

Diseases and pathogens of marine invertebrate corals in Indian reefs

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Abstract

Diseases in marine invertebrate corals have been reported worldwide and have been associated with infection by various microbial pathogens that cause massive mortality. Several bacterial species, especially *Vibrio* species but also members of the cyanobacteria, fungi, viruses, and protists, are described as important pathogens associated with coral disease and mortality. The present work provides an updated overview of main diseases and implicated microbial species affecting corals in Indian reefs. Further study on pathogen diversity, classification, spread and environmental factors on pathogen-host interactions may contribute a better understanding of the coral diseases.

Keywords: corals; disease; environment; microbes; pathogen; stress

1. Introduction

Scleractinian corals are major reef-building organisms that act as a natural barrier against damaging effects of wave action and tropical storms and also serve as a habitat for numerous life forms. Coral reefs worldwide are in decline due to global changes including warming ocean waters, sea level rise, changes in storm patterns and precipitation, altered ocean currents, ocean acidification, over-exploitation of reef resources, nutrient enrichment caused by pollution and coastal development (Coles and Brown, 2003, Bourne et al., 2009, Ainsworth et al., 2010). The synergistic action of these stresses causes severe damage to coral reef ecosystems and impedes coral recovery (Harley et al., 2006). Another major emerging factor contributing to coral decline is the outbreak of destructive diseases, by biotic and/or abiotic factors (Woodley et al. 2008). Diseases can cause significant changes in coral reproduction and growth rates that subsequently alters community structure, species diversity and abundance of reef-associated organisms (Loya et al., 2001). Moreover, infectious diseases caused by microorganisms such as bacteria, viruses, fungi, protozoa lead to lesions or bands of tissue loss on the coral colonies and, consequently, may affect the entire reef ecosystem (Sokolow 2009).

Coral diseases in the Indian coastal region are poorly documented and very little is known about the prevalence, distribution, environmental interaction and the pathology of these diseases. Moreover, no substantial or systematic investigations of coral diseases have been conducted. The only diseases that can be diagnosed in the field are easily observable pathogens and symptoms, such as those caused by cyanobacterial infections (black band disease) or ciliates (brown band diseases, skeletal eroding band). The other coral lesions, especially tissue loss, cannot be diagnosed in the field and a diagnostic assumption has been made. For example, the causative agents of multifocal lesions such as white pox, white spot, and ulcerative white spot are difficult to differentiate in the field due to similar and variable macroscopic signs and rate of progression (Bythell et al., 2004). These difficulties in diagnosing the diseases have resulted in a systematic approach of forming standard criteria for characterizing the morphology of coral lesions at the gross level (Work and Aeby 2006; Raymundo et al., 2008). These standard criteria for disease identification will better define various types of disease and aid the identification of their corresponding causative agents. In this review, we aimed to report on the status of microbial coral diseases in Indian reefs to further our understanding of coral diseases and to identify coral species that are the most susceptible to specific microbial diseases.

2. Coral diseases in Indian reefs

There are four major coral reefs in India, the platform reefs of Gulf of Kachchh (GoK) and Lakshadweep atolls in the Arabian Sea; fringing reefs of Gulf of Mannar (GoM) and Palk Bay; and fringing and barrier reefs of Andaman and Nicobar Islands in the Bay of Bengal (Fig.1). Space Application Centre (SAC), a major centre of the Indian Space Research Organisation (ISRO), used remote sensing images to show that the overall reef area in India is 2,375 km² (Venkataraman 2007). A total of 478 coral species have been recorded from Indian reefs, which include 19 families and 89 genera (Kathiresan and Ajmal Khan 2013). The Andaman and Nicobar Islands are the richest in coral diversity, followed by GoM and Lakshadweep. GoK and the central west coast have lowest species diversity. In total, 14 coral diseases (Table 1) have been reported from the Indian coral reefs. Some of the described diseases (Table 1) in Indian corals are arguably not diseases or there is not sufficient evidence, such as histology, of pathology. Eleven different coral diseases are described in GoM, which is comparatively higher than all the other reefs (Kumaraguru et al., 2005, Chellaram et al., 2006, Thinesh et al., 2009, Thangaradjou et al., 2016, Ramesh et al., 2019) (Fig. 2, Table 1). Although most of the diseases were common to all regions of Indian reefs, yellow band disease was recorded only from GoM (Table 1), and of 10 different diseases identified in Lakshadweep, pink blue disease (PBSS) (Ravindran et al., 1999, Ravindran et al., 2001, Ravindran and Raghukumar, 2002 and 2006, Jeyabaskaran and Raghukumar, 2004, Jeyabaskaran, R., 2006, Thangaradjou et al., 2016) has not been reported or described from any other Indian major reefs (Fig. 2, Table 1). Andaman and Nicobar Islands have also been described with 10 different diseases (Raghukumar and Raghukumar, 1991, Chakkaravarthy and Raghunathan, 2011; Ramesh et al., 2014, Sreeraj et al., 2017) (Fig. 2, Table 1). Though Palk Bay is located near the GoM of southeast coast of India, only seven diseases have been recorded in this area (Kumaraguru et al., 2005, Thinesh et al., 2011, Thinesh et al., 2014, Edward et al., 2015) (Fig. 2, Table 1). Four different diseases have been recorded in Gulf of Kachchh (GoK), all of which were observed in all the other major Indian reefs (Yogesh Kumar et al., 2014). There has not been much exploration of central west coast coral diseases and only one disease was reported (Manikandan et al., 2016) (Fig. 2, Table 1).

Porites sp. and *Acropora* sp. are the most dominant coral species in the Indian reefs that are affected severely by various diseases (Raghukumar and Raghukumar, 1991, Ravindran et al., 1999, Ravindran et al., 2001, Ravindran and Raghukumar, 2002 and 2006, Jeyabaskaran and Raghukumar, 2004, Kumaraguru et al., 2005, Chellaram et al., 2006, Thinesh et al., 2009, Chakkaravarthy and Raghunathan, 2011, Thinesh et al., 2011, Thinesh et al., 2014, Ramesh et al., 2014, Yogesh Kumar et al., 2014, Edward et al., 2015, Thangaradjou et al., 2016, Manikandan et al., 2016, Sreeraj et al.,

2017, Ramesh et al., 2019) (Fig. 3, Table 1). Earlier studies showed that environmental stress factors such as water pollution (Mitchell and Chet, 1975; Szmant, 2002), warming temperature, decrease in salinity, sea level rise, subsequent changes in ocean circulation (Harvell et al., 2002, Bruno et al., 2007) and over-fishing (Jackson et al., 2001) are responsible for the increase in prevalence of coral disease (Green and Bruckner, 2000). These stresses, along with other processes such as siltation, soil erosion, quarrying corals from the shore and reefs, and sponge attack are possible factors that reduce the immunity of corals, increasing susceptibility to pathogens in Indian corals.

2.1. Coral diseases and causative agents

Pathogens and parasites causing infectious diseases of stony corals in India include bacteria, fungi, viruses, and parasitic infections by protozoans (*e.g.*, ciliates, amoeba), metazoans (*e.g.*, trematodes, flatworms, flukes) or parazoans (*e.g.*, sponges). These diseases can lead to partial or entire colony mortality. In addition, physiological and morphological changes (*e.g.*, tissue loss or discoloration and growth anomalies) due to agents such as toxins or toxicants, sedimentation, pollution, and other environmental stressors (*e.g.*, temperature) also affect coral health, causing disease and bleaching due to loss of zooxanthellae (Coles and Brown 2003). Tissue damage due to environmental stressors can cause symptoms similar to diseases caused by pathogens. Without histopathology or molecular analyses, pathogenic agents may not be correctly diagnosed.

2.2. White Band Disease

Observations of white band disease (WBD) have been made on 34 coral species in nine countries, including India (Green and Bruckner 2000). The highest mortality (90%) due to WBD was observed in *Acropora cervicornis* in Florida and *Acropora palmata* in the US Virgin Islands (Green and Bruckner, 2000). WBD is differentiated into two distinct types as WBD type I and WBD type II based on the pattern of tissue loss, although symptoms are similar. The infectious nature of WBD type I in the Caribbean was demonstrated using antibiotic treatment (Sweet et al., 2014) and suggested to be bacterial (Kline and Vollmer, 2011; Sweet et al., 2014). WBD type II occurs predominantly in the Bahamas and the associated two putative pathogens belong to the order *Vibrionales* and *Rickettsiales* has been identified (Ritchie and Smith 1998; Gil-Agudelo et al. 2006; Casas et al., 2004; Gignoux-Wolfsohn and Vollmer, 2015).

WBD has been reported from three major Indian coral reefs, GoM and Palk Bay, Lakshadweep and Andaman and Nicobar Islands (Jeyabaskaran, R., 2006, Thinesh et al., 2009, 2011 and 2015, Chakkaravarthy and Raghunathan 2011, Thangaradjou et al., 2016, Sreeraj et al., 2017) (Table 1.1). *V. charcharii* was also isolated and identified from the WBD infected corals in India

(Table 1.1) but its role as a causative agent was not experimentally demonstrated. *Rickettsiales* bacteria has also been associated with the disease (Ritchie and Smith 1998, Casas et al., 2004; Gignoux-Wolfsohn and Vollmer, 2015). WBD disease signs appear similar to those reported for white plague and also it has been noted that active WBD in coral is a precondition for the development of black band disease (BBD) (Green and Bruckner 2000). In some cases, corals in India affected with plague, WBD type I, II and BBD may have been misidentified.

2.3. White plagues

White plagues (WP) are differentiated into three types (I, II and III) based on tissue loss progression rates (Richardson et al., 2001). An infectious agent, the bacterium *Aurantimonas corallicida*, was hypothesized to be the cause of WP type II in the coral *Dichocoenia stokesii* in the Caribbean (Denner et al., 2003). In contrast to the Caribbean, the causative agent in the Red Sea is known to be a different bacterial pathogen, *Thalassomona slojana* (Thompson et al., 2006). A virus, another causative agent of WP type I-like infection in *Montastraea annularis*, was shown to produce WP-like disease (Soffer et al. 2014). In India, white plague-like diseases are reported from almost all the reef regions of GoM and Palk Bay, GoK, Andaman and Nicobar, Lakshadweep and Central west coast of India (Table 1.2), However, no descriptions of a specific causal agent and the type of WP disease that occurred has been described (Thinesh et al., 2009, 2011 and 2015; Yogeshkumar et al., 2014; Ramesh et al., 2014; Thangaradjou et al., 2016; Manikandan et al., 2016; Sreeraj et al., 2017) (Table 1.2).

2.4. White pox

White pox disease (or “patchy necrosis” or “necrotic patch syndrome”) (Bruckner, 2009) is a disease of corals that differs from white-band disease by appearing as distinct white patches and tissue loss on the coral colony (Patterson et al., 2002). Small circular to larger uneven patches of denuded skeleton develop within 5 to 7 days. The disease was observed to progress from the base of a coral branch upward to the branch tip in a concentric ring manner (Patterson et al., 2002). Top surface branches of the Elkhorn coral (*Acroporapalmata*) are affected by this disease and *Serratia marcescens*, a common fecal enterobacterium has been identified as a causal agent (Patterson et al., 2002). In India, White pox has been observed on the coral colonies of *Porites annae*, *Acropora* sp., *Porites* sp., *Platygyra* sp., *Gardineroseris* sp., from major reefs of Andaman and Nicobar, GoM and Lakshadweep Islands (Chakkaravarthy and Raghunathan, 2011, Sreeraj et al., 2017, Thangaradjou et al., 2016) (Table 1.3). Patchy necrosis was described in *Porites* sp., *Goniastrea* sp., *Goniopora* sp., *Montipora* sp., *Favia* sp., *Acropora* sp., *Pocillopora* sp., *Platygyra* sp. and *Cyphastrea* sp., from

Andaman and Nicobar, GoM and Lakshadweep reefs (Raghukumar and Raghukumar 1991, Ravindran et al., 2001, Thangaradjou et al., 2016, Jeyabaskaran, R., 2006) (Table 1.4). Necrotic patches observed on coral in the Andaman Islands were described as an association of epilithic algae and hyphomycetous fungus (Raghukumar and Raghukumar, 1991, Ravindran et al., 2001), with epilithic algae on the top layer of the necrotic patches followed by a thin black zone of fungal growth (Raghukumar and Raghukumar, 1991; Ravindran et al., 2001, Bruckner 2009) (Table 1.4). White pox was also reported from the Andaman Islands on colonies of *Porites* sp., (Chakkaravarthy and Raghunathan, 2011, Thangaradjou et al., 2016, Sreeraj et al., 2017) (Table 1.3).

2.5. Black band disease

Black band disease (BBD) has been observed in 26 different countries, including India, in 42 different coral species (Green and Bruckner 2000). BBD is caused by a pathogenic microbial mat consortium, which includes five different types of microorganisms. These are the filamentous cyanobacterium, *Phormidium corallyticum* (Rutzler and Santavy 1983), several heterotrophic bacteria (Garrett and Ducklow, 1975), marine fungi (Ramos-Flores, 1983) and both sulfide-oxidizing (*Beggiatoa*) and sulfate-reducing (*Desulfovibrio*) bacteria (Ducklow and Mitchell, 1979; Carlton and Richardson 1995; Richardson, 1996). The cyanobacterial population is characterized by a band color of blackish-brown to red. The band is 1 mm thick and ranges in width from 1 to 3 mm. A relatively small proportion of the colonies affected by BBD die from a single infection event, with mortality occurring primarily in small colonies (Bruckner 2016). The observations on BBD mortality in Indian reefs were not clearly described but one microbe associated with the consortium, the cyanobacterium *Phormidium corallyticum*, was isolated and identified from the affected coral (Table 1.5). Also, the association of two cyanobacterial species, *Phormidium* sp., and *Synechocystis* sp., along with *Vibrio* sp. and *Pseudomonas* sp. from diseased colonies were isolated and described from the GoM and Palk Bay reef region (Thinesh et al., 2011 and 2013). It was demonstrated that *P. corallyticum* also causes BBD in the soft corals (Order Alcyonacea; formerly known as gorgonians) *Pseudopterogorgia acerosa* and *Pseudopterogorgia americana* (Feingold, 1988) and the mode of tissue loss is similar to BBD in the scleractinian corals.

2.6. Yellow blotch/band disease

Yellow blotch/band disease (YBD) has been reported for its effects in the major reef-building coral *Montastraea* sp. throughout the Caribbean, and *Fungia* spp., *Herpolitha* spp., and *Diploastraea heliopora* in numerous locations in the Indo-Pacific (Cervino et al., 2008). YBD develops as a pale-yellow blotch on the coral tissue and eventually expands into a band as the disease progresses

(Cervino et al., 2004). This paleness was demonstrated to be a decrease in chlorophyll concentration due to a lack of symbiotic zooxanthellae (Brown et al. 1995). Four novel *Vibrio* sp. together with *Vibrio alginolyticus* have been described as a consortium that causes YBD (Cervino et al., 2008). Cervina et al. (2004) demonstrated that the microbial consortium attacks the zooxanthellae *in situ* within the gastrodermis causing lysis of zooxanthellae, suggesting that YBD is a disease of the symbiotic algae and not of the host coral. In India, YBD was reported and described as “yellow spot” or “blotch” on *Porites* sp., *Acropora* sp., *Favia* sp., *Favites* sp. and *Goniastrea* sp., from major reefs of GoK, GoM, Andaman and Nicobar and Lakshadweep Islands (Table 1.6), and as YBD in *Porites* sp. from GoM and Palk Bay (Table 1.7). However, no associated microorganisms were isolated (Table 1.6 and 1.7).

2.7. Brown band disease

Brown band disease (BrB) is noted for its macroscopic field signs- the presence of a distinctive brown zone of variable width between healthy coral tissues and exposed white skeleton. The brown band was reported to be formed by a dense concentration of motile protozoan ciliates that feed on coral tissue and accumulate zooxanthellae (Symbiodiniaceae) intracellularly, resulting in the characteristic brown coloring and rapid tissue loss (Willis et al., 2004, Ulstrup et al., 2007, Bourne et al., 2008). The ciliate has been identified as a member of Class Oligohymenophorea, Subclass Scuticociliatia (Bourne et al., 2008). The ciliates may be opportunistic; healthy tissues are impaired by bacteria as primary pathogens allowing the ciliates to proliferate at the disease lesion as secondary invaders (Sweet and Bythil 2012). Bacterial pathogens *Arcobacter* sp. and *Aeromonas* sp. were noted to increase in numbers in the healthy tissues before any disease lesions on the colony (Sweet and Bythil 2012). In India, BrB was reported in the coral *Leptoria phrygia* in Andaman and Nicobar islands without description of lesions or pathogens (Table 1.8) and was not observed in other regions of major coral reefs of India.

2.8. *Porites* ulcerative white spot disease (PUWS)

Porites ulcerative white spot disease is characterized by discrete, bleached, round foci, 3 to 5 mm in diameter, which may either regress or progress to full tissue-thickness ulcerations that coalesce, occasionally resulting in colony mortality (Raymundo et al., 2003). PUWS was reported affecting *Porites* species in the Philippines (Raymundo et al., 2003; Arboleda and Reichardt, 2010), Indonesia (Haapkylä et al., 2007), Japan (Weil et al., 2012), northern Egyptian Red Sea (Sera et al., 2013) and Gulf of Thailand (Samsuvan et al., 2019). In the Hawaiian Archipelago, *Porites* multi-focal tissue loss, which has disease signs similar to PUWS (Raymundo et al., 2003), was observed (Aeby et al., 2011), however, no further analyses were done to characterize the observed disease

signs as PUWS (Aeby et al., 2011). A *Vibrio* sp., closely related to *Vibrio natriegens* and *Vibrio parahaemolyticus*, was reported to be the causative agent of PUWS (Arboleda and Reichardt, 2010). *Vibrio coralliilyticus*, a Red Sea pathogen of *Pocillopora damicornis*, was also described as causing white spots that progressed to tissue loss similar to the symptoms of PUWS (Ben-Haim et al. 2003). Raymundo et al. (2003) reported that PUWS disease symptoms such as lesion development and tissue loss occurred rapidly at temperatures above 26°C. PUWS was observed on colonies of *Porites* sp. and *Favites* sp. from GoK (Yogeshkumar et al., 2014), but no proper description or characteristic features of the disease or causative agent has been described (Table 1.9).

2.9. Red band disease (RBD type I and RBD-II)

Red band disease (RBD type I and RBD-II) presents as a reddish band that separates healthy tissue from the recently denuded white skeleton on the surface of the coral. RBD is very similar to BBD (Richardson, 1992) and can be easily misidentified. RBD is similar to BBD in its development of a microbial consortium in a mat that contains cyanobacteria, sulfur-oxidizing bacteria in the genus *Beggiatoa*, heterotrophic bacteria and the nematode, *Araeolaimus* (Santavy and Peters 1997). However, unlike black band disease, which also contains cyanobacteria, red band disease lacks white filaments or specks associated with *Beggiatoa*. Several cyanobacteria are reddish in color and commonly found associated with corals. RBD-I was first identified on soft corals in Belize in the 1980s and has since been reported from 12 countries in the Caribbean, with records from 10 scleractinian corals, hydrozoans (*Millepora* spp.) and the sea fan (*Gorgonia ventalina*) (Rutzler and Santavy, 1983). RBD-II has only been observed in a single location in the Bahamas (Richardson, 1992). Two cyanobacteria species in the genus *Oscillatoria*, of two distinct sizes, were identified from infected corals and reported to be causative agents of RBD (Richardson, 1992). In India, RBD was reported from the Lakshadweep Islands, India as Red plague syndrome and the associated cyanobacteria, *Oscillatoria* sp. was isolated (Table 1.8) (Jeyabaskaran and Raghukumar 2004, Jeyabaskaran 2006, Bruckner 2009). RBD was also recorded from the GoM reef region in *Turbinaria mesenterina* and *Turbinaria peltate*. *T. mesenterina* was more susceptible to RBD (Chellaram et al., 2006) (Table 1.11). No particular cyanobacterium species has been observed to be associated with the diseased corals, and different species have been reported to be responsible for causing RBD in different locations (Santavy and Peters 1997).

2.10. Pink line syndrome/disease

Pink line syndrome/disease (PLS) in the *Porites* spp. was observed on Caribbean and Indo-Pacific reefs (Sutherland et al., 2004), in La Reunion, Mayotte and South African reefs of the western Indian Ocean (Sere et al., 2015), Gulf of Thailand and Andaman Sea (Samsuvan et al.,

2019). However, PLS was first reported in 2001 affecting the scleractinian corals *Porites lutea* and *Porites compressa* of Kavaratti Island, Indian Ocean (Ravindran et al., 2001, Sutherland et al., 2004). PLS is a band of pink pigmented tissue separating skeleton of recently killed coral and normal tissue; it may begin as a small ring and progress outward (Ravindran et al., 2001, Sutherland et al., 2004, Sere et al., 2015). The extension of the zone of dead skeleton covered by green or brown algae exhibits the rapid rate of disease progression observed for other coral diseases (Ravindran et al., 2001, Sere et al., 2015). Cyanobacteria were observed in PLS-affected coral in Lakshadweep atolls and also from all the other major coral reef regions of India (Table 1.11) (Ravindran et al., 2001, Ravindran and Raghukumar, 2002; Kumaraguru et al., 2005; Chakkaravarthy and Raghunathan 2011, Ramesh et al., 2014; Sreeraj et al., 2017, Thangaradjou et al., 2016). An association of the cyanobacterium *Phormidium valderianum* with PLS was hypothesized for its influence in formation of the pink coloration in affected coral tissue and presence increasing levels of pCO₂ and was confirmed (Ravindran and Raghukumar, 2002 and 2006) (Table 1.12). PLS is the only disease in Indian corals for which the causative agent was confirmed by experimental analysis (Ravindran and Raghukumar 2006).

2.11. Pink-blue spot syndrome

The appearance of pink-blue spots in tissues of the scleractinian corals *Acropora* sp., *Porites* sp. and *Goniastrea* sp. were observed along the Sinai coasts (Gulf of Eilat, Red Sea) and was named "pink-blue spot syndrome" (PBSS). (Bongiomi and Rinkevich, 2005). The pink/blue pigmentation in *Porites* sp. and *Acropora* sp. was interpreted as a local response to stress (Bongiorni and Rinkevich 2005, Benzoni et al. 2010), as a coral disease (Ravindran and Raghukumar 2006), and as *Porites* trematodiasis (Aeby et al., 2011). The pigment production was found to be associated with the immune response of *Acropora millepora* and *Porites* sp. (Palmer et al. 2008), and a family of GFP-like proteins are responsible for the pink-blue color (Dove et al., 2001, Oswald et al., 2007, Alieva et al., 2008, D'Angelo et al., 2012). PBSS was reported as pink to blue discoloration adjacent to lesions from coral of Lakshadweep Islands, India (Ravindran et al., 2001) (Table 1.14). It has been demonstrated that in *Acropora eurystoma* compounds in the light-regulating pigment family pocilloporin are responsible for the pink-blue colors in pocilloporid and acroporid corals (Bongiomi and Rinkevich, 2005). It was also reported that pink-blue color could be experimentally induced in *A. eurystoma* by tissue-to-tissue contacts between distressed and non-distressed allogeneic branches (Bongiomi and Rinkevich 2005). PBSS in Indian reefs needs to be experimentally analyzed for its symptoms and causative agents.

3. Coral bleaching

Coral bleaching results from the expulsion of associated symbiotic algae, zooxanthellae (Symbiodiniaceae), which leads to the whitening of reef-building corals. Several factors such as acidification, sedimentation, nutrient inputs, physiological, algal, host-related stresses, and various ecological and anthropogenic factors are causes of bleaching (Wilkinson, 1999, Krishnan et al., 2011). In addition, the warmer ocean temperatures caused by El Niño, above average solar radiation, and global warming causes stress, which leads to coral bleaching and eventually causes mass mortality (Jokiel and Coles, 1990, Krishnan et al., 2011). Another hypothesis is that the high-temperature influences virulence factors of coral-associated microorganisms which inhibit the photosynthesis and disintegrate the symbiotic algae (Ben-Haim et al., 2003, Rosenberg and Falkovitz 2004). Indian coral reefs have experienced 29 widespread bleaching events since 1989, but intense bleaching occurred in 1998 and 2002 (Krishnan et al., 2011). There were four bleaching events reported at Andaman and Nicobar islands in the years 1998, 2002, 2005 and 2010 (Krishnan et al. 2011, Marimuthu et al., 2013). The 1998 bleaching-related mortality reached as high as 26% in Lakshadweep, 23% in GoM (Arthur, 2000) and 83% in the Andaman Islands (Ravindran et al., 1999). In 2010, 73% of the total corals in Lakshadweep Island were bleached (Vinoth et al., 2012) and massive bleaching events were reported from Andaman and Nicobar islands (Krishnan et al., 2011). Coral species such as *Acropora cerealis*, *Acropora humilis*, *Montipora* sp., *Favia pallida*, *Diploastrea* sp., *Goniopora* sp., *Fungia concinna*, *Gardineroserius* sp., *Porites* sp., *Favites abdita*, and *Lobophyllia* sp., were severely affected during the survey of bleaching event of 2010, where the sea surface temperature (SST) increased from 30.5 °C to 34°C (April to May 2010) within the bays of Port Blair. The branching corals (*Acropora* spp.) were the worst affected due to bleaching (Marimuthu et al., 2013). Similar massive bleaching of branching corals such as *Acropora formosa*, *Acropora nobilis*, *Acropora robusta*, *Acropora breuggemanni* and *Acropora grandis* in Andaman occurred (Krishnan et al., 2011). Furthermore, corals of GoM and Palk Bay were bleached due to heavy sedimentation (Kumaraguru et al., 2005) and elevated sea temperature (Edward et al., 2018). An assessment was carried out in the Malvan regions where temperature fluctuation of 1°C caused significant coral bleaching (Diraviya Raj et al., 2018). Bacteria are major factors in coral bleaching and effects have been experimentally examined using *Vibrio shiloi* and *Vibrio coralliilyticus* in the corals *Oculina patagonica* and *Pocillopora damicornis*, respectively, as model systems (Banin et al., 2000; Kushmaro et al., 2001; Ben-Haim et al., 2003). However, there have been no studies in Indian reefs to determine the effects of microbial pathogens on bleaching. Therefore, the occurrence of

severe bleaching events in Indian reefs should be analyzed for the influence of temperature on the role of pathogens in coral bleaching.

4. Parasitic infections

There have been no reports on parasitic infections from Indian reefs. Reporting parasitic diseases such as trematodiasis would require either microscopic observations locating the parasitic metacercariae within the swollen tissue or in histological examination (Aeby 1993, Aeby 1998), but these examinations have not been included in trematodiasis reports from the reefs of India (Kumaraguru et al., 2005; Manikandan et al., 2016; Adhavan et al., 2017). Until proper diagnostic methods have been used, the disease should be described as swollen multi-focal pink spots with gross signs similar to *Porites trematodiasis*.

Protozoan ciliates have been shown to invade (Nugues and Bak, 2009) and devour the tissues (Cooper et al., 2007) of vulnerable corals, suggesting that ciliate parasitism is a serious threat to coral reef health (Sweet and Bythell, 2012). Also, a previous report showed that of the 28 species of ciliates associated with the various coral diseases studied, six species ingest of zooxanthellae (Symbiodiniaceae) cells among (Sweet and Sere, 2015). However, there are no studies on the association of ciliate species with specific coral diseases described from Indian scleractinian corals, and no other protozoan associations have been described

5. New and unknown diseases

Most of the diseases described from the Indian coral reef regions may be new and unknown (Fig. 4 and 5) because the gaps in our understanding about many factors affecting coral health are vast and there has been little in the way of diagnostics or field tests for disease surveillance (Fig. 4 and 5). Most coral diseases have no confirmed etiology nor have the diseases been rigorously classified. Among the diseases described in Indian reefs, only the coral colonies affected with PLS were observed experimentally to determine causative agents, in this case the cyanobacterium, *Phormidium valderianum* (Ravindran et al., 2006). Though the BBD-associated microbes have been isolated and identified (Thinesh et al., 2011 and 2013) there was no experimental demonstration of causative agents based on Koch's postulates. Moreover, several diseases are indistinguishable because of their nearly identical appearance (*e.g.*, white plague I and white plague II) which are differentiated almost exclusively by the rate of lesion progression over the infected colony (Sutherland et al., 2004). The similar gross signs of coral abnormalities in field observations have resulted in misidentification; different diseases may be diagnosed to be the same, or one disease may be identified as multiple diseases (Richardson 1998). Even predation scars have been wrongly

classified as a disease (Patterson et al., 2002). Disease etiology needs to be confirmed by laboratory or *in situ* experiments. In addition, the disease names and signs should be systematically described (Work and Aeby, 2006; Raymundo et al., 2008) to avoid further confusion in naming the diseases. Studies on coral disease indicate that a single disease may be caused by multiple biotic or abiotic factors. Thus, multidisciplinary studies incorporating techniques from biochemistry, ecology, histopathology, microbiology, physical oceanography, physiology, toxicology, and virology will enable future efforts to test for causative agents and accurate descriptions and naming of the diseases (Santavy and Peters, 1997).

6. Conclusion

Diseases and pathologies reported in corals are associated with multiple factors of natural and anthropogenic stress; thus, unraveling the interactive effects between the diseases and associated factors becomes essential. Synergistic effects of environmental factors that influence the virulence of the causative agent from the same host or through vectors and the host's susceptibility to parasites and microbial pathogens need to be studied to understand the specific causes and mechanisms underlying each disease. At present, very few microbes are identified as coral pathogens and most of the diseases are reported to be polymicrobial. Identifying the microbes and their pathogenicity using Koch's postulates will be difficult. However, improving the understanding of the interactions among hosts, the environment, and pathogens and parasites may aid in mitigating the coral decline. Corals have been reported to resist microbial disease with their innate immunity and other defense mechanisms that are not well understood. Elucidation of the coral immune systems against diseases and accurate disease diagnostics will help to improve the microbial infection-related coral declines.

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Figure Legend

- Fig. 1.** Major coral reef regions of India. Map showing Indian coral reefs areas of (a) Gulf of Kachchh (GoK). (b) Central west coast of India. (c) Lakshadweep Islands. (d) Gulf of Mannar (GoM). (e) Palk Bay and (f) Andaman and Nicobar islands
- Fig. 2.** Diseases in Indian coral reefs. Eleven different coral diseases were described from GoM, which is comparatively higher than for other reefs. Yellow band disease (YBD) was recorded only from GoM. Ten different diseases, including pink blue disease (PBSS), have been described from Lakshadweep. PBSS has not been reported or described from any other major Indian reefs. Ten diseases also have been reported from Andaman and Nicobar islands, excluding YBD and PBSS. Palk Bay is located near the GoM of the southeast coast of India, but only 7 different diseases have been recorded from this area. Four diseases have been reported from GoK, all of which were observed in the other major Indian reefs. One disease, white plague, was recorded from the central west coast, where there had been little exploration for coral diseases.
- Fig. 3.** Number of different diseases affecting the two major coral genera in the Indian coral reef regions of India. *Porites* sp. is predominantly affected with 13 different diseases, followed by 7 in *Acropora* sp.. PLS, yellow band disease, pink spot, and white spot diseases were only reported for *Porites* species. Brown band disease was reported only in *Leptoria* sp. All the other reported diseases had been observed in multiple coral genera.
- Fig. 4.** Unknown diseases/ discoloration/ syndromes in Indian reefs - (a) Diffuse bleaching, in *Porites* sp. in Kurusadai island, GoM at Latitude and longitude 9°14'46.0"N; 79°13'12.6"E.; note diffuse white discoloration demarcated from normal brown tissue. (b) *Porites* (pink spots) (*Porites* sp.) from various reef areas of Palk Bay and Gulf of Mannar group of islands; note pink discoloration due to boring organisms (arrows). (c) Discoloration with black color and tissue loss (black necrotic mat) *Porites* sp., in Kurusadai island, GoM at Latitude and longitude: 9°14'46.0"N; 79°13'12.6"E; Note areas of black tissue discoloration (arrows). (d) Purple discoloration (like endolithic hypermycosis) of *Acropora* sp. in Poomarichan Island, Mandapam group of islands, Gulf of Mannar at Latitude and longitude: 9°14'56.7"N; 79°10'45.4"E.; note areas of purple tissue discoloration (arrows). (e) Pink discoloration (similar to Pink Blotch); note areas of pink tissue discoloration with undulating to serpiginous margins (arrows). (f) *Porites* multi-focal tissue loss (pink spots) from various reef areas of Palk Bay and Gulf of Mannar group of islands. Note areas of pink tissue discoloration (arrows).
- Fig. 5.** Unknown diseases/ discoloration/ syndromes in Indian reefs - (a) White patch like syndrome in *Porites* sp.; diffuse, medium to large, circular to oblong tissue loss, surrounded by swollen white tissue. The dead skeleton was progressively colonised by opportunistic algae in various reef areas of GoM and Palk bay. (b) Pink line syndrome; diffuse, central to peripherally, distinct, irregular area of tissue loss leaving bare skeleton separated from normal tissue by pink colouration linear, undulating annular border (arrows) in *Porites* sp., from various reef areas of Palk Bay and Gulf of Mannar group of islands. (c) and (d) White syndrome of *Acropora* sp.; lesions may be annular or linear, spreading from the base to the tips, or starting at a branch bifurcation and spreading up or down; tissue loss may progress up the underside or upper surface of the branch in various reef areas of GoM. (e) Turf algal overgrowth on the *Favia* sp., in GoM. (f) *Porites* (pink spots) (*Porites* sp.) from various reef areas of Palk Bay and Gulf of Mannar group of islands; note pink discoloration due to boring organisms (arrows).

Figure 1

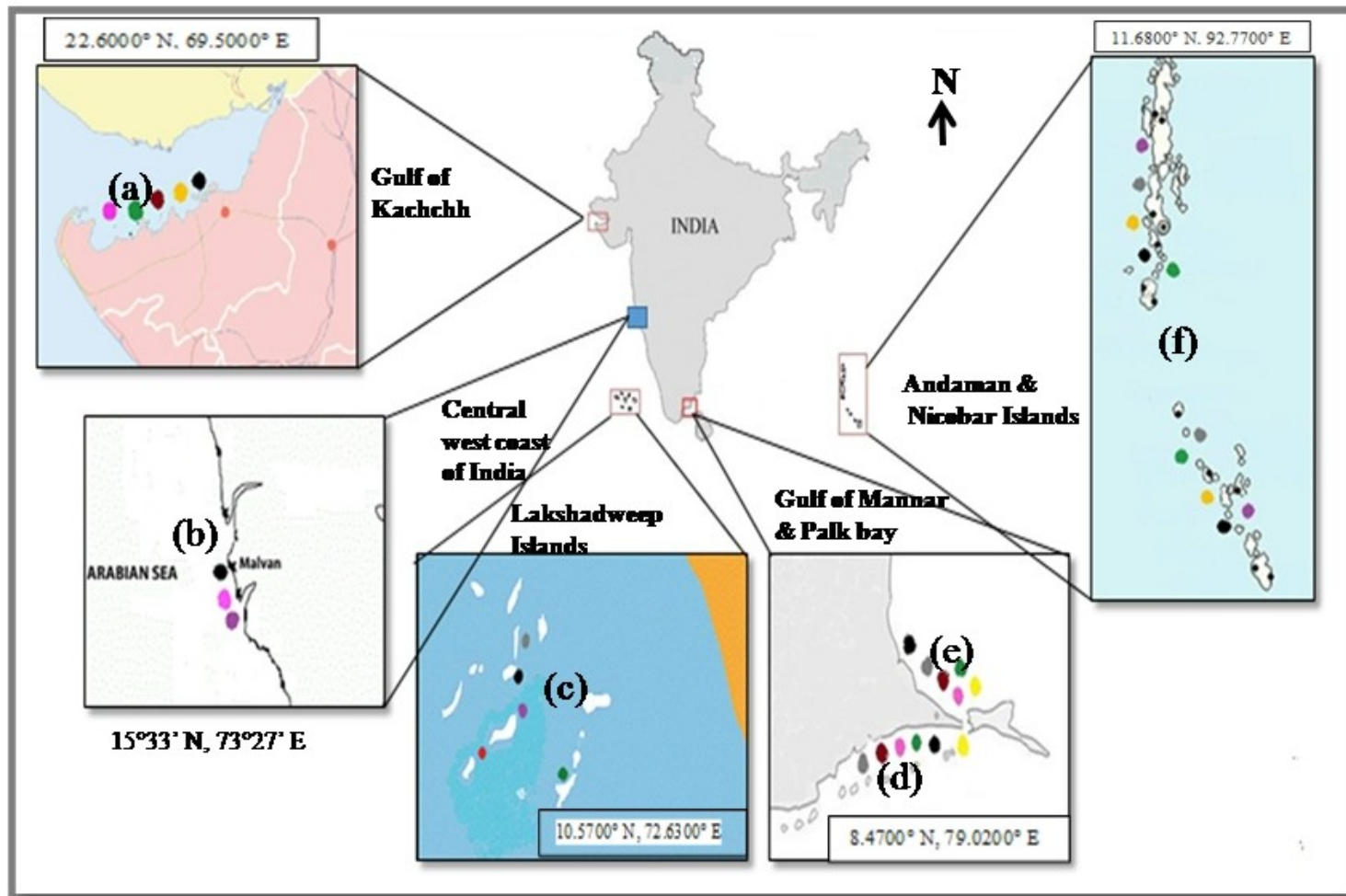


Figure 2

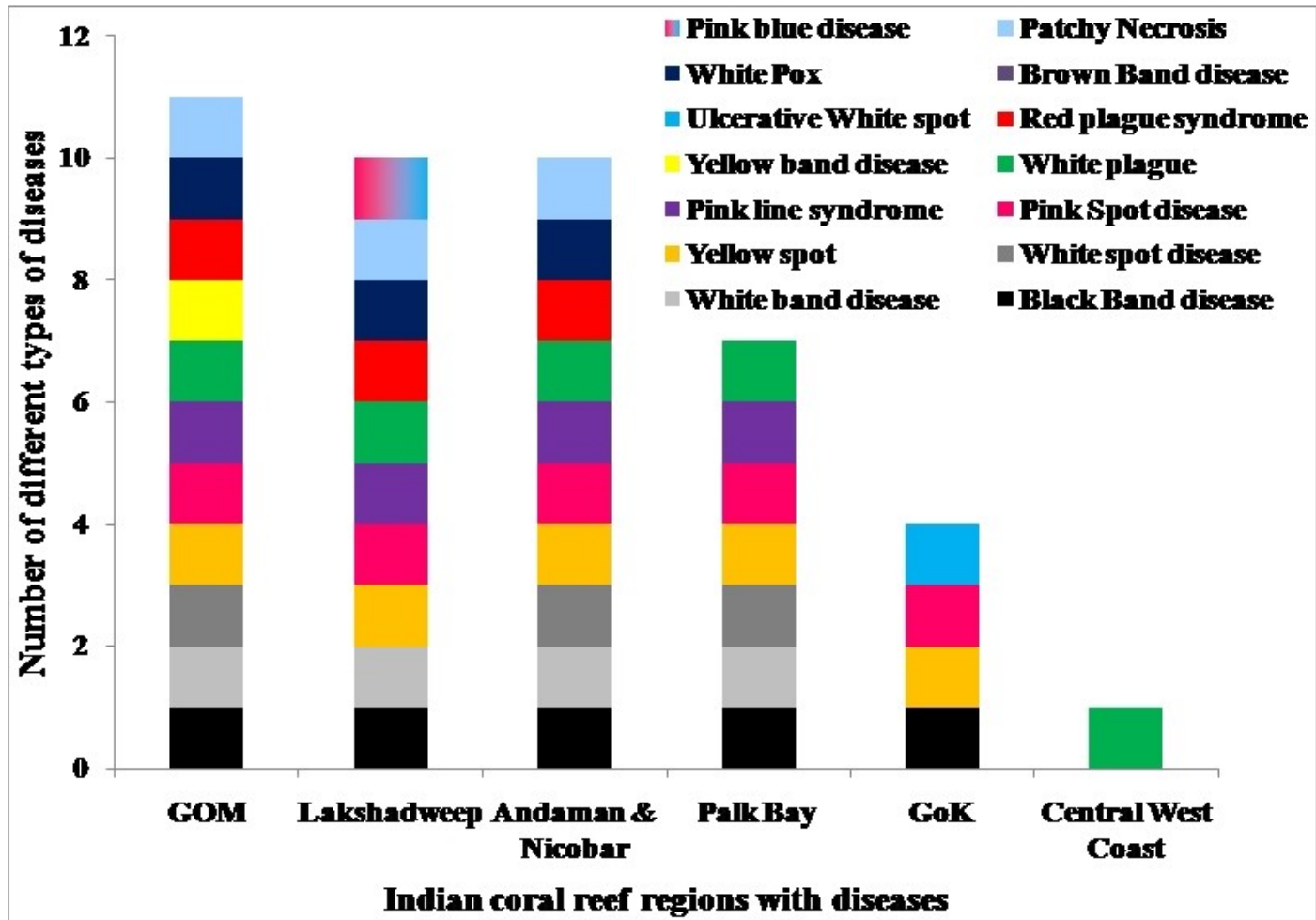


Figure 3

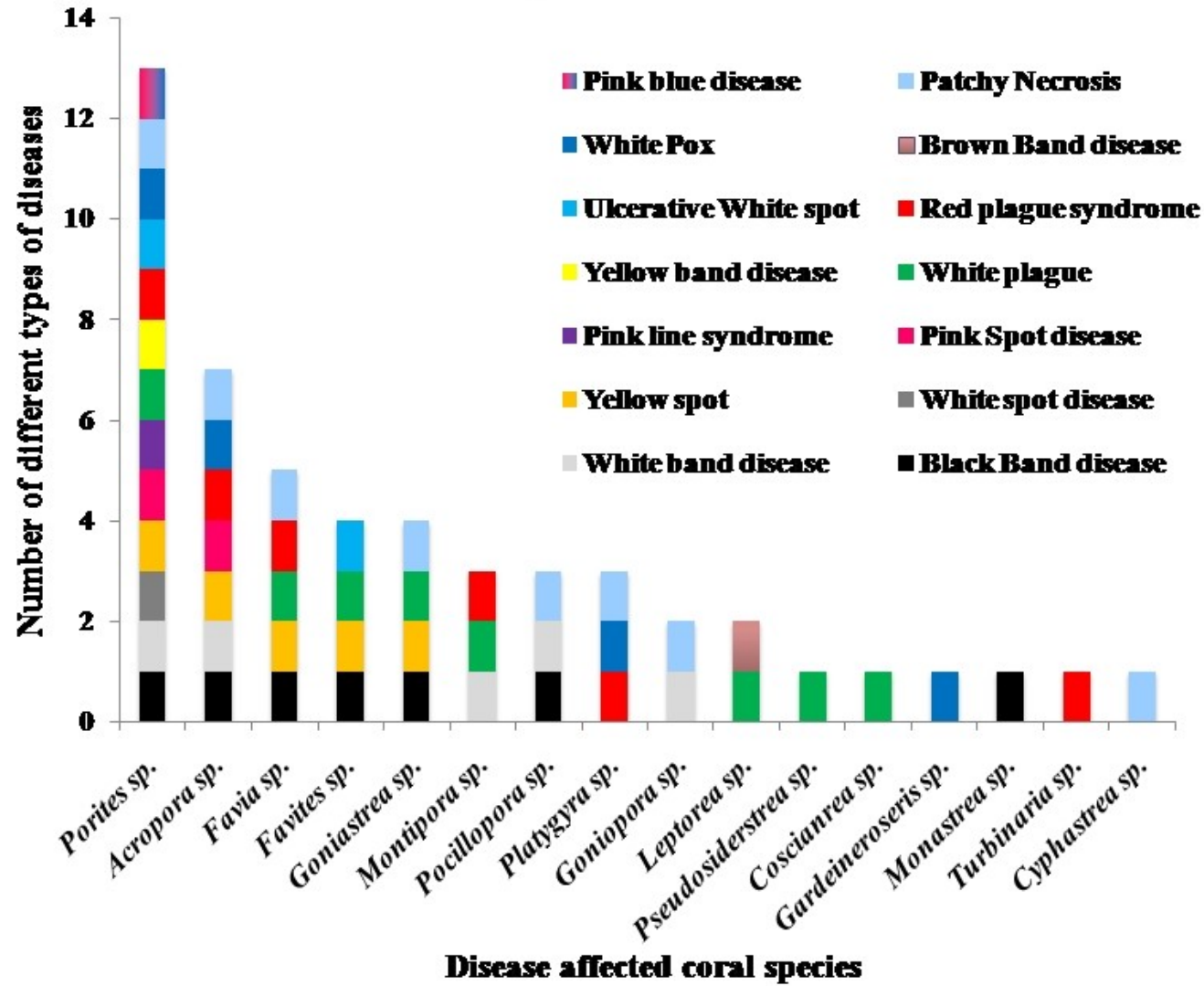


Figure 4

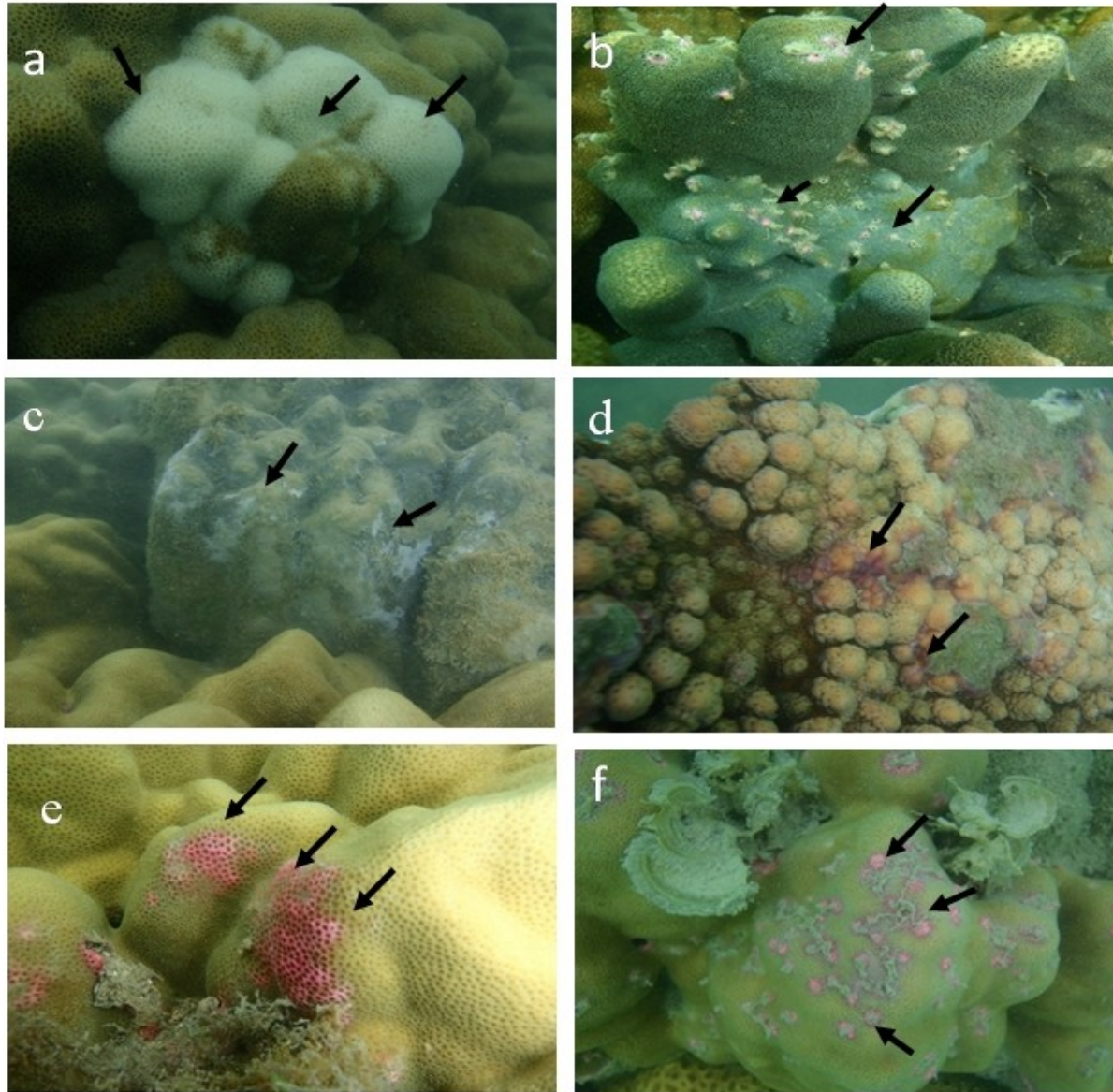


Figure 5

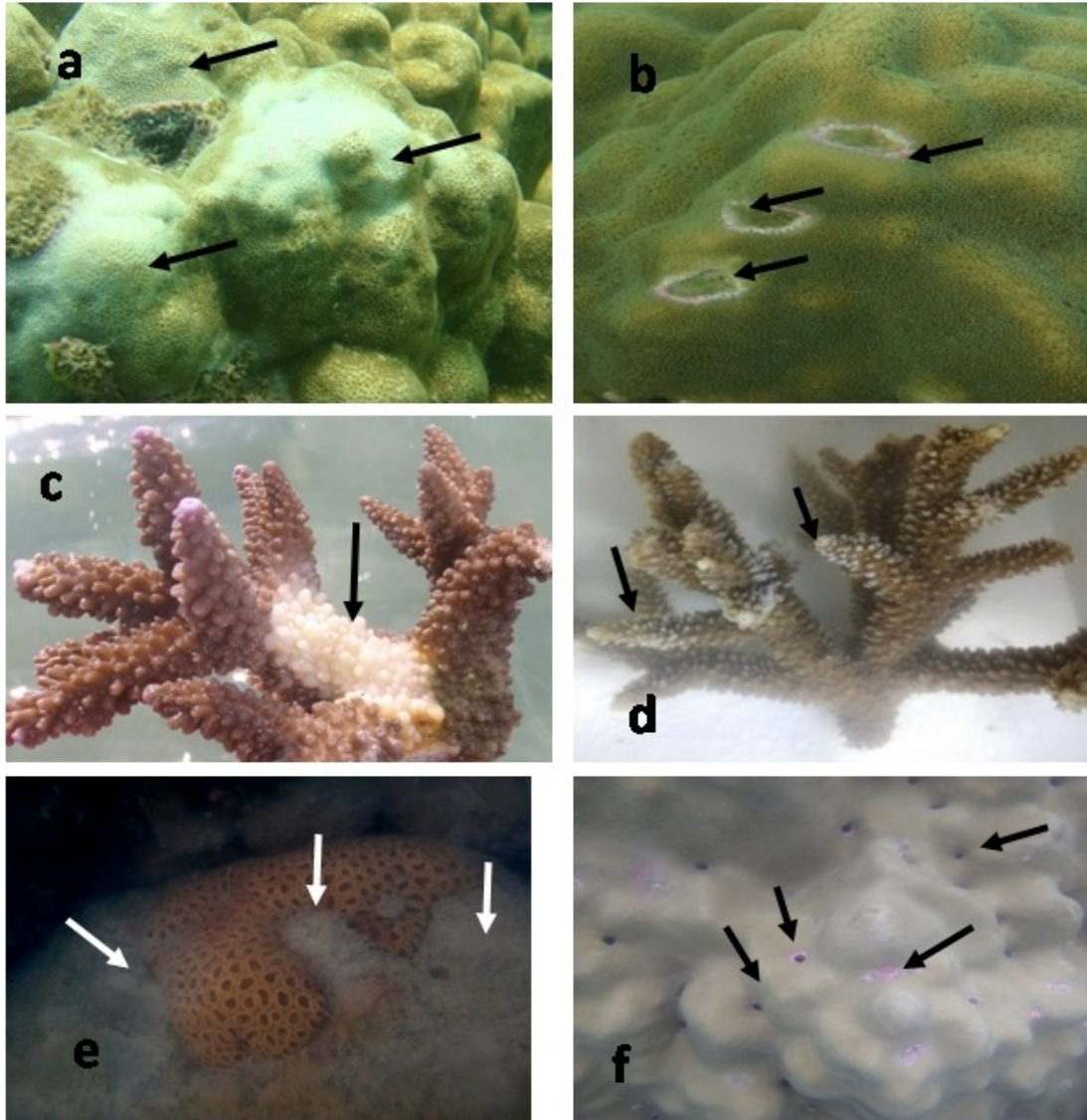


Table 1. Coral disease reported in India and disease description according to Work and Aeby (2006)

| S. no | Disease Name | Description (according to Work and Aeby, 2006) | Morphologic Diagnosis | Associated micro-organisms | Dominant host and reef Regions | Source |
|-------|--------------------|--|---|--|--|---|
| 1. | White band disease | Diffuse, basal to peripherally situated distinct line of bleached but intact coral tissue revealing skeleton with undulating white band between healthy tissue and dead tissue | Severe, basal to peripherally located, acute bleaching event leaving exposed Skeleton | <i>Vibrio charcharii</i> | <i>Acropora</i> sp., <i>Montipora</i> sp., <i>Porites</i> sp., <i>Pocillopora</i> sp., <i>Goniopora</i> sp., (GoM & Palk Bay, Lakshadweep and A & N) | Ravindran et al., 1999, Jeyabaskaran, R., 2006; Thinesh et al., 2009, 2011 and 2014; Edward et al., 2015; Chakkaravarthy And Raghunathan 2011; Sreeraj et al., 2017; Thangaradjou et al., 2016, Ramesh et al., 2019 |
| 2. | White Plague | Multifocal to coalescing, central to peripherally situated, large, distinct, irregular area of tissue loss exposing white Skeleton | Focal or Multifocal: Linear or Annular margin: Discrete band of bare skeleton separates live tissue from algal-colonized Skeleton | Unknown | <i>Porites</i> sp., <i>Favia</i> sp., <i>Favites</i> sp., <i>Goniastrea</i> , <i>Leptorea</i> sp., <i>Montipora</i> sp., <i>Pseudosidera streatayami</i> , <i>Coscianrea</i> sp. (GoM and Palk Bay, GoK, A & N, Lakshadweep Central west coast of India) | Thinesh et al., 2009 and 2011; Edward et al., 2015; Yogeshkumar et al., 2014; Ramesh et al., 2014 and 2019; Sreeraj et al., 2017; Thangaradjou et al., 2016; Manikandan et al., 2016 |
| 3. | White Pox | Diffuse, central to peripherally located, small, distinct area of tissue loss revealing bare skeleton | Mid, acute tissue loss with intact bare skeleton with algal colonization | Unknown (Possible bacterial pathogen <i>Serratia marcescens</i> has been identified) | <i>Porites annae</i> , <i>Acropora</i> sp., <i>Porites</i> sp., <i>Platygyra</i> sp., <i>Gardineroser is</i> sp. (A & N, GoM and Lakshadweep Islands) | Chakkaravarthy And Raghunathan, 2011, Thangaradjou et al., 2016, Sreeraj et al., 2017 |
| 4. | Patchy Necrosis | Lesions are focal to multifocal, coalescing lesions, irregular in shape, completely surrounded by living tissue | - | Fungus infection (<i>Scolecobasidium</i> sp.) | <i>Porites</i> sp., <i>Goniastrea</i> sp., <i>Goniopora</i> sp., <i>Montipora</i> sp., <i>Favia</i> sp., <i>Acropora</i> sp., | Raghukumar And Raghukumar 1991; Ravindran et al., 2001; Thangaradjou |

| | | | | | | |
|----|-------------------------------|--|--|---|--|---|
| | | | | | <i>Pocillopora</i> sp., <i>Platygyra</i> sp., <i>Cyphastrea</i> (A&N; GoM; Lakshadweep islands) | et al., 2016; Jeyabaskaran, R., 2006 |
| 5. | Black Band Disease | Diffuse, centrally to peripherally situated, large, irregular, distinct area of tissue loss revealing intact bare skeleton separated from normal tissue by non-uniform thin blackish to brownish line | Moderate to severe, acute to sub-acute lesion and tissue loss with intact skeleton with black annular Margin | Microbial consortium of cyanobacteria, <i>Phormidium corallyticum</i> & <i>Synechocystis</i> sp., <i>Vibrio</i> sp., & <i>Pseudomonas</i> sp. | <i>Porites</i> sp., <i>Acropora</i> sp., <i>Montastrea curta</i> , <i>Favites</i> sp., <i>Favia</i> sp., <i>Goniastrea</i> , <i>Pocillopora</i> sp., (GoM/Palk bay, GoK, A & N; Lakshadweep Islands) | Ravindran et al., 1999, Thinesh et al., 2009, 2011, 2013 & 2014; Edward et al., 2015; Chakkaravarthy and Raghunathan, 2011; Yogeshkumar et al., 2014; Ramesh et al., 2014 and 2019, Thangaradjou et al., 2016 |
| 6. | Yellow Spot or Blotch | Diffuse, centrally located, distinct, circular to oblong area of tissue loss and narrow band of pale yellow at the colony margin, revealing bare white skeleton colonized by algae | Severe, diffuse, acute tissue loss revealing bare Skeleton | Unknown | <i>Porites</i> sp., <i>Acropora</i> sp., <i>Favia</i> sp., <i>Favites</i> sp., <i>Goniastrea</i> (GoK, GoM, A & N and Lakshadweep Islands) | Chakkaravarthy and Raghunathan, 2011, Thinesh et al., 2009; Yogeshkumar et al., 2014, Ramesh et al., 2014, Thangaradjou et al., 2016 |
| 7. | Yellow Band disease | Annular and linear margins of pale yellow bordered by healthy tissue | Focal and multifocal. Annular to linear Margins | Unknown | <i>Porites</i> sp. (GoM & Palk Bay) | Thinesh et al., 2009 and 2011; Edward et al., 2015; Thangaradjou et al., 2016 |
| 8. | Brown Band Disease | - | A brown band Separating healthy tissue from dead white tissue with varying width. | Unknown | <i>Leptoria phrygia</i> (A & N) | Chakkaravarthy and Raghunathan, 2011 |
| 9. | Porites Ulcerative white spot | Small number of multifocal to coalescing (3-5 mm) progressing to full-tissue thickness ulceration, central to peripherally distributed, small to medium, distinct, circular, oblong and pyriform, areas of | Severe, central to peripheral, multifocal to coalescing, acute ulceration and tissue loss. | Unknown | <i>Porites</i> sp., <i>Favites</i> sp., (Gulf of Kachchh) | Yogeshkumar et al., 2014 |

| | | | | | | |
|-----|---------------------|--|---|--|--|--|
| | | tissue loss due to | | | | |
| | | Ulceration | | | | |
| 10. | White spot disease | Multifocal to coalescing, central to peripherally located, large distinct, circular to irregular areas of tissue loss, revealing the bare white skeleton | Multifocal, annular, Severe, acute to sub-acute tissue loss with intact Skeleton | Unknown | <i>Porites</i> sp. (A & N, GoM & Palk Bay) | Chakkaravarthy And Raghunathan, 2011; Thinesh et al., 2009 and 2011; Edward et al., 2015 |
| 11. | Red Plague Syndrome | Diffuse, central to peripherally located, distinct, area of tissue loss revealing intact bare skeleton separated from normal tissue by undulating red annular border | Severe, central to peripheral, diffuse, acute to sub-acute tissue loss with intact skeleton and red annular margin | cyanobacteria, <i>Oscillatoria</i> sp. | <i>Acropora</i> sp., <i>Montipora</i> sp., <i>Porites</i> sp., <i>Platygyra</i> sp., <i>Favia</i> sp., <i>Turbinaria mesenterina</i> , <i>T. peltata</i> | Jeyabaskaran. R., 2006; Jeyabaskaran & Raghukumar 2004: Chellaram et al., 2006 (Lakshadweep; A & N and GoM) |
| 12. | Pink Line syndrome | Diffuse, central to peripherally, distinct, irregular area of tissue loss leaving bare skeleton separated from normal tissue by pink colouration linear, undulating annular border | Moderate to severe, central to Peripheral location, diffuse, sub-acute to chronic tissue loss, leaving bare skeleton with pink border between tissue and bare skeleton. | Cyanobacteria, <i>Phormidium valderianum</i> Fungi | <i>Porites lutea</i> , <i>Porites solida</i> . (Lakshadweep, A & N and GoM /Palk Bay, Lakshadweep Islands) | Ravindran et al., 2001, Ravindran and Raghukumar 2002; Chakkaravarthy And Raghunathan 2011; Ramesh et al., 2014 and 2019; Kumaraguru et al., 2005; Sreeraj et al., 2017, Thangaradjou et al., 2016 |
| 13. | Pink Spot disease | Numerous, small (3-5mm), multifocal to coalescing, distinct, areas of tissue loss, affecting polyps with filamentous algal growth on dead tissue and bare skeleton | Severe, colony-wide, multifocal to coalescing tissue loss and affecting polyps | Unknown | <i>Porites</i> sp. (GoM/ Palk Bay; Gok, A & N, Lakshadweep islands) | Thinesh et al., 2009 and 2011; Edward et al., 2015; Yogeshkumar et al., 2014: Chakkaravarthy and Raghunathan 2011; Sreeraj et al., 2017; Thangaradjou et al., 2016 |
| 14. | Pink-blue disease | Multifocal or diffuse areas of pink, purple or blue brightly coloured | Pink to blue Colouration adjacent to lesions | Unknown | <i>Acropora</i> sp., <i>Porites</i> sp., (Lakshadweep islands) | Ravindran et al., 2001 |