwater were recorded by photography using Nikon Coolpix. All coral diseases observed in the field were verified and identified following the Global Coral Disease Database (GCDD) and ReefBase and following published illustrations and descriptions available in the literature [21-27]. Blooms forming invasive algal communities overgrowing different coral species were also identified using standard reference keys [28, 29].

2.5 Data Analysis

Disease prevalence in each coral type and algal cover on corals were calculated by following formulas [30, 31].

$$\text{Disease prevalence \%} = \frac{\text{Number of disead colonies}}{\text{Total number of colonies investigated}} \times 100$$

$$\text{Algal percent cover} = \frac{\text{Length of algal category}}{\text{Length of Transect}} \times 100$$

3. Results

Coral diseases and algal invasion were relatively more prevalent in Shingle Island (SI) and Hare Island (HI) than other islands (Tables 2&3, Figures 2-8). Pink line disease on *Porites* species was the most prevalent disease in this study. Hare Island presented most of threats, followed by Shingle and Manoli Island. Branching *Acropora* coral patches and individual colonies in both north and south side of Hare Island were mostly affected with invasive algal blooms such as *Caulerpa racemosa, C. sertuloides, C. peltata, C. verticillata, Ahnfeltia plicata, Turbinaria ornata, T. decurrens, T. conoides, C. taxifolia* and various species of sponges especially *Cliona* sp. (Figure 5; Tables 2&3). Despite of algal blooms on reefs, various other algal species also caused stress on massive and branching coral colonies by growing on a fragment of coral (Figures 6&7). Non focal bleaching occurrence on *A. hyacinthus* was frequently seen only in south side of Hare Island and north side of Manoli Island. Bleaching of *Acropora* corals due to destructive fishing and anchoring was observed mostly in Hare Island. Coral reefs in Manoli Island were mostly affected with *Ahnfeltia plicata* (55%) in 20m^2 area. *C. racemosa* and *C. taxifolia* invasion was insignificant, but have caused stress on a soft coral species and *Pavona decussatus*, respectively.

Table 1. Characteristics of studied sites and water quality parameters recorded from study sites.

Study site	GPS coordinates	Reef type	Beach feature	Water quality parameters				
				Dissolved Oxygen (mg/L)	Salinity (mg/L)	pH	Reef crest depth (m)	Water temp (°C)
Hare Island	09°11.780 N 079°04.426E	Fringing reef	Sandy, coral rubbles	6.17	34.62	8.14	1.9	29.82
Manoli Island	09°12.046N 079°04.702E	Fringing reef	Sandy clay & muddy	6.28	34.95	8.17	3.05	30.92
Manoliputti Island	09°11.777N 079°04.426E	Fringing reef	Sandy, coral rubbles	6.18	33.52	8.2	2	29.31
Poomarichan Island	09°14.414N 079°10.707E	Fringing reef	Sandy, coral rubbles	6.13	33.02	8.07	0.99	29.57
Pullivasal Island	09°14.020N 079°12.189E	Fringing reef	Sandy, coral rubbles	6.15	34.01	8.15	2	29.62
Kurusadai Island	09°14.319N 079°12.184E	Fringing reef	Sandy, coral rubbles	6.19	33.78	8.13	1-3	30.15
Shingle Island	09°14.741N 079°14.152E	Fringing reef	Sandy, coral rubbles	6.15	34.38	8.11	1-4	29.08

Table 2. Coral diseases and other threats prevalence in Mandapam group islands. HI: Hare Island; MI: Manoli Island; MPI: Manoliputti Island; POI: Poomarichan Island; PUI: Pullivasal Island; KI: Kurusadai Island; SI: Shingle Island.

Threat prevalence (in %)	Geographical distribution						
	HI	MI	MPI	POI	PUI	KI	SI
Pink line disease	83%	60%	25%	50%	87.5%	14.28%	64.28%
Pink spots	16%				12.5%		10.71%

Black band disease	11.11%	8.3%					
Localised bleaching	28.57%	8.3%			1.2%	7.14%	
White band disease	11%						21.42%
White line disease							6.6%
White plague	5.5.%						
Compromised tissue	11.11%			16.6%		28.57%	
Coralline lethal orange disease (CLOD)						7.14%	
Coralline white-band syndrome (CWBS)	4.76%		4.16%				10.71%
Coralline white patch disease (CWPD)			8.33%				3.57%
Ash green patch disease (AGPD)							21.42%
Infestation of sponges	38.8%					3.57%	
Infestation of CCA	27.7%				37.5%		14.28%
Serpulid worms	33.3%				62.5%		21.42%
Drupella cornus	5.5.%		3.12%				
Coralliophilia sp.						2.08%	3.57%

Table 3. Diseases and algal invasions recorded in Mandapam group islands with indication of the main coral species affected.

S.No	**Type of threat**	**Affected coral**	**Geographic distribution**							**Reference**
			HI	**MI**	**MPI**	**POI**	**PUI**	**KI**	**SI**	
1.	Diseases									
	Pink line disease	*Porites* species	■	■	■	■	■	■	■	Present study
	Pink line disease	*Acropora* sp. & *Porites* sp.		■				■		[32]
	Pink spot disease	*Porites* sp.		■				■		[32]
	Pink spot disease	*Porites* sp.	■				■		■	Present study
	Black band disease	*Acropora cytherea*							■	[33]
	Black band disease	*Porites, Pocillopora* & *Goniastrea*		■				■		[32]
	Black band disease	*Favites abdita, F. halicora, Pavona decussatus* and *Montipora digitata*	■	■						Present study
	Fungal blotch	*Acropora, Goniastrea, Favites, Favia*		■						[32]
	White band disease	*A. cytherea* and *Montipora digitata*							■	[33]
	White band disease	*Acropora* sp. & *Pocillopora* sp.						■		[32]
	White band disease	*Favia stelligera*	■							Present study
	White patch disease	*Porites solida*	■						■	Present study
	White pox	*Porites* sp.		■				■		[32]
	White plague	*Porites* sp.						■		[32]
	Whigte plague	*Porites solida*	■							Present study
	Yellow band	*Acropora*		■						[32]
	White line disease	*P. lutea*							■	Present study
	Compromised tissues	*Porites* sp.	■					■		Present study
	Necrosis	*Acropora* sp., *Montipora* sp. & *Porites* sp.						■		[32]
2.	Bleaching									
	Localized bleaching (focal & non focal)	*A. hyacinthus, P. lutea*	■	■	■		■	■	■	Present study
	Anthropogenic mediated bleaching (AMB)	*Acropora formosa, A. hyacinthus*	■		■		■	■	■	Present study
	Global level massive bleaching event (GLMBE)	*Acropora formosa, A. intermedia, A. nobilis, A. cytherea, Montipora foliosa, M. digitata, M. divaricata, M. hispida* and *Pocillopora damicornis*	■	■	■	■	■	■	■	[17]

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	GLMBE	*Porites solida, P. lutea, Favia* sp., *Acropora cytherea, A. intermedia, A. formosa, A. nobilis, M. digitata*								[16]
	GLMBE	*A. formosa, Montipora samarensis, Favia lizardensis, P. lobata, P. luteu, Pavona variance, Pocillopora damicornis*								[15]
	Coralline algal bleaching	*Neogoniolithon* sp.								Present study
3.	Algae invasion									
	Ahnfeltia plicata	*Montipora digitata*, *Favites* sp., *A. digitifera, A. muricata, Pavona decussatus*								Present study
	Caulerpa racemosa	*A. formosa, Favia pallida, Echinopora lamellosa, Pavona decussatus*, soft coral								Present study
	C. fergusonii	Dead *Acropora* patch								Present study
	C. racemosa	*Echinopora* spp.								[34]
	C. peltata	*P. decussatus*								Present study
	C. verticillata	*A. hyacinthus*, *Porites lutea*								Present study
	C. scalpelliformis	Foliose corals								[34]
	C. sertularioides	*P. decussatus, P. lutea, A. formosa*								Present study
	C. taxifolia	*Echinopora lamellosa* and *A. formosa*								[10]
	C. taxifolia	*P. decussatus* and *A. formosa*								Present study
	Halimeda opuntia	*P. lutea* and *A. formosa*								Present study
	Hypnea pannosa	*M. digitata, Acropora millipora*, *E. lamellosa*, *P. decussatus, Favia favus*								Present study
	Kappaphycus alvarezii	*A. nobilis, A. formosa, A. cytherea, Monipora digitata, M. foliosa* and *Porites lutea*								[8, 9, 35]
	Turbinaria decurrens, T. ornata & *T. conoides*	*Acropora* sp. and *Porites* sp.								Present study
	Sargassum sp.	*Porites* sp.								Present study
	Moorea sp.	*Acropora* sp.								Present study
	Padina boergesenii	Dead *Acropora* reef and live *Acropora*								Present study
	Stoechospermum marginatum	Dead *Acropora* reef								Present study
	Lyngbya majuscula	Live and dead *Acropora* reef								Present study
	Ulva reticulate	*Acropora* sp.								[34]
	Hydrolithon spp.	Dead *A. formosa,* live *A. hyacinthus* and live *Porites* sp.								Present study
4.	Faunal invasion									
	Coralliophilia sp.	*Acropora* sp. and *Porites* sp.								Present study
	Drupella cornus	*Acropora formosa* and *Porites* sp.								[36]
	Other sponges (Fig. 5)	*P. lutea, A. formosa, A. digitifera, A. hyacinthus*								Present study
	Terpios hoshinota	*A. formosa, Montipora* sp. and *P. lutea*								Present study
	Sponge *Cliona* sp.	*Acropora* and *Porites*								Present study
	Sea urchin *Stomopneustes variolaris*	Dead reef, *Acropora*, *Porites*								Present study
	Zoanthids *Palythoa mutuki*	Live *Acropora* corals								Present study
	Rhodoliths CCA invasion	Dead *Acropora* reef								Present study
	Barnacle*, Balanus reticulatus* invasion	Soft coral *Subergorgia suberosa*								Present study
5.	Sedimentation	*Porites* sp., *E. lamellosa*, *Platygyra lamellina* and *Acropora* tabular								Present study
6.	Entanglement of fish nets									
	Gill nets	*Acropora digitifera, A. hyacinthus*								Present study
	Trawl net	*Acropora formosa* and *P. compressa*								Present study

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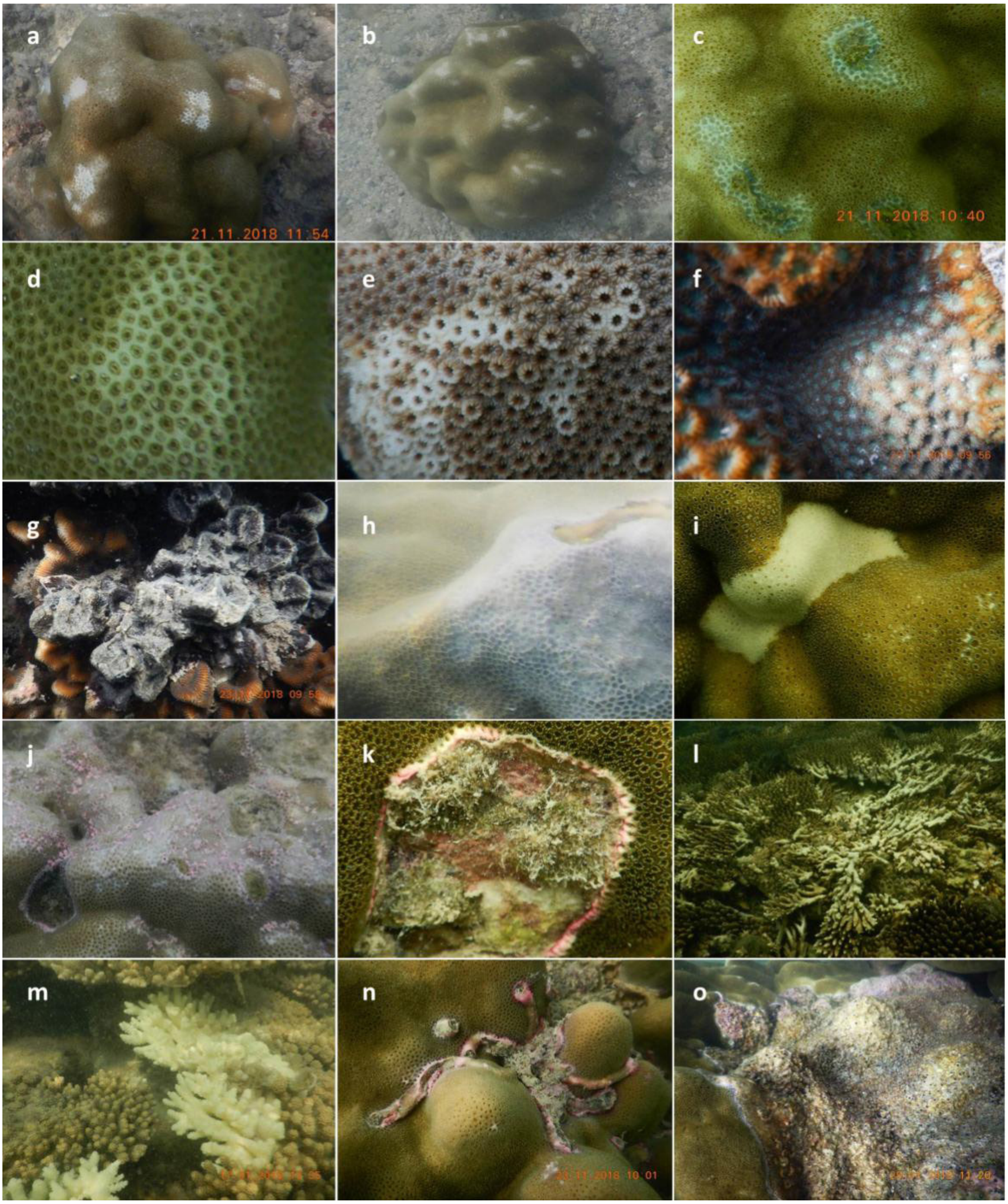

Figure 2. White spot (a) and white pox (b) diseases on *Porites lutea*; development of black band disease (early stage) on *P. lutea* (c); paling of coral color and tissue loss in *Porites* sp. (d); white band disease on *Favia stelligera* (e); black band disease propagation on *Favites abdita* (f); dead coral fragment of *Favites halicora* due to black band disease (g); white plague (h) and white patch syndrome (i) on *Porites solida*; Scattered and swollen pink nodules on *P. solida* due to trematode *Podocotyloides* sp. infection (j); pink line disease on *P. solida* (k); bleaching in destroyed coral *Acropora hyacinthus* due to destructive fishing (l); partial bleaching in some fragments of healthy *A. hyacinthus* (m); Serpulid worms overgrowing *P. lutea* (n); worm shells *Dendropoma* sp. (black spots are shell openings) cemented by crustaceous coralline algae *Neogoniolithon* sp. on *P. lutea* (o).

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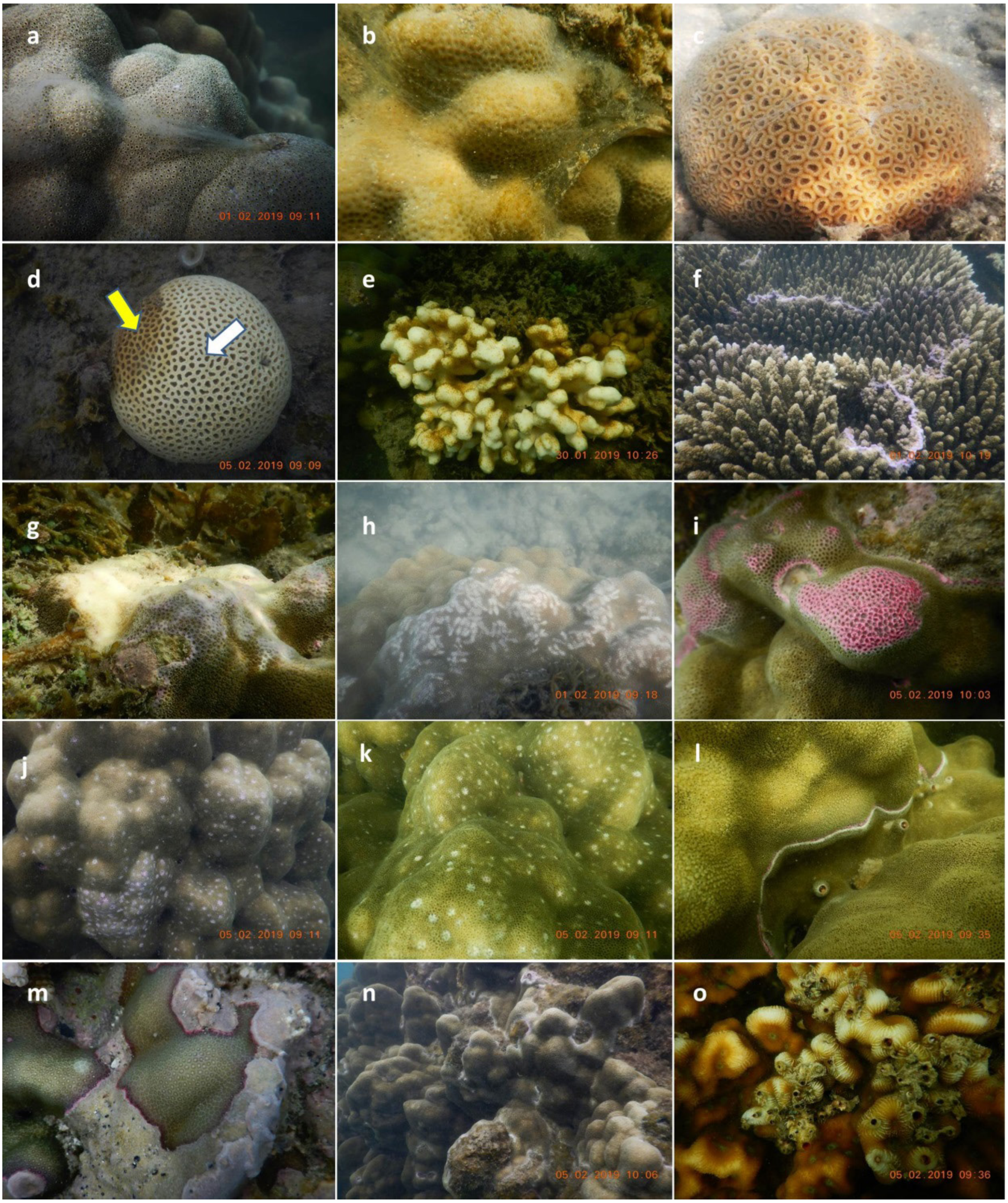

Figure 3. Mucus oozing out by *Porites lutea* (a), *Porites* sp. (b) and *Favia favus* (c); Tissue loss (white arrow) in *F. favus*, and yellow arrow indicates healthy condition of tissue in brownish color (d); bleached coral fragments of *Psammocora contigua* (e); abnormal growth on *Acropora hyacinthus* (f); damaged coral body of *P. lutea* (g); spot biting on *Porites* sp. probably due to parrot fishes (h); trematode infections on *Porites* colony (i); multi-focal pink spots (j) and *Porites* ulcerative white spots (k) diseases on *P. lutea*; white line syndrome on *P. lutea* (l); pink line disease propagation on rhodoliths infested coral (m); cyanobacterial infection on *P. lutea* (n); boring worms on *Favites halicora* (o).

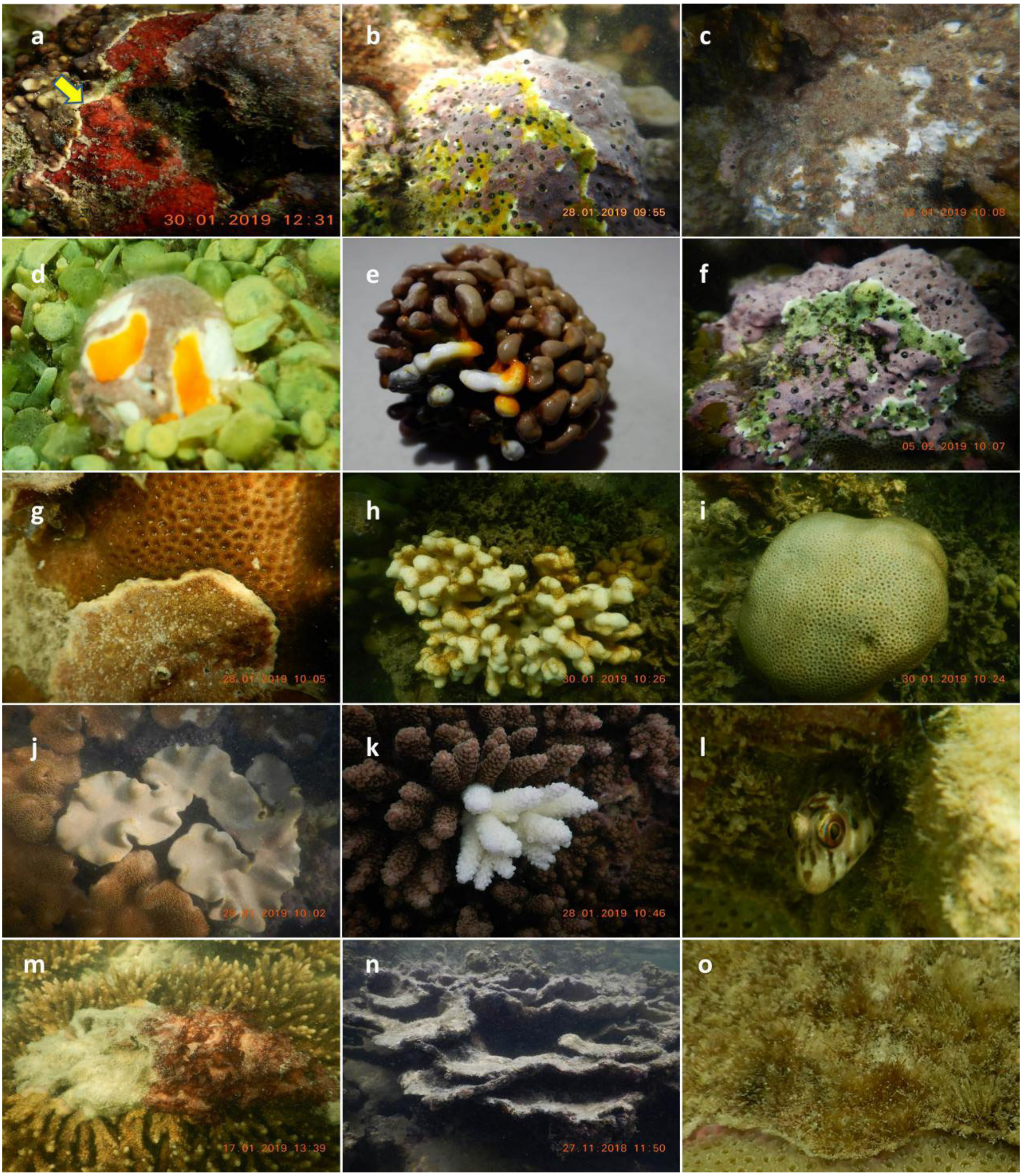

Figure 4. Coralline white-band syndrome (CWBS) (a), Coralline lethal orange disease (CLOD) with Coralline white-band syndrome (b), Coralline white patch disease (c) and CLOD on *Neogoniolithon* sp. (d) and *Hydrolith* (e); ash green patch disease (probably initial stage of coralline fungal disease) along with CWBS on *Neogoniolithon* sp. (f); white patch disease infested by cyanobacteria on *Favites* (g); non focal bleaching in *P. compressa* (h), *Favia* (i), soft coral *Lobophyton* sp. (j) and *A. cyatherea* (k); a blenny fish *Blenniella* sp. dwelling in the wholes on *P. lutea* (l); cyanobacteria Oscillatoria sp. mat on sedimented areas of coral *A. hyacinthus* (m); a view of turf algal assemblage on dead *Echinopora* coral patch (n); microbialites on live coral *P. lobata* (o).

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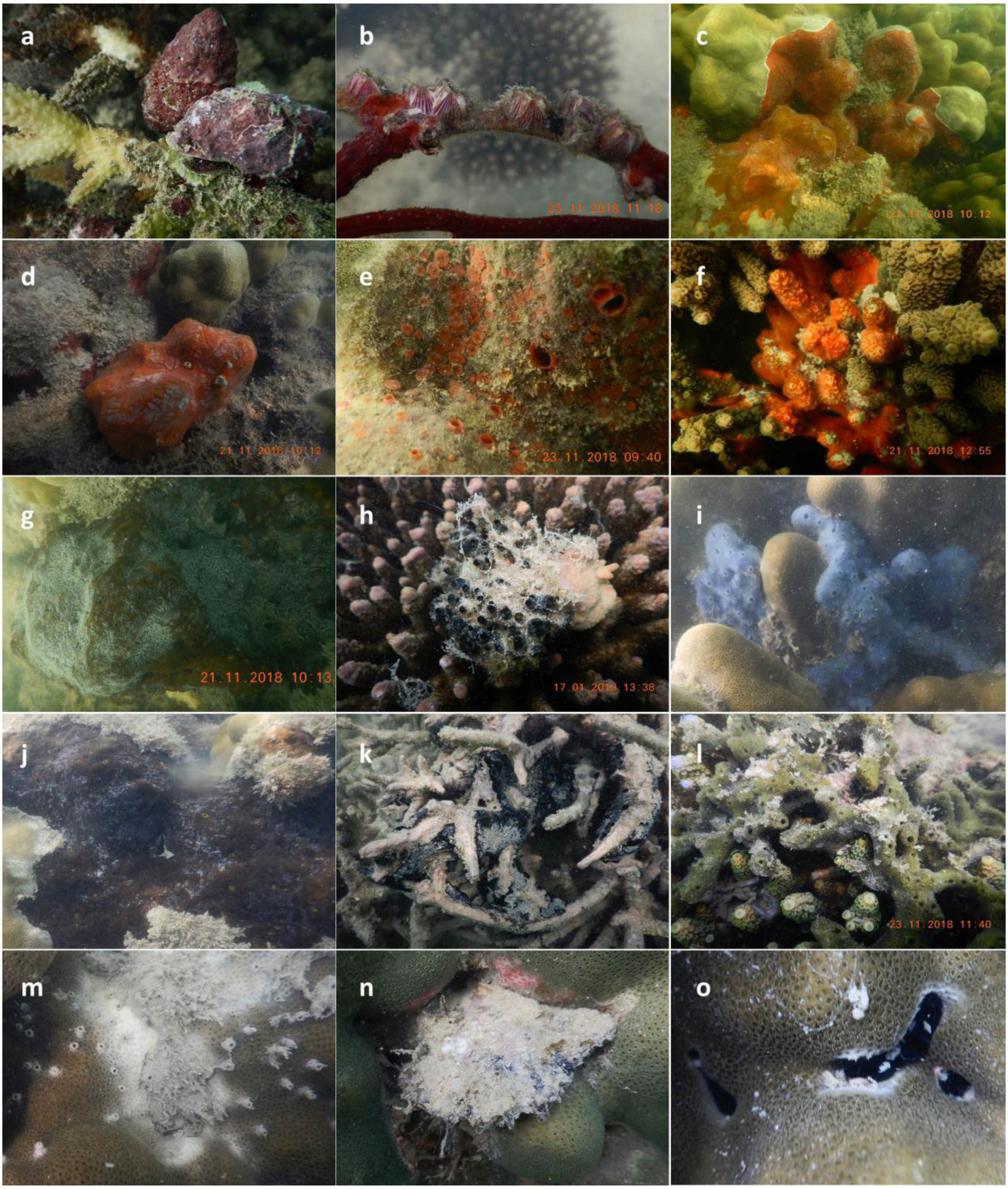

Figure 5. Infestation of invasive sponges, gastropods and algae on coral reefs of GoM. The muricid gastropod *Drupella cornus* feeding on polyps of *Acropora formosa* (a); *Balanus reticulatus* overgrowing *Subergorgia suberosa* (b); sponge *Cliona* sp. overgrowing *Porites lutea* (c & d); boring sponge *Cliona* sp. on *P. lutea* (e); *Cliona* sp. overgrowing *Acropora hyacinthus* (f); sponge *Cliona viridis* cover on *P. lutea* (g); unidentified black sponge overgrowing *Acropora* (h);sponge *Haliclona* sp. propagating on *P. lutea* (i); coral killing sponge *Terpios hoshinota* on corals *P. lutea* and *A. formosa* (j&k); *Neopetrosia* sp. sponge overgrowing *Acropora millepora* (l); skeletal aberrations on *Porites lobata* due to boring spionid polychaetes (m); bio-eroding bivalve *Pinctada fucata* on *P. lobata* (n); bioerosion scars on *P. lobata* (o).

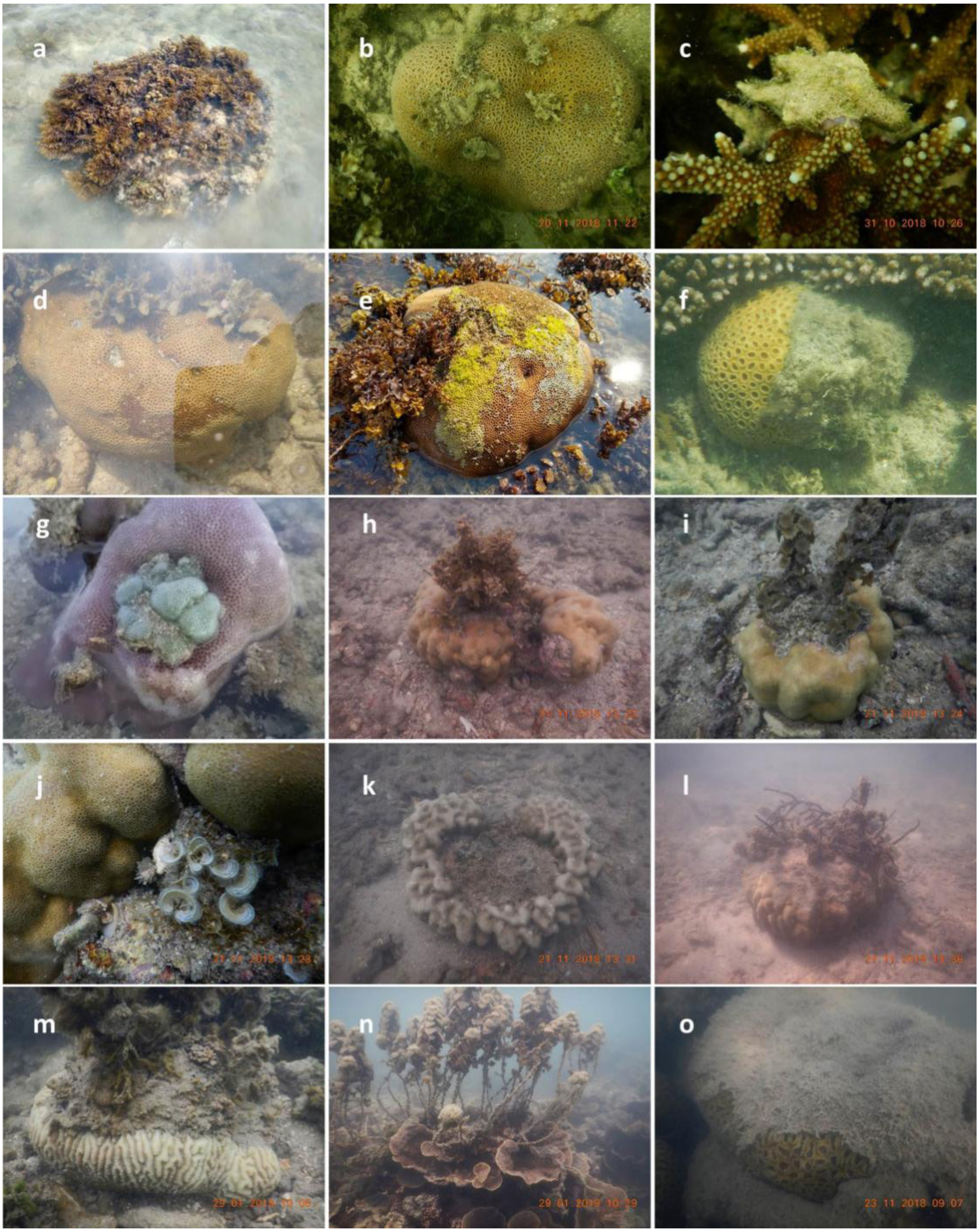

Figure 6. Upper body surfaces of massive corals affected with sedimentation at different angles. *Sargassum* sp. on *Porites solida* (a), Cyanobacterial growth on *Favia favus* (b), partially dead coral fragment of *Acropora formosa* (c), *Padina gymnospora* and *Sargassum* sp. on *Porites solida* (d), cyanobacterial mat overgrowing *Porites solida* (e), partly dead coral body of *Favia favus* (f), Dictyosphaeria cavernosa settlement on *Porites solida* (g), *Sargassum* sp. development on *Porites lutea* (h), *Turbinaria ornata* on *P. lutea* (i), *P. gymnospora* and algal mat on *P. lutea* (j), sediment pit in the middle of *P. lutea* body (k), *Sargassum* sp. and *Turbinaria* sp. overgrowing *P. lutea* (l), profuse growth of *Turbinaria* on sedimented tissue areas of *Platygyra lamellina* (m), and *Echinopora lamellosa* (n), sedimentation on upper surface of *Favia* speciosa (o).

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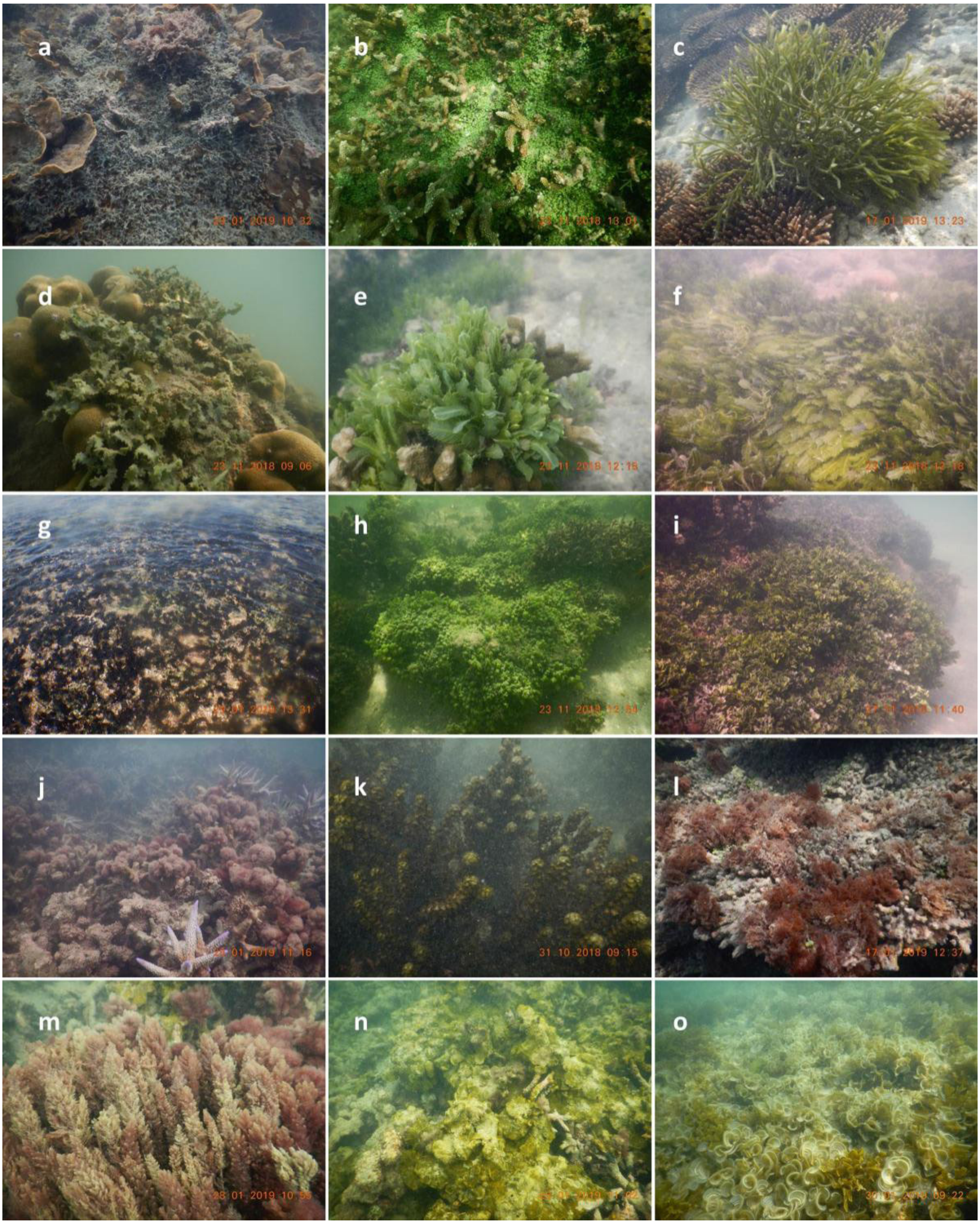

Figure 7. Different species of algae overgrowing on corals. *Lyngbya majuscula* on *Echinopora lamellosa* (a); *Caulerpa peltata* on live *Acropora formosa* (b); *Codium fragile* overgrowing *Acropora hyacinthus* (c); *Caulerpa serrulata* growing on *Porites lutea* (d); *Caulerpa taxifolia* on *Montipora digitata* (e); *Caulerpa sertularioides* on growth on *Porites solida* (f); *C. racemosa* on *M. digitata* (g) and *P. solida* (h); *Halimeda opuntia* on *P. lutea* (i); red filamentous cyanobacterium *Moorea* sp. on *A. formosa* (j); *Turbinaria* species on *Porites* sp. (k); *Portieria hornemannii* on *Acropora* corals (l); *Asparagopsis taxiformis* (m) and *Lobophora variegata* (n) overgrowing live and dead *A. formosa*; *Padina boergesenii* bloom on dead *Acropora* reef (o).

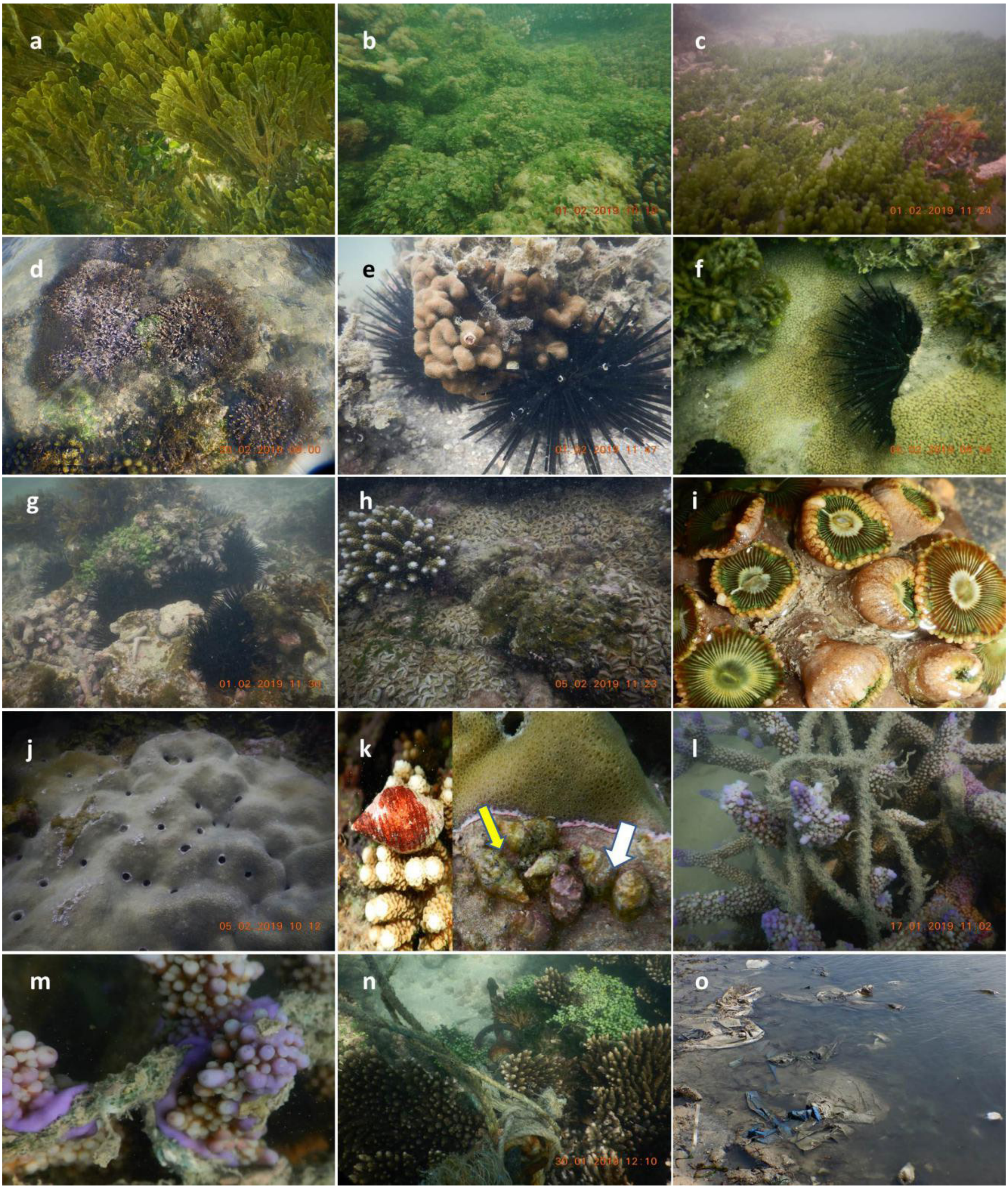

Figure 8. Bloom of *Stoechospermum marginatum* on dead *Acropora* reef (a); *Caulerpa verticillata* overgrowing *A. hyacinthus* (b); *Caulerpa fergusonii* bloom on dead *Acropora* patch (c); *Ahnfeltia plicata* overgrowing *Acropora* & *Montipora* (d); *Stomopneustes variolaris* boring *Porites* species (e, f) and dead reef (g); Benthic zoanthid invasion on recruitment of *Acropora* species (h & i); serpulid worm holes on *Porites lutea* (j); *Coralliophilia* sp. on *Acropora* and *Porites* (white mark) (k); entanglement of fish nets to *Acropora* (l), fishing rope hindering the growth of *Acropora muricata* (m); boat anchoring causing breakage of *A. hyacinthus* (n); solid waste on shoreline (o).

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In all the study areas, damage of corals was documented due to anchoring and boating in reef area for fishing (Fig. 2l & 8n). While, entangled and torn fish nets were more frequently found on live and dead corals, causing localised growth inhibition of live corals (Fig. 8l&m). Comparatively, broken *Acropora* coral colonies were frequently encountered in Hare Island than other islands. Despite of great abundance of algae found on reefs in all the islands, reefs found to be sparsely-populated with invertebrates such as sponges and gastropods and vertebrates like reef fish. Reefs in all 7 islands of Mandapam group were well occupied by assemblage of various species of algal communities (Figure 7&8).

The shape of coral has a major role in avoiding sedimentation and algal growth. Coral reefs in Mandapam group islands have revealed that massive and branching corals with flat surface were highly prone to sedimentation followed by algal assemblage. Among all types of corals investigated, *Porites* species were highly affected with sedimentation and algal assemblage (Figure 6). Extensive underwater surveys of this study have revealed that a small amount of sediment deposition on any type of coral has promoted development of various species of algae and invertebrates (Figure 3-6).

Corals in the Poomarichan Island were mostly dead excluding some patches of *Porites* species. Poomarichan Island comprises mostly seagrass beds and dead reef areas with algal cover. Profuse growth of *Halimeda, Turbinaria*, *Caulerpa peltata*, and *C. racemosa* were found on these dead coral reefs in Poomarichan Island. Interestingly, in Pullivasal Island, *Moorea* sp. (80%) *Lobophora variegata* (40%), and *Asparagopsis taxiformis* (Rhodophyta, Bonnemaisoniaceae) (20%) have completely covered *Acropora* coral patches spanning up to 20m^2 area. Some massive *Porites* sp. colonies (n=7) covered by *Caulerpa peltata* were also found in Pullivasal Island (Figure 7 & 8).

In Kurusadai Island, the dead *Acropora formosa* coral patches representing >50m^2, >30m^2 and >50m^2 were fully occupied by *Padina boergesenii* (100%), *Stoechospermum marginatum* (70%) and *Turbinaria* (100%) species respectively (Fig. 7). The dead and live *A. hyacinthus* coral patches were also covered by *C. racemosa* (20%), *C. peltata* (50%) and *Halimeda opuntia* (>25%) in a 50m^2 area (Fig. 7). While the dead massive *Porites* coral patches were occupied by *Lyngbya majuscula* (100%), *Calpomenia sinulosa* (50%), and *Sargassum* sp. (60%) in 50m^2, 20m^2 and 30m^2 transect areas respectively (Fig. 7). Although the recruitment of *Echinopora* corals on dead *Echinopora* patches in Kurusadai Island were well appreciated, the red alga *Hypnea pannosa* overgrown (60%) on these *Echinopora* corals (Fig. 7). The crustose coralline algae *Hydrolithon* sp. is highly predominant on dead corals found in Manoliputti Island, Pullivasal Island and Kurusadai Island. Dead *Acropora* reef of 20m^2 area on northern side of Shingle Island has fully covered by *C. fergusonii* (80%) in Shingle island. Similarly, live *Acropora* species regenerating substratum area of 50m^2 on southwestern side of Shingle Island was dominated with 60% of zoanthids *Palythoa mutuki* (Fig. 8h&I; Table 2 & 3). Boring of massive corals by sea urchin *Stomopneustes variolaris* was recorded only in Shingle Island merely (Fig. 8). Coral killing snails, *Drupella cornus* and *Coralliophilia* sp. were documented from Hare Island and Manoliputti Island, and Kurusadai Island and Shingle Island respectively.

For the first time, this study has documented disease of crustose coralline algae (CCA) such as CLOD, CWBS, CWPD and AGPD (probably initial stage of coralline fungal disease (CFD)) were recorded from Shingle Island and Kurusadai Island (Figure 4; Table 3).

4. Discussion

Coral reefs in GoM islands are under stress from several environmental factors (physico-chemical and biological) and anthropogenic activities. Many reef areas in GoM are now experiencing a widespread degradation, especially around Mandapam group of islands and Tuticorin group of islands due to anthropogenic mediated bleaching, destructive fishing (blast, trap fishing, shore seines, trawling, etc.), coral mining, sedimentation due to land runoff, invasive seaweed culture, marine litter and tourism [6, 37]. Decades ago (during early 1960s and 1970s), coral reefs in Palk Bay and Mandapam group of islands were quarried about 250 m^3 per day for industrial purpose [38, 39]. Regardless of these threats, several other potential natural threats competing with corals were documented during this study.

In situ observations revealed that sedimentation is one of the significant factors which destruct typically *Acropora* coral reefs in Mandapam group Islands. A study on corals from Palk Bay waters found that high sedimentation had severely affected the live coral cover of *Acropora* corals [40]. Reportedly the sedimentation rate in Mandapam group islands was high with an average sedimentation rate of 77.52 mg $cm^{-2}d^{-1}$ [34]. Due to high sediment carry over from Palk Bay region, Gulf of Mannar waters face more sediment deposition and highly turbid conditions in northern sides of Mandapam group islands. Relatively, underwater observations revealed that southern sides of Mandapam group islands have clear water with less turbid and less sedimentation. Based on the field investigations and evidences, coral health status was differentiated by generating color codes (mostly *Acropora* species but also other corals) (Fig. 9). Healthy corals are appeared in

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brown blue, brick brown, fluorescent green; zooxanthellae expulsion stage in creamy yellowish; sedimentation stage grey, bleaching stage white, algal cover stage pale green to dark green, and crustose coralline algae deposition stage pinkish, red, dark red, orange green or metallic green and yellowish (Fig. 9). Some of these color codes are similar to the previously proposed color code chart for corals [41]. Specially, white colored coral fragments need more attention to confirm the root cause of whitening, as discoloration is not always associated with bleaching but it could also be due to *Drupella* sp. predation and white plague. In previous dives, whitening of *Acropora* coral fragments was misidentified as *Acropora* white syndrome, it was evidently confirmed as a result of coral killing snails *Drupella* species or coral damage. Localized lesions identified in *A. formosa* was identified as *Acropora* white syndrome.

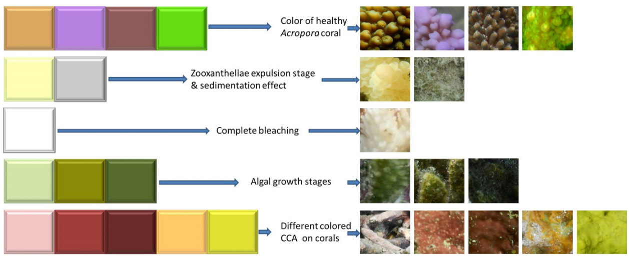

Figure 9. Illustration showing health status of *Acropora* corals and different species of reef building CCA through different color codes (left image: color code; right image: in situ color).

Occurrences of diseases and bleaching incidences have varied across the islands and between species to species, in a single species and within the fragments of an individual coral colony. A dramatic changes of disease dynamics in coral reefs in Mandapm group islands (Table 3).Studies on incidents such as these observations will help to fulfil knowledge gaps for better understanding variations of bleaching and disease incidents in corals of GoM. Irrespective of depth specific distribution of coral species, *Porites* are more affected with diseases than other coral species. Conversely, corals in the Palk Bay have relatively high prevalence of coral diseases (21%) than corals in GoM (8.9%) [30], especially the prevalence of black band (9.8%) and white band (5.5%) diseases [31]. Among the Mandapam group islands, highest disease prevalence inflicting coral losses was recorded at Poomarichan Island (10.90%), followed by Manoli (9.38%), Pullivasal (9.28%), Hare (8.64%), Kurusadai (8.27%) and Shingle (6.82%) [30]. Significantly, corals in Shingle Island were damaged mostly due to coral diseases [42]. However in the present study disease prevalence was evidently high in Hare Island (23.0%) and Shingle Island (17.79%) (Table 2 & 3). Later, a study documented the high coral disease persistence in Mandapam group islands during summer (20.79%) and less (17.59%) in monsoon [34]. Whereas, during winter monsoon, coral diseases were observed to be high in Kurusadai (23.42%) and Manoli (15.23%) islands, and *Porites* spp. was being the highly affected coral (18.2%) [32]. The present study surveys revealed that coral diseases caused partial mortality of corals which is followed by sedimentation, algal assemblage and biofoulers and sometimes mortality of entire coral colony, and this same trend of interaction or coral algal shift phase was reported from Mandapam group Islands [34]. Significantly, borers, biofoulers and algal growth on massive *Porites* corals have aided the disease propagation faster than the naturally infected corals. Among all diseases documented, pink line disease is the most common disease on *Porites* colonies. Whereas, very commonly found purple blue pigmentation in *Acropora* corals are as result of immune response [43] to various stresses like sedimentation, entanglement of fish nets (Fig. 8m), interaction of coral fragments (Fig. 10a). There is a need to gain and to establish better understanding on disease dynamics within and between GoM and Palk Bay.

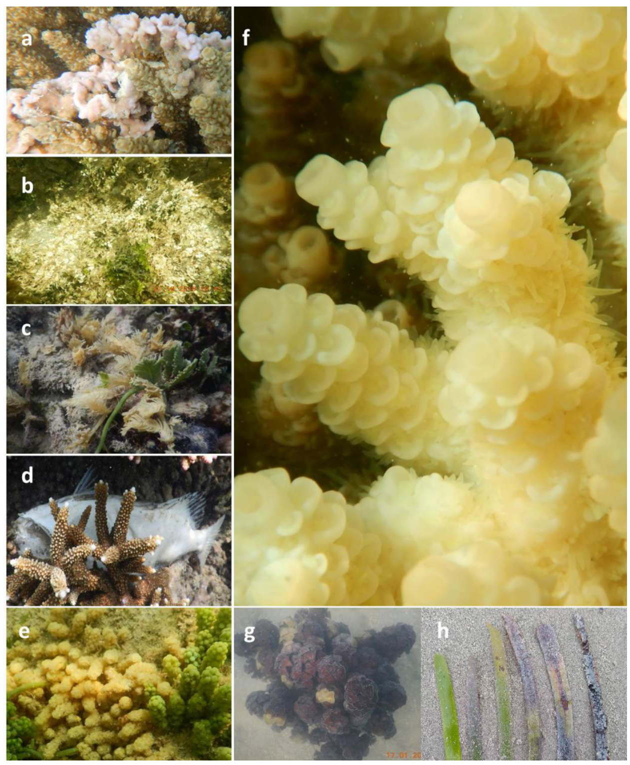

Figure 10. Some of the research areas less understood from coral reefs. Growth anomaly (hyperplasia) on *A. hyacinthus* (a); bleaching of coralline algae (b); withering of *C. taxifolia* (c); unidentified infectious disease causing fish mortality (d); withering of *C. racemosa* (e); pigmentation change after expulsion of zooxanthellae in live *A.*

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hyacinthus polyps (f); blackening of *Turbinaria* sp. (g); seagrasses wasting disease and epiphytic infections (h).

The invasion of coral killing sponge *Terpios hoshinota* was recorded from *Porites* sp. coral in Palk Bay [44] and *Montipora* divaricata in Vaan Island, GoM [11]. This sponge infestation has not been well studied from Mandapam group of Islands. In this study we recorded *T. hoshinota* overgrowing *Porites* in Hare Island. Infestation of some unidentified sponges on *Turbinaria mesenterina* and *T. peltata* were documented in Tuticorin coastal waters [45]. The excavation of invasive sponge *Cliona viridis* invading 38.58% of *Turbinaria mesenterina* colonies in 60 m^2 area was documented from Vilanguchalli Island, Tuticorin [46]. Earlier study had documented boring nature of three species of *Spirastrella* and *Cliona* sp. in GoM [12]. While, snowflake coral, Carijoa riisei invading live corals was documented from Vembar and Keelakarai group islands in GoM [47]. However, these species occurrence (except *Cliona* & *Terpios*) was not sighted from Mandapam group Islands in this study. Similarly, the algal community assemblage on coral reefs has been emphasized scarcely.

Infestation of invasive algal species distribution in coral reefs of GoM has not been well understood. Coral algal phase shift was well recorded from Tuticorin group islands, where the amount of *Halimeda* sp. was high during January to April and was less during May to September [48]. Whereas, seven invasive algal species (*T. ornata, T. conoides, C. scalpelliformis, C. racemosa, C. lentillifera, C. peltata, C. sertularioides, K. alvarezii, P. gymnosphora, S. wightii,* and *U. reticulata*) proliferation on degraded and live corals life forms in Mandapam group Islands [34], indicating a possible sign of phase shift of corals. Loss of coral cover from 36.8% to 16.5% was recorded due to *C. taxifolia* bloom in 2013 at Manoli Island [10]. Some of these observations are correlated with the present study; however, several other algal species and sponges were observed during this study (Table 3). Although *C. scalpelliformis, C. lentillifera, C. taxifolia*, and *U. reticulata* were recorded during this study, invasive nature of these algal species was not observed at any island. Significantly, removal of the invasive alga, *K. alvarezii* from coral reef ecosystem of Kurusadai Island has resulted negative impact [49]. However, in the present study, invasion or occurrence of *K. alvarezii* was not at all observed anywhere in Kurusadai Island. Based on the evidences, it is to infer that corals in GoM are heading towards destruction by increased stress factors of sedimentation and algal assemblages.

Cyanobacterial infestation was mostly prevalent on massive *Porites* sp. and bleached coral fragments of *Acropora*. Cyanobacterial infestation was reported to cause gradual increase of black band disease [50], and the same observation was encountered on a colony of *P. lobata* in Hare Island. Likewise, prevalence of gelatinous masses and hairy microbialites recorded from Hare Island and Manoliputti Island, indicated the importance of microbes in biogeochemical processes in coral reef as reported earlier [51]. Similarly, infestation of crustaceous coralline algae, *Neogoniolithon* sp. on *P. lutea* has enhanced the growth of vermetid gastropod *Dendropoma* sp (Fig. 2o). This observation is in concurrence with previous study [52]. Another species of coralline algae, *Hydrolithon* spp. growing on sedimented areas of live and dead *A. formosa*, *A. hyacinthus* colonies and live *Porites* sp. colonies were also documented from Hare Island, Manoliputti Island and Shingle Island. However, this species impact is very less in this study, but the same species was reported to overgrow live corals in Yemen [53]. Some other coralline algal diseases which were previously well documented from pacific coral reefs [54], such as CLOD, coralline algae bleaching, CWPD, CWBS, and possibly CFD were documented for the first time in this study from Mandapam group islands.

Bleaching events in corals of GoM have occurred as a result of increased sea surface temperatures due to El Nino currents [55]. The maximum temperatures recorded during bleaching events occurred in GoM were 31°C in 1998 [55] and 31.2°C to 32.6°C in 2016 [17]. Although global bleaching events are not frequent in GoM, but reefs were severely destructed on a single event [17]. Despite of coral bleaching, –coralline algal bleaching, withering of *Caulerpa sertularioides* and *C. racemosa*, blackening of *Turbinaria* sp., mysterious fish mortality (this could be due to dermal parasites as it was reported elsewhere) [56], and seagrass diseases found in Mandapam group islands are not studied so far (Fig. 10). Bleaching of crustose coralline algae *Hydrolith* sp. was also recorded from Manoliputti Island during this study. Therefore, to understand all these incidents, studies are needed in this era of rapid climate change to address and to establish the knowledge gap remained in GoM.

5. Conclusion & Prospects for the Future

Although coral reefs of GoM are recruiting very rapidly, some of the critical environmental factors and anthropogenic involvement have raised alarm to make reef conservation measures. Identification and characterization of pathogens responsible for these diseases are yet to be determined from GoM. This concern will be of great interest to define the actual etiology of each disease. The geographical influences on variation of pathogenic microbial community assemblage on healthy and diseased corals have to be investigated to understand the actual factors triggering coral diseases. Interestingly, faunal biodiversity in reef areas is apparently declined in contrast to healthy reef biodiversity seen elsewhere. We believe that reef faunal diversity might have shifted to deeper waters or degrading rapidly due to dense assemblage of deterrent algal communities. Therefore, there is an urgency to study the spatial distribution of faunal diversity in GoM. Also, to avoid the damage of corals, fishing in the reef area shall be restricted by implementing mitigation approaches such as fishing free zones and anchor free zones and by providing entry passes through local government. While, reef replacing algal species growing in different seasons can be removed carefully or informed to stakeholders or drug chemist for biomedical studies. There are several other less understood research aspects such as heavy sedimentation, currents, wave pattern, coral ridge formation and sand bar accretions, which are need to be studied to gain better understanding and management of reef environment.

Conflicts of interest

Authors declare that there are no conflicts of interests.

Author contribution

CR designed the concept, wrote manuscript, acquired field data, identification of species and data analysis. SK and TS performed field surveys and wrote manuscript. TS and MVR guided the project, red and approved the manuscript.

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