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# 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 and Contiguous International Waters

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**Abstract:** Photographic evidence of some important coral diseases (black band disease, black disease/*Terpios hoshinota*, white syndrome, pink line syndrome, pink spots, invertebrate galls, skeletal growth anomalies, tissue loss), coral competing sponges, and coral–algal phase shifts (competitive overgrowth of the seaweed *Caulerpa* spp. over corals and competitive scleractinian interactions such as with *Halimeda* spp.) have been collected during field observations in a few atolls within the Lakshadweep archipelago, Arabian Sea. Further, earlier reports of similar diseases and other stressors within the Indian Exclusive Economic Zone (EEZ) and its contiguous international waters, including the reefs of the Maldives and Sri Lanka, are highlighted and their distributional ranges are shown.

**Keywords:** Indian Ocean; phase shift; black band disease; *Terpios hoshinota*; white syndrome



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Coral reefs in the Lakshadweep atolls, located in the Arabian Sea, were severely bleached following the 1998 global mass bleaching event [1,2] and due to the rise in sea surface temperature following climate change. Several similar events have followed in subsequent years, greatly affecting these reefs [2–6]. However, information on coral diseases, which have historically been proven to be positively correlated with post-bleaching events on Indian reefs [7] and elsewhere, viz., the Persian Gulf or the Caribbean [8,9], seems to have been documented only a few times in this region (e.g., [10,11]). Apart from hindering disease resistance, such large-scale events can also give rise to other stressors and lead to shifts in community composition [1]. They also provide space for opportunistic species to overcome scleractinian dominance. Herein, we provide photographic evidence of coral diseases in the Lakshadweep atolls, especially at Bangaram and Thinnakara (BT), Cheriyam (uninhabited) (CHE) and Kalpeni (KAL) (Kalpeni Atoll), and Suheli (uninhabited) (SUH) (Figure 1). These areas were surveyed in 2016 as a part of a national project to assess the ecologically sensitive areas (ESAs) and critically vulnerable coastal areas (CVCAs) within the Indian exclusive economic zone (EEZ). Further, we have also performed comparisons with earlier reports published on the occurrence of these diseases, phase shifts, and stressors in the other reefs within the Indian EEZ and its contiguous international waters, which include the Maldives and Sri Lanka (Figure 1), to highlight the distributional ranges of those reef health impacts.

The Indian EEZ harbors four major coral reef ecosystems located in the Gulf of Mannar Biosphere Reserve (GoMBR) and Marine National Park (GoMMNP), the Andaman and Nicobar Islands (ANI), the Gulf of Kachchh (GoK), and the Lakshadweep atolls [12,13]. It is to be noted that only limited information is available on coral diseases within the Indian EEZ [13] and that the same is the case for the broader Indian Ocean region (IOR) [14].

Approximately 20~30 min timed snorkel surveys or until the area was covered were conducted in the outer lagoon areas of these atolls to record the habitat characteristics, as described by Raymundo et al., with some modifications [15] (Figure 1). The underwater pictures were taken (with a Canon Power-shot G15 placed in an underwater housing) at each survey location (BT = 34; KAL = 34; CHE = 26; SUH = 51); the survey area ranged from 10 × 10 to 50 × 50 m depending on the reef topography. Visual morphological observations such as "disease-like", "infected", or "unhealthy conditions" were later evaluated from the photographs, and disease prevalence was calculated from the photographs by counting disease colonies/total number of colonies × 100 [16] (Supplementary Table S1–S3). As no diving was involved, deeper reefs were not considered. Overall, a total of 2239 colonies belonging to 20 different genera were evaluated (Supplementary Table S4). Water quality parameters (sea surface temperature, pH, and DO) were additionally acquired through a multi-parameter water quality sonde (YSI optic probe no. 15K100034) and triplicate observations were made at each of the surveyed atolls at one or two selected locations (Figure 1A–C). The environmental parameters are provided in Table 1. Major diseases, stressors, and phase shifts observed in this study are summarized in Table 2.

**Table 1.** Environmental parameters recorded at each surveyed site (November 2016).

| Location (Islands) | Sea Surface Temperature (SST;°C) | pH | Dissolved Oxygen (mg/L) | Figures |
|---|---|---|---|---|
| Bangaram and Thinnakara (BT) | 29.97 (±1.29) | 7.63 (±0.04) | 6.82 (±1.2) | Figure 1A |
| Suheli (SUH) | 29.5 (±1.34) | 7.6 (0) | 7.72 (±0.5) | Figure 1B |
| Cheriyam (CHE) | 29.6 (±0.28) | 7.6 (±0.05) | 5.9 (±0.03) | Figure 1C |
| Kalpeni (KAL) | 29.1 (±1.34) | 7.5 (0) | 6.63 (±2.3) | Figure 1C |

**Table 2.** Disease and coral health conditions observed in Lakshadweep Atolls and its associated significance.

| Location | GPS Coordinates | Genus/Sp. | Disease/Stressors/Transitions | Figures | Date of Survey | Additional Ref./Reading | Comments/Remarks |
|---|---|---|---|---|---|---|---|
| Bangaram and Thinnakara (BT) | 10.94999 N, 72.29684 E | *Goniastrea edwarsi* | White syndrome | Figure 2A | 12 November 2016 | [17–19] | Following Bourne et al., [18] and Bythell et al., [19] this observation is placed under the general category of white syndrome |
| | | *Hydnophora* sp. | Black band disease (BBD) | Figure 2B | | | First report from the Arabian sea |
| | | *Goniastrea edwarsi* | Tissue loss | Figure 2C | | | |
| | | *Astreopora ocellata* | Pink line syndrome (PLS) | Figure 2D | | [10] | First report from Indian EEZ |
| | | *Porites solida* | Trematodiasis/pink spots (PS) | Figure 2E | | [20] | Requires lab verification for confirmation |
| | | *Isopora palifera*; *Cyphastrea* spp.; *Porites lutea* | Black disease (BD)/*T. hoshinota* | | | [21] | |
| | | *Porites cylindrica* | Black disease (BD)/*T. hoshinota* | Figure 2F | | [21] | BD presence overlooked at this site by Das et al., [21] (Figure 1A—White arrow) |
| | | *Dipsastraea lizardensis* | Black disease (BD)/*T. hoshinota* | Figure 2G | | [21] | |
| | | *Acropora* spp. | Skeletal growth anomalies (GAs) | Figure 2H | | | |
| | | *Fungia* sp.; *Herpolitha* sp. | Compromised health signs (CHS) | Figure 2I | | | |
| | | *Pocillopora* sp. | Invertebrate galls (IGs) | | | | No reports from the Indian EEZ, Maldives, or Sri Lanka. |
| | | *Goniopora* sp. | Black band disease (BBD) | | | | |
| Cheriyam (CHE) | 10.14353 N, 73.65811 E | *Acropora* dominated reef | Massive overgrowth of *Caulerpa racemosa* | Figure 3A | 7 November 2016 | [22,23] | Similar opportunistic invasion reported in Maldives [22] and mainland India [23]. |
| | | *Porites* sp. | Coral competing sponge (CCS) overgrowth | Figure 3B | | | |
| | | *Acropora muricata* | Overgrowth of colonial asicidian | Figure 3C | | | |
| | | *Acropora muricata* | Coral competing sponge (CCS) overgrowth | Figure 3D | | | |
| | | *Porites solida* | Tissue loss | Figure 3E | | | |
| | | *Porites* sp. | Predation/fish bites | Figure 3F | | [11] | |
| | | *Acropora* sp. | Multifocal tissue loss/white syndrome followed by growth of turf algae. | Figure 3G | | [17–19] | Further studies related to white syndrome, involving multiple techniques remains necessary [18]. |
| | | *Acropora* sp. | Association with *H. opuntia* leading to tissue loss (white syndrome?) | Figure 3H | | [17–19,24,25] | Necessary to study interaction and pathogen reservoir potential of *H. opuntia* [25]. |

**Table 2.** *Cont.*

| Location | GPS Coordinates | Genus/Sp. | Disease/Stressors/Transitions | Figures | Date of Survey | Additional Ref./Reading | Comments/Remarks |
|---|---|---|---|---|---|---|---|
| | | *Reef habitat* | *C. racemosa* overgrowing *Acropora* spp. dominated reef habitat | Figure 3I | | [22] | |
| Kalpeni (KAL) | 10.08134 N, 73.63442 E | *Isopora palifera* | White syndrome in association with *Halimeda opuntia* | Figure 4A | 7 November 2016 | [17–19] | Reported as white band disease by Thaha and Rathod [26], needs lab verification/confirmation. |
| | | *Porites* spp. | *Caulerpa racemosa* overgrowth | Figure 4B | | [23] | |
| | | *Pavona varians* | Black band disease (BBD) | Figure 4C | | [26] | |
| | | *Acropora* spp. | *C. racemosa* overgrowth | Figure 4D | | [22] | |
| | | *Porites* sp. | Coral competing sponge (CCS) | Figure 4E | | | |
| | | *Porites* sp. | Skeletal growth anomalies (GAs) | Figure 4F | | | |
| | | *Reef habitat* | Macroalgae causing coral mortality | Figure 4G | | | |
| | | *Acropora* spp. | Multifocal tissue loss, followed by algal overgrowth | Figure 4H | | | |
| | | *Isopora palifera* | White syndrome following algal overgrowth. Presence of *H. opuntia* noted. | Figure 4I | | [17–19] | |
| Suheli (SUH) | 10.07667 N, 72.29111 E | *Pocillopora damicornis* | Invertebrate galls (IGs) | Figure 5A | 9–10 November 2016 | | Not reported from the Indian EEZ, Maldives, or Sri Lanka. |
| | | *Porites solida* | Pink line syndrome (PLS)/pink spot (PS)-like condition | Figure 5B | | [10,20] | |
| | | *Porites* sp. | Fish bites and pink spots (PS) | Figure 5C | | [11] | |
| | | *Platygyra pini* | Skeletal growth anomalies (GAs) | Figure 5D | | | |
| | | *Herpolitha* sp. | Pink line syndrome (PLS) | Figure 5E | | | |
| | | *Acropora* sp. | Coral competing sponge (CCS) overgrowth | Figure 5F | | | |
| | | *Porites cylindrica* | Skeletal growth anomalies (GAs) | Figure 5G | | | First report from the Indian EEZ |
| | | *Pocillopora grandis* | CCA-related partial mortality in association with *H. opuntia* | Figure 5H | | | |
| | | *Acropora* spp. | Tips of *Acropora* showing algal overgrowth. A possible scenario following tissue loss. | Figure 5I | | | |

The photo-documentation provides evidence regarding the occurrence of coral diseases, stressors, coral competing sponges, and coral–algal phase shifts, even in reefs where human presence is minimal. Nevertheless, recent reports have suggested that live coral cover has increased in the atolls since 2006 [27]. Coral disease-specific surveys to quantify the damage caused by pathogens, reef-associated invertebrates, and sedimentation in the Lakshadweep atolls have been scarce. Along with studies on ecologically sensitive areas under a project, we have availed ourselves of the opportunity to explore and record coral diseases and other stressed conditions with photographic evidence. Our observations were compared with other records gleaned from previous literature related to the region, which would help to describe the possible human impacts on the reefs observed in this survey and those reported in other studies.

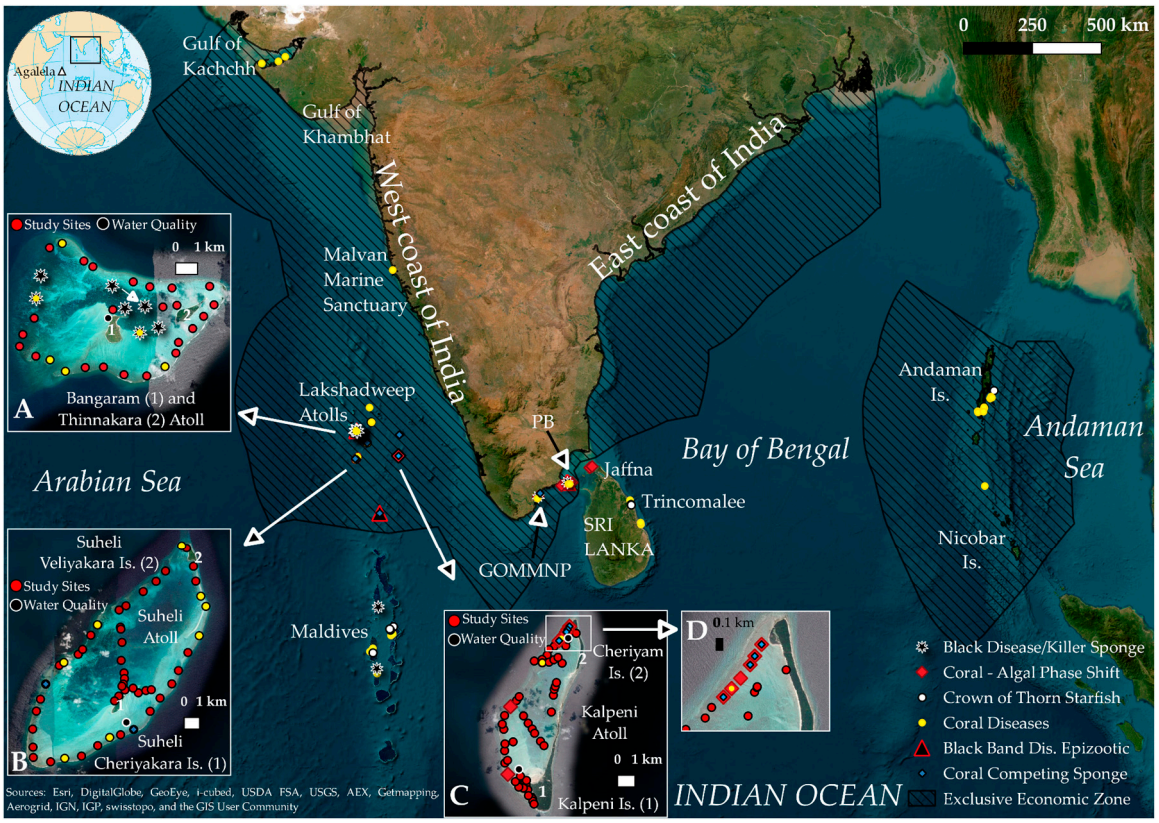


**Figure 1.** The Indian Exclusive Economic Zone (EEZ) indicates the current study locations and studies pertaining to different aspects of coral diseases, coral competing sponges (CCS), and coral–algal phase shift within the EEZ and contiguous international waters. (**A**) Sites at Bangaram and Thinnakara Atoll; adapted and updated from [21], white arrow, a previously unreported BD site. (**B**) Sites at Suheli Atoll. (**C**) Sites at Kalpeni Atoll. (**D**) Zoomed on the location of reefs near Cheriyam Is. (Kalpeni Atoll) [GOMMNP: Gulf of Mannar Marine National Park; PB: Palk Bay; black disease = *T. hoshinota*)]. Globe top-left: https://www.worldatlas.com/aatlas/infopage/oceans/indian.gif (Accessed on 6th December 2022).

Growth Anomalies (GAs): During our observation, nodular GAs were observed in tabular *Acropora* spp. (0.9%; 4, Tot. Col = 447) (at BT) (Figure 2H), while the overall prevalence of GAs in the common host *Porites* was (0.33%; 2, Tot. Col = 603)) (Figure 4F). Four colonies of *Platygyra* spp., including *P. pini* (Total Col. = 37), were also noted with GAs and BT) (Figure 5D). The classification of GAs based on morphology is available in the literature [28]. GAs within the Indian EEZ have been reported in *T. mesenterina*, *Pavona* sp., *A. humilis*, and *Porites* spp. [29–31], with no current reports from Maldivian atolls and a lack of specific details from the reefs of Sri Lanka.

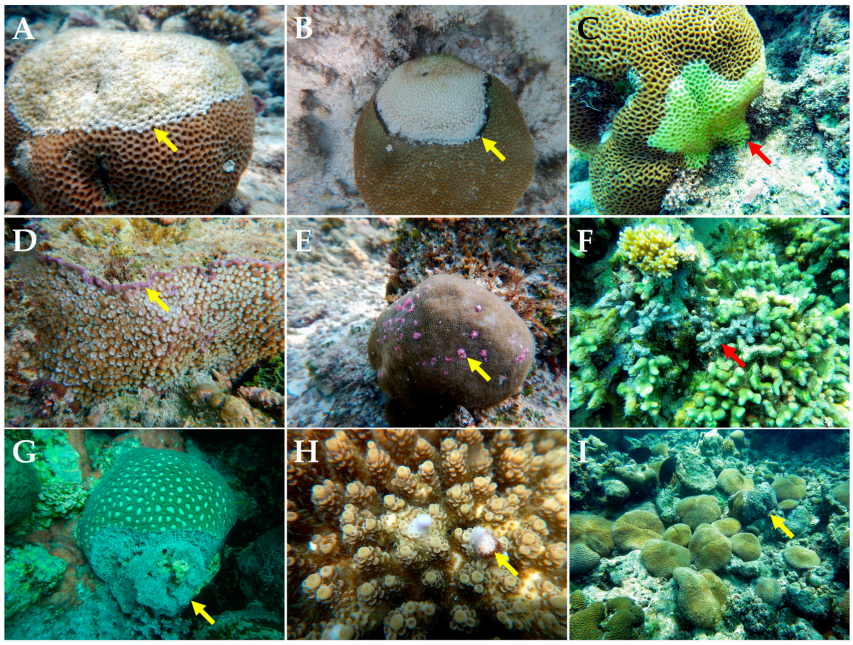


**Figure 2.** Bangaram and Thinnakara (BT Atoll): (**A**) White syndrome in *G. edwarsi* (yellow arrow); (**B**) Black band disease in *Hydnophora* sp. (yellow arrow); (**C**) Tissue loss in *G. edwarsi* (red arrow); (**D**) PLS in *A. ocellata* (yellow arrow); (**E**) Trematodiasis/PS in *P. solida* (yellow arrow); (**F**) BD/*T. hoshinota* and CHS on *P. cylindrica* (yellow arrow) [21]; (**G**) BD/*T. hoshinota* overgrowing *D. lizardensis* (yellow arrow) [21]; (**H**) Gas in *Acropora* sp. (yellow arrow); (**I**) CHS (yellow arrow) in Fungiidae [Photos by R.R.Das, C.R.Sreeraj, G.Mohan].

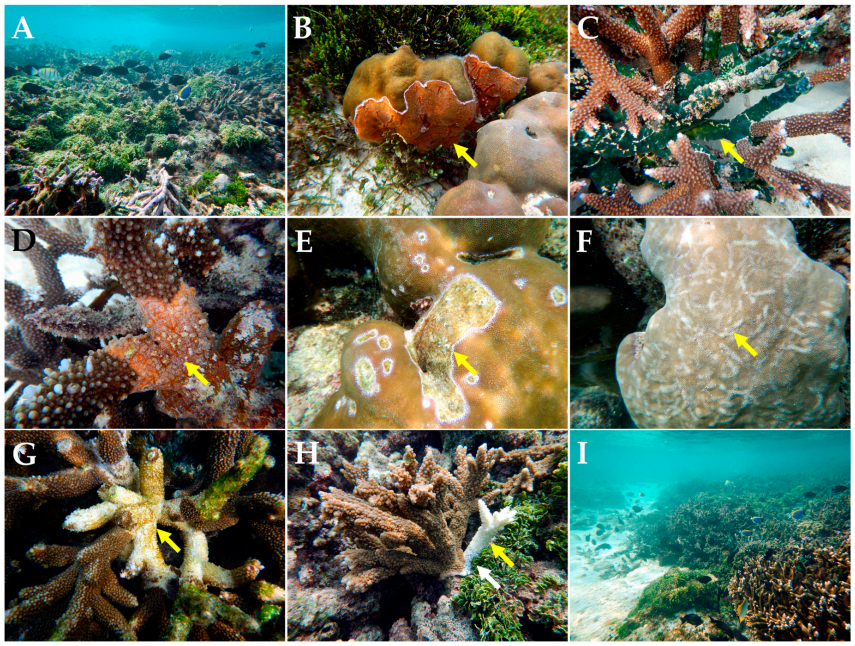


**Figure 3.** Cheriyam: (**A**) *C. racemosa* overgrowth in a coral reef habitat; (**B**) Overgrowth of unknown coral competing sponge on *P. solida*; (**C**) Overgrowth of colonial ascidian species on *A. muricata*; (**D**) Coral competing for sponge over *Acropora* sp.; (**E**) Tissue loss in *P. solida*; (**F**) Predation/fish bites in *Porites* sp.; (**G**) *Acropora* white syndrome depicting multi-focal tissue loss; (**H**) *Acropora* depicting tissue loss (yellow arrow) in areas in contact with *H. opuntia* (white arrow); (**I**) Macroalgae overgrowing reefs [Photographs by R.R. Das, C.R. Sreeraj, and G. Mohan].

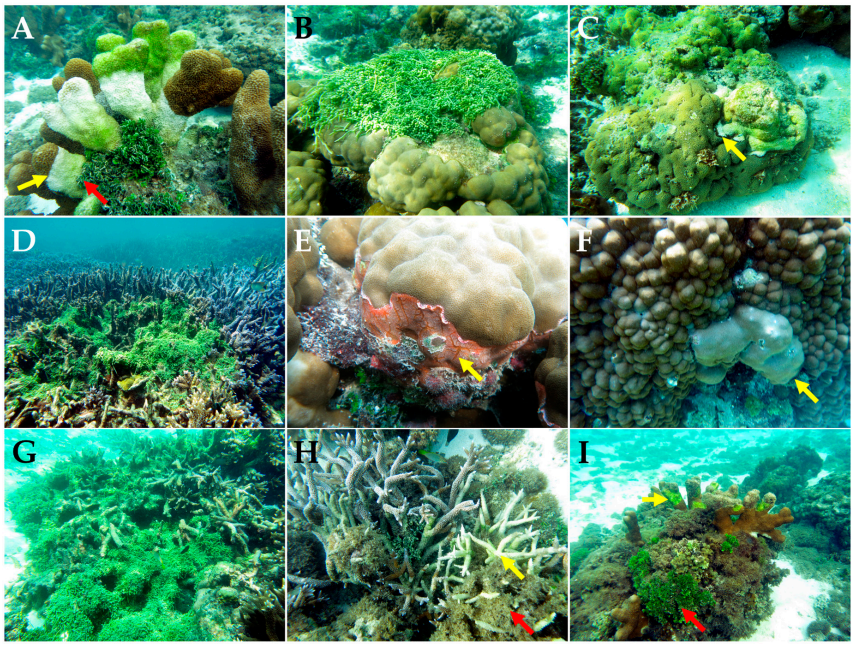


**Figure 4.** Kalpeni: (**A**) White syndrome in *I. palifera* (yellow arrow) along with overgrowth and coral contact with *H. opuntia* (red arrow); (**B**) *C. racemosa* in *Porites* spp.; (**C**) BBD in *P. varians* (yellow arrow depicting progressing cyanobacterial band); (**D**) *C. racemosa* overgrowing *Acropora* dominated reefs; (**E**) coral competing sponge overgrowing *Porites* sp.; (**F**) GAs in *Porites* sp.; (**G**) coral mortality due to *C. racemosa* overgrowth (**H**) Multifocal acute tissue loss/White Syndrome in *A. muricata* (Yellow arrow) followed by algal overgrowth (red arrow); (**I**) Algal overgrowth of white syndrome affected *I. palifera* (yellow arrow), along with the presence of *H. opuntia* (Red arrow) [Photographs by R.R. Das, C.R. Sreeraj, and G. Mohan].

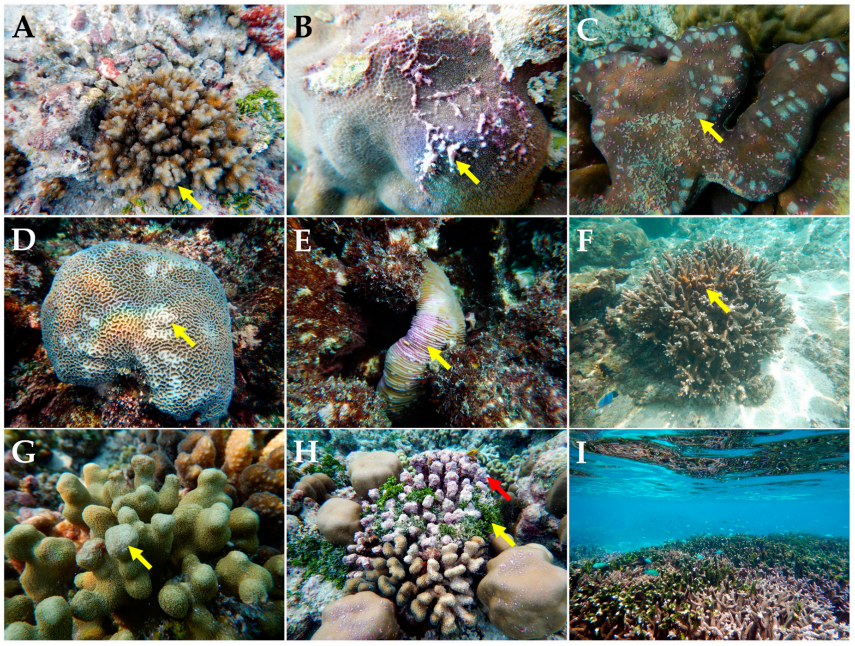


**Figure 5.** Suheli: (**A**) Invertebrate galls in *Pocillopora damicornis*; (**B**) PLS/PS-like condition in *Porites* sp.; (**C**) Predation and PS in *Porites* sp.; (**D**) GAs in *Platygyra pini*; (**E**) PLS in *Herpolitha* sp.; (**F**) Sponge overgrowth on *Acropora* sp.; (**G**) GAs in *Porites cylindrica* (yellow arrow); (**H**) CCA overgrowth *Pocillopora grandis* (red arrow) in association with *H. opuntia* (yellow arrow); (**I**) Algal overgrowth on *Acropora* beds [Photographs by R.R. Das, C.R. Sreeraj, and G. Mohan].

Pink Line Syndrome (PLS): Our observation of PLS in *A. ocellata* at BT (Figure 2D) is the first report from the Indian EEZ. We have also observed PLS in *P. solida* and mushroom coral at SUH. Not much comprehensive information is available on PLS from the Maldives or Sri Lanka.

Trematodiasis/Pink Spots (PS): Our observation of PS was mostly limited to *P. solida* at the BT and SUH atolls (Figure 2E and Figure 5B), as seen elsewhere in the Indo-Pacific [32]. PLS/PS combined gave a prevalence on the common host *Porites* ranging from 5.5% (16, Total Col. = 294 at BT) up to 23.4% (37, Total Col. = 158 at SUH) (Figure 2E and Figure 5B).

Black Band Disease (BBD): Within the atolls, BBD has greatly influenced tissue loss in massive corals, which showed coral mortality after the 1998 global bleaching event [7,11] as well as in GoMMNP [33]. Surveys in the Maldives have shown BBD to have a broader host specificity [34], with limited information from Sri Lankan reefs. We observed BBD in the genera *Hydnophora* (Figure 2B) and *Goniopora* (at BT). BBD was also observed in *P. varians* (at KAL) (Figure 4C). However, no epizootic occurrence of BBD was observed (RRD pers. obs.) as noted elsewhere in the Indo-Pacific [16]. The prevalence of BBD in the Maldives is much lower; reports suggest that although it is widespread in the atolls, it has not exceeded 0.5% [34].

Invertebrate Galls (IGs): There has been no report on gall formation in scleractinians within the Indian Reefs, nor from the Maldives or Sri Lanka. We observed IGs in *Pocillopora* in the atolls of BT and *Montipora*, along with *Pocillopora* at SUH (Figure 5A).

White Syndrome (WS): WS was observed in several instances during our surveys. *I. palifera* seemed to be one of the major hosts for WS, with an overall prevalence of 4.4% (9, Total Col. = 205), and in some cases associated with *H. opuntia*. WS was additionally noted in *G. edwarsi*, (Figure 2A), *Acropora*, and *Porites*. Our observation of focal to multifocal tissue loss among branching *Acropora* spp. (Figure 3G,H) can also be categorized under the general category of WS [18]. *Acroporids* are major hosts for WS in the Maldives, and it has also been observed in the genera *Echinopora*, *Psammocora*, *Pavona,* and *Pocillopora* [14,35].

*Terpios hoshinota*/Black Disease (BD): The genera *Terpios*, first mentioned in the Maldives in 2012 [36]; confirmation of its presence and outbreak were only available in 2015 [37]. Within the EEZ, initial reports were from Palk Bay [38,39], and followed by GoMMNP [40] and Lakshadweep atolls [21]. With a relatively short larval dispersal strategy [41], it is unlikely that BD has spread over such distances, but climate change-driven habitat variability might have allowed BD to overtake several scleractinian dominant habitats. [21,39,40]. Our observation of BD on *Porites cylindrica* was previously overlooked (Figure 2F), while the highest prevalence of BD/*T. hoshinota* was observed in *Acropora* spp. (3.6%, 16, Tot. Col = 447 at BT).

Coral Competing Sponges (CCS): CCS-like *Cliona* sp. complex, *Clathria* (*Microciona*) *aceratoobtusa*, *Cliona kempi*, had severely overgrown common scleractinian colonies in the Indian EEZ [42,43]. In the atolls, however, the presence of CCS is not recent; its spread has been observed since the early 1980s [44]. In several instances, we observed CCS overgrowing *Acropora* spp., *A. muricata*, and *Porites* (at CHE and KAL) (Figures 3D, 4D and 5F), and further recommend assessing the spicules to understand their taxonomy.

Crown of Thorns Starfish (COTS): No COTS were observed during the present study, but previous records of COTS outbreaks can be visualized in Figure 1 based on [45–52].

Coral–Algal Phase Shift: The invasion of algal species within the India EEZ has been well documented [53,54]. The extensive spread of *C. racemosa* is observed in the northernmost, southern, and central regions of Kalpeni Atoll overgrowing *Acropora* reefs has resulted in severe mortality (Figure 1C,D and Figure 3A,I) [21]. Within the Maldivian archipelago, the devastating effect of *C. racemosa* on reefs of *A. muricata* has been noted since 2011 [22]. In the reefs of Sri Lanka, the rapid growth of algae has been observed, comprising *Turbinaria* sp., *Caulerpa* sp., and *Sargassum* sp., [12,55]. As a matter of fact, phase-shift has been occurring at an alarming rate at GoMMNP, where almost 50% of the benthic component is algae [54].

In general, the surveys revealed that the shallow reefs within the atolls of Lakshadweep are generally abundant with common Indo-Pacific genera, viz. *Acropora*, *Porites*, *Isopora*, and *Pocillopora*. Although site-specific variation might be expected, overall, the presence of 20 genera was noted. Specific details of disease prevalence can be found in the Supplementary Tables (Tables S1–S4). High coral mortality was noted in BT (*Acropora* = 21.0%; 94, Total Col. 447; *Porites* = 5.1%; 15, Total Col. 294; *Isopora* = 8.8%; 15, Total Col. = 171), KAL (*Acropora* = 28.5%; 85, Total Col. 298), and SUH (*Acropora* = 13.1%; 29, Total Col. 222). Although it is hard to confirm the cause of this mortality, it can be conjectured that the reefs were not in a very healthy state.

Further, information on coral diseases within the Indian Ocean region is limited when compared to other areas [13,14,34,35]. In this paper, we have provided some interesting photographic evidence, apart from disease prevalence supplements, which highlights the variety of diseases and poor health conditions within the Lakshadweep atolls. Additionally, their presence within other reefs in India and contiguous international waters has been visualized through the application of GIS. Hughes et al. [6] did mention this region (the northernmost Maldivian atolls) as being severely affected by the 2015/16 mass bleaching event; however, such direct mass bleaching observation was not performed, and it would be ignorant to make such a correlation at this stage. Even within Sri Lankan waters, which are considered to possess diverse tropical coral reef ecosystems, there is surprisingly little information. Thus, our observation calls for continuous monitoring in these regions to understand the outbreaks of coral disease epizootics, along with regular monitoring of bleaching events. Further, when performing coral disease assessments, there needs to be a clear understanding of different concepts, such as prevalence and incidence, and consistency should be maintained in disease terminology to avoid confusion while collecting data [17,56]. As a concluding note, through our observations in the atolls, we were able to highlight several diseases and symptoms, but we were not able to detect a very high prevalence of BBD as mentioned by Ranith et al., [11]. Similarly, with the diplomatic cooperation of Mauritius, India's plans for development in the remote island of Agalela (Western Indian Ocean) calls for extensive and mandatory EIA studies (Figure 1).

**Supplementary Materials:** The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/d15030382/s1, Table S1: Coral disease prevalence in Bangaram and Thinnakara Atoll; Table S2: Coral disease prevalence in Kalpeni Atoll; Table S3: Coral disease prevalence in Suheli Atoll; Table S4: Overall coral disease prevalence. (Acronyms, NFB = Non-Focal Bleaching; BBD = Black Band Disease; GA = Growth Anomalies; Pre = Predation; WS = White Syndrome; BD = Black Disease/*T. hoshinota*; IG = Invertebrate Galls; TL = Tissue Loss; PLS/PS = Pink Line Syndrome/Pink Spots; CHS = Compromised Health Signs).

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