

Current status and scope of coral reef research in India: A bio-ecological perspective

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Coral reefs are staggeringly diverse and complex ecosystem. But, this tropical wonder is currently degrading at alarming rates and, facing a high risk of extinction due to several anthropogenic and natural disturbances. Despite knowing the complex and huge reefs India has, and all the benefits this country gets from its reefs; the efforts to manage and conserve appears poor. Review of research suggests that better management coupled with trained marine biologists, modern infrastructure facility and long-term funding. This review also intends to highlight the current focal area of bio-ecological research in Indian coral reefs and, discuss scopes for further study on some of the key themes on which primary research is being conducted globally. Moreover, there is a pressing need for effective communication between the scientific community and stakeholders for the strict implication of conservation practice to protect the spectacular coral reef ecosystem.

[Keywords: Coral reef, India, Biodiversity, Climate change, Human impact, Conservation]

Introduction

Coral ecosystem plays a significant role in the economy of several tropical and subtropical countries and provides various services around to millions of people. Reefs are also one of the key attractions of tourist globally, but these amazing ecosystems have been impacted singly or synergistically by human and natural perturbations¹. The overall degradation of coral reefs, observed on a global level, is alarming. Not only are coral mortality rates escalating, but the concurrent dramatic decline in coral growth rates is striking as well. The rate of calcification of corals has reduced by 15%–30% since 1990, because of swelling thermal stress², and estimations have forecasted further decreases of up to 78% due to the greenhouse gas concentrations projected for 2100³. On the other side, the structural complexity of reefs declined

radically and many reefs have gone through or in the vulnerability of phase shift phenomena^{4, 5}. For example, the coral coverage in the Caribbean has been declined in the last few decade by ~1.4% year⁻¹, from ~55% in 1977 to the current ~10% average coral coverage⁶, outpaced by the current rate of decline in the Great Barrier Reef, which over the last three decades was 0.53%year⁻¹ in coral cover, increased substantially from 2006 at the rate of ~1.51%·year⁻¹⁷.

Most of the Indian reefs are under the MPAs and therefore, are well protected by laws. They have been studied moderately well and several studies are ongoing, which is certainly a good indication. However, more intensive studies on ecology, biology, microbial disease, bleaching, and restoration is need of the hour. The restricting factors of reef research in India mainly

remoteness, deep water submerged presence, distance from the mainland which makes their access difficult. Also, deep water reef studies require specialized research vessels with the modern technology, trained oceanographers or marine biologists, SCUBA divers, and equipment, those are still sparse in India. Thus, it heightens the need for reviewing the current status of coral research in India and to cast light on the critical knowledge gap.

The Indian Ocean is characterized by highly diverse reefs in its tropical and subtropical region. Interestingly, the baseline map of Indian coral reef prepared by data derived from RESOURCESAT-1 (IRS-P6) satellite and revealed an area of 2383.87 km² coral coverage⁸. More fascinatingly, India is blessed with all the major type of coral reefs (Fig 1) - Fringing reef (Andaman and Nicobar Islands) 1021.46 km², Gulf of Kachchh (GoK) 352.50 km², Gulf of Mannar (GoM) 75.93 km²; Barrier reef (GoM, A&N Islands); Atoll (Lakshadweep Islands, 933.7 km²)⁹. Apart from these three main types, there are other types such as patch reef, with a low generic diversity of corals, small structures within the lagoon of other reef and coral bank, which are reported during different studies but not investigated extensively. Such as, a coral bank is located about 100 km off the coast of Malpe (north of Mangalore), named Gaveshani Bank¹⁰. The presence of hermatypic corals along the shore is reported from Quilon in the Kerala coast to Enayem in Tamilnadu¹¹. There are also reports on occurrence of coral reefs from the intertidal region of Ratnagiri, Malvan and Redi in the Maharashtra coast¹², presence of submerged reef system on the continental shelf of the same coastal region between Vengurla and Vijaydurg, parallel to the shoreline at water depths of 60 to 110 m¹³, in the Grande Island, Goa coast with the presence of 15 coral genera¹⁴, existence of a patch reef in the Netrani Island off Karnataka consisting of 14 coral species¹⁵. More recently, Ingole *et al.* 2016¹⁶ surveyed the Angria Bank, a submerged plateau located ~60-70 nautical miles west of Vijaydurg and reported more than 50 genera of coral and reef associated biota. On the east coast of India, presence of coral reported between Parangipettai (Porto Novo), south of Cuddalore and Pondicherry¹⁷. A recent survey of Central Marine Fisheries Research Institute (CMFRI), Kochi, revealed the occurrence of reef coral at off coast of Puri in Orissa¹⁸.

Additionally, each new discovery of coral atoll or

submerged reef system always should be followed with periodical quantitative and qualitative surveys, biodiversity assessment, and detailed studies on reef health and conservation. Besides this, initial surveys and studies may be conducted to all the potential deep water or mesophotic reef sites with equipped divers and if not possible then maybe by remotely operated vehicles (ROVs) and such other submersibles.

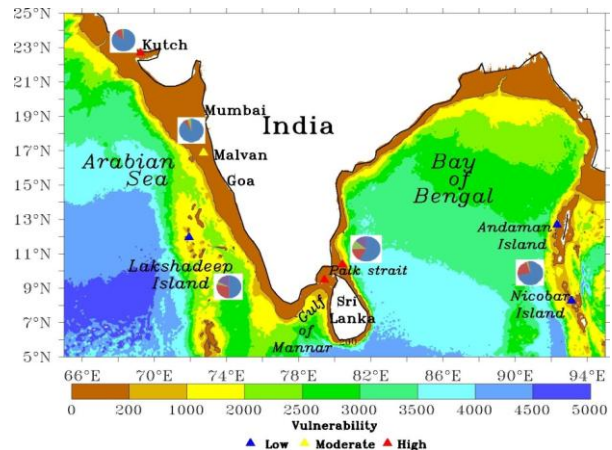


Fig. 1- Indian coral reefs and major theme of coral reef study in India (%)

- Biodiversity and ecology
- Coral bleaching and other threats
- Disease
- Microbiology and biotechnology

Recently, a survey in the A&N Islands by indigenously developed ROV by the National Institute of Ocean Technology, Chennai, heightens the usefulness of modern technologies in coral reef research¹⁹. In addition, satellite based remote sensing and GIS could be very useful tools to study the spatial arrangement of coral reef habitats and ecosystem health including coral bleaching monitoring. It is assumed that there may be more patch or submerged reefs scattered across the Indian waters which are yet to be discovered. Therefore, research should be encouraged by providing necessary facilities, long-term funding, and infrastructure.

Coral reef biodiversity

Speaking about the biodiversity of Indian coral reefs, it is undoubtedly high, and documentation of coral reef fauna dates back to 1847 from Nicobar Islands²⁰. The flora and fauna reported so far from Indian water include 1284 species of fish, 3271 species of molluscs, 765 species of echinoderms, 519 species of sponges, 345 species of coral belonging to 87 genera, 607 species of crustaceans and 624 species of algae^{21, 22}. Faunal

richness in A&N Islands is remarkably high (6000 species), accounting 7.5% of total Indian fauna, which constitutes approximately 3% of the terrestrial fauna and 4.6 % of marine fauna²². A series of new occurrence reports on scleractinians and other reef-associated fauna from A&N Islands subsequently increased existing list of coral reef fauna from 208 to 478 species, belong to 89 genera and 19 families by the Zoological Survey of India (ZSI)²³. The highest diversity of 424 species of hard corals belonging to 86 genera and 19 families recorded from A&N region²⁴. In Lakshadweep, occurrence of 163 species of hard corals, 86 species of macrophytes, 10 species of anomuran crabs, 81 species of brachyuran crabs, 155 species of gastropods, 24 species of bivalves, 13 species of sea stars, 6 species of brittle stars, 23 species of sea cumpers, 15 species of sea urchins and 120 species of fish recorded²⁵. The presence of 106 species of hard coral belonging to

30 genera and 11 species of ahermatypic coral belonging to 10 genera were reported from the GoM and Palk Bay (PB)²⁶.

Reef fishes are often one of the most diverse and conspicuous constituents of the reef fauna and because of their wider ecological significance; their monitoring is necessary. A review of reef fish fauna of A&N Islands and found 1089 species of reef habitant fish²⁷. In the GoM, 117 species of reef-associated fish belonging to 79 genera and 42 families documented²⁸. Moreover, in the small reef in the Netrani Island a rich diversity of reef fishes was found, which is linked with the complex coral reef system²⁹. Furthermore, research for assessment and documentation of each reef's biodiversity is fundamental for better understanding ongoing ecosystem dynamics and future changes which in turn will be useful for conservation and management of the reef.

Table 1- List of references on bio-ecological study on Indian reefs

Name of the reef	Topic	Reports
Gulf of Kachchh	Biodiversity and ecology	Apte <i>et al.</i> , 2010 Bhagirathan <i>et al.</i> , 2008 Parasharya & Padate, 2014 Dixit <i>et al.</i> , 2010 Parmar <i>et al.</i> , 2015 Nair, 2002 Parasharya, 2014 Patel, 1978 Pillai & Patel, 1988 Ramamoorthy <i>et al.</i> , 2012 Subburaman <i>et al.</i> , 2014 Yogesh Kumar <i>et al.</i> , 2014 Kannapiran <i>et al.</i> , 2008 Singh <i>et al.</i> , 2006 State of Environment Report; Gujarat; 2005 State of Environment Report; Gujarat; 2005 Deshmukhe <i>et al.</i> , 2000 Sen Gupta <i>et al.</i> , 2003 Raghunathan <i>et al.</i> , 2004 Pandey <i>et al.</i> , 2010 Patel, 1976 Patel, 1985a Patel & Bhaskaran, 1978 Patel, 1985b Pillai <i>et al.</i> , 1979 Prasanna 2008 Raval <i>et al.</i> , 2002 Sen Gupta & Deshmukhe, 2000 Wafar <i>et al.</i> , 2000 Pillai <i>et al.</i> , 1979 Rao & Sastry, 2005 Annon, 1992 Arthur & Jhala, 1997 Parulekar & Untwale, 1978 Parulekar & Untwale, 1976 Wafar <i>et al.</i> , 1997 Chandresh <i>et al.</i> , 2012

		Sharma <i>et al.</i> , 2008
	Coral bleaching and other threats	Adhavan <i>et al.</i> , 2014
		Joshi <i>et al.</i> , 2014
		Joshi <i>et al.</i> , 2015
		Shah <i>et al.</i> , 2014
Mumbai	Disease	Yogesh Kumar <i>et al.</i> , 2014
Malvan	Biodiversity and ecology	Ambekar <i>et al.</i> , 2016
	Biodiversity and ecology	Bhosale, 2003
		ICMAM, 2001
		Qasim & Wafar, 1979
		Parulekar, 1981
		Barman <i>et al.</i> , 2007
	Coral disease	Hussain <i>et al.</i> , 2016
Angria	Coral bleaching and other threats	De <i>et al.</i> , 2015
	Biodiversity and ecology	Sivakumar & Joshi, 2015
		Ghosh & Fernandes, 2014
		Ingole <i>et al.</i> , 2015
Grande Island	Biodiversity and ecology	Manikandan <i>et al.</i> , 2016
		Rodrigues <i>et al.</i> , 1998
		Sreekanth <i>et al.</i> , 2015
		Patro <i>et al.</i> , 2015
		Anil & Wagh, 1984
Netrani	Biodiversity and ecology	Thomas <i>et al.</i> , 2011
		Zacharia <i>et al.</i> , 2008
Palk Bay and Gulf of Mannar	Biodiversity and ecology	Asta & Sundaramanickan, 2010
		Balasubramanian & Wafar, 1974
		Edward <i>et al.</i> , 2007
		Edward <i>et al.</i> , 2008
		Edward <i>et al.</i> , 2004
		Edward, 2005
		Edward & Ayyakkannu, 1996
		Edward, 2009
		Edward <i>et al.</i> , 2012
		Edward & Bhatt, 2012
		Geetha & Yogesh Kumar, 2012
		George and Sukumaran, 2007
		Kumaraguru <i>et al.</i> , 2006
		Manikandan <i>et al.</i> , 2014
		Manikandan <i>et al.</i> , 2016
		Marimuthu <i>et al.</i> , 2010
		Muthiah <i>et al.</i> , 2003
		Pillai, 1973
		Pillai, 1975
		Pillai, 1977
		Pillai, 1986
		Pillai, 1986
		Pillai, 1969
		Raghuram & Venkataraman, 2005
		Rajasuria, 2007
		Rajendran & David, 1969
		Ramesh <i>et al.</i> , 2008
		Rao, 1972
		Sukumaran <i>et al.</i> , 2005
		Sukumaran <i>et al.</i> , 2011
		Varghese <i>et al.</i> , 2011
		Venkataraman <i>et al.</i> , 2004
		Venkataramani <i>et al.</i> , 2005
		Venkataramanujam & Santhanam, 1989
		Venkataramanujam <i>et al.</i> , 1981
		Yogesh Kumar <i>et al.</i> , 2013
		Edward <i>et al.</i> , 2015
		Raj <i>et al.</i> , 2015 a, b
		Mathews <i>et al.</i> , 2015
		Sridhar <i>et al.</i> , 2008
		Vinithkumar <i>et al.</i> , 1999
		Thangaradjou <i>et al.</i> , 2005
		Sridhar <i>et al.</i> , 2008
	Coral bleaching and Other threats	Kumaraguru <i>et al.</i> , 2003

		Ravindran <i>et al.</i> , 2012
		Wilson <i>et al.</i> , 2005
		Kumaraguru <i>et al.</i> , 2005
		Kumaraguru <i>et al.</i> , 2003
		Manikandan <i>et al.</i> , 2016
		Thinesh <i>et al.</i> , 2015
		Joshi & Marimuthu, 2015
		Pereira & Verlecar, 2005
		Kamalakannan <i>et al.</i> , 2014
		Chandrasekaran <i>et al.</i> , 2008
		Kamalakannan <i>et al.</i> , 2010
	Coral disease	Thinesh <i>et al.</i> , 2011
		Aeby <i>et al.</i> , 2015
		Raj <i>et al.</i> , 2016
		Thinesh <i>et al.</i> , 2014
		Thinesh <i>et al.</i> , 2013a
		Thinesh <i>et al.</i> , 2013b
		Thinesh <i>et al.</i> , 2009
		Padamakumar <i>et al.</i> , 2011
		Thangaradjou <i>et al.</i> , 2016
	Microbiology and biotechnology	Ravindran <i>et al.</i> , 2013
		Babu <i>et al.</i> , 2004
		Kannapiran, and Ravindran, 2012
		Kannapiran <i>et al.</i> , 1999
		Raveendran <i>et al.</i> , 2011
		Chellaram & John, 2015a
		Chellaram & John, 2015ab
		Chellaram <i>et al.</i> , 2012
		Chellaram <i>et al.</i> , 2011
		Mol <i>et al.</i> , 2010 a, b
Andaman & Nicobar	Biodiversity and ecology	Mondal <i>et al.</i> , 2010a,
		Mondal <i>et al.</i> , 2010b
		Mondal <i>et al.</i> , 2011a
		Mondal <i>et al.</i> , 2011b
		Mondal <i>et al.</i> , 2011c
		Mondal <i>et al.</i> , 2011d
		Mondal <i>et al.</i> , 2011e
		Mondal <i>et al.</i> , 2011f
		Mondal <i>et al.</i> , 2011g
		Mondal <i>et al.</i> , 2011h
		Mondal <i>et al.</i> , 2011i
		Mondal <i>et al.</i> , 2011j
		Mondal <i>et al.</i> , 2011k
		Mondal <i>et al.</i> , 2011l
		Mondal <i>et al.</i> , 2012a
		Mondal <i>et al.</i> , 2012b
		Mondal <i>et al.</i> , 2012c
		Mondal <i>et al.</i> , 2012d
		Mondal <i>et al.</i> , 2012c
		Mondal <i>et al.</i> , 2012d
		Mondal <i>et al.</i> , 2012e
		Mondal <i>et al.</i> , 2012f
		Mondal <i>et al.</i> , 2012g
		Mondal <i>et al.</i> , 2013a
		Mondal <i>et al.</i> , 2013b
		Mondal <i>et al.</i> , 2013c
		Mondal <i>et al.</i> , 2013d
		Mondal <i>et al.</i> , 2013e
		Mondal <i>et al.</i> , 2013f
		Mondal <i>et al.</i> , 2013g
		Mondal <i>et al.</i> , 2014a
		Mondal <i>et al.</i> , 2014b
		Mondal <i>et al.</i> , 2014c
		Mondal <i>et al.</i> , 2014d
		Mondal <i>et al.</i> , 2014e
		Mondal <i>et al.</i> , 2014f
		Mondal <i>et al.</i> , 2014g
		Mondal <i>et al.</i> , 2014h

		Mondal <i>et al.</i> , 2015a
		Mondal <i>et al.</i> , 2015b
		Mondal <i>et al.</i> , 2015c
		Mondal <i>et al.</i> , 2015d
		Mondal <i>et al.</i> , 2015e
		Mondal <i>et al.</i> , 2015f
		Mondal <i>et al.</i> , 2015g
		Mondal <i>et al.</i> , 2016
		Raghuraman <i>et al.</i> , 2012
		Rajan & Sreeraj, 2013
		Jeyabaskaran, 2007
		Kishore, 2015
		Turner <i>et al.</i> , 2009
		Dorairaj & Sundarajan, 1997
		Arthur, 1996
		Kulkarni <i>et al.</i> , 2001
		Jeyabaskaran, 1999
		Sadhukhan & Raghunathan, 2011
		Dhivya <i>et al.</i> , 2012
	Coral bleaching and other threats	Jeyabaskaran & Rao, 2007
		Krishnan <i>et al.</i> , 2011
		Marimuthu <i>et al.</i> , 2013
		Jha <i>et al.</i> , 2013
		Jogesh Kumar & Raghunathan, 2012
		Marimuthu <i>et al.</i> , 2011
		Marimuthu & Wilson, 2005
		Mondal <i>et al.</i> , 2011 a
		Mondal <i>et al.</i> , 2013
		Mondal <i>et al.</i> , 2014a
		Mondal <i>et al.</i> , 2014b
		Mondal <i>et al.</i> , 2014c
		Ramachandran <i>et al.</i> , 2005
		Krishnan <i>et al.</i> , 2013
		Ramesh <i>et al.</i> , 2014
		Jha <i>et al.</i> , 2011
		Vardhan <i>et al.</i> , 2012
		Vousden, 2001
		Sarkar & Ghosh, 2013
	Coral disease	Ravindran <i>et al.</i> , 1999
		Ramesh <i>et al.</i> , 2014
	Microbiology and Biotechnology	Swarnakumar <i>et al.</i> 2008
		Rao <i>et al.</i> , 1994
Porto novo	Biodiversity and ecology	Ramaiyan & Adiyapatham, 1985
Lakshadweep	Biodiversity and ecology	Anand & Pillai, 2003
		Anand & Pillai, 2005
		Anand & Pillai, 2007
		Desai <i>et al.</i> , 2003
		Dhargalkar & Shaikh, 2000
		George, 2008
		Goswami & Goswami, 1983
		Harithsa <i>et al.</i> , 2005
		Jeyabaskaran, 2009
		Mohammed, 2000
		Nobi <i>et al.</i> , 2009
		Nobi & DineshKumar, 2014
		Suresh, and Mathew, 1995
		Venkatesh <i>et al.</i> , 2008
		Yadav <i>et al.</i> , 2016
		Pillai, and Jasmine, 1989
		Pillai, 1971
		Pillai, 1986
		Pillai, 1996
		Sreenath <i>et al.</i> , 2015
		Gad, 2008
		Ravindran <i>et al.</i> , 2014
		Anand, and Pillai, 2002
	Coral bleaching and other threats	AjithKumar & Balasubramanian, 2012
		Anu, and Nair,, 2008

		Arthur <i>et al.</i> , 2005
		Arthur, 2002
		Arthur <i>et al.</i> , 2006
		Dhaneesh <i>et al.</i> , 2009
		Rodrigues, 1996
		Netramani, 2016
		Masood <i>et al.</i> , 2014
		Thomas, 1988
		Ramar <i>et al.</i> , 2012
		Wallace <i>et al.</i> , 2007
		Bhandari & Sharma, 2010
	Coral disease	Thangaradjou <i>et al.</i> , 2016
		Ravindran & Raghukumar, 2006 , a, b, c
		Ravindran <i>et al.</i> , 2001
	Microbiology and Biotechnology	Feby, and Nair, 2010
		Parameswaran <i>et al.</i> , 1989
		Raghukumar & Raghukumar, 1991
		Raghukumar <i>et al.</i> , 2003
		Raghukumar & Balasubramanian, 1991
		Raveendran <i>et al.</i> , 2011
		Sarma <i>et al.</i> , 1995
		Sarma & Rao, 2005
	GIS	Chauhan and Nayak, 2005
Indian Reef	Biodiversity and ecology	Hoon, 1997
		Venkataraman, 2004
		Rajan <i>et al.</i> , 2011
		Wafar, 1986
		Wolstenholme & Venkataraman, 2003
		Kingston & Ramadhas, 2005
		Pillai, 1983
		Apte, 2012
		Muley <i>et al.</i> , 2000
		Balasubramanian & Khan, 2001
		Scheer, 1999
		Wallace & Paul, 2005
		Venkataraman <i>et al.</i> , 2003
		Ramaiyan, 1995
		Venkataraman, 2004
	Coral bleaching and other threats	Wilhelmsson <i>et al.</i> , 2005
		Kannan <i>et al.</i> , 2006
		Pet-Soede <i>et al.</i> , 2000
		Vivekanandan, 2008
		Vivekanandan, 2009
		Sridhar <i>et al.</i> , 2012
		Sheppard, 2003
	Coral disease	Ravindran & Raghukumar, 2012
		Raghukumar & Ravindran, 2012
	Microbiology and Biotechnology	Sarma <i>et al.</i> , 2009
		Senthil Kumar <i>et al.</i> , 2011
	GIS	SAC, 1997
		SAC, 2033
		SAC, 2010
		Bahuguna & Nayak, 1998
		Nayak & Bahuguna, 1998
		Nayak & Bahuguna, 2008

Coral reef microbiology and biotechnology

Coral reefs harbour great microbial diversity in terms of both prokaryotes and eukaryotes³⁰. Bacterial strains isolated from different intracellular niches of corals including the surface mucus layer³¹, tissues³² and coral skeleton³³. Some of the key roles studied so far

that microbes play in healthy functioning of coral holobiont includes – conferring immunity to the coral host and protecting it against pathogenic and invasive microbes by producing range of antibiotics³⁴ and quorum sensing inhibitory molecules³⁵, providing nutrients to corals and their photosynthetic algae, essential

for their survival and growth in oligotrophic waters by nitrogen fixing³⁶, sulphur³⁷, phosphate³⁸ and such nutrient recycling and reusing.

As far as Indian research is concerned, apart from some scanty reports so far there is not much systemic research done on this emerging new area of coral reef microbial biology and ecology³⁹. Feby and Nair, 2010⁴⁰ studied sponge-associated culturable bacteria from coral reefs of Lakshadweep. Badhai *et al.*, 2013⁴¹ studied culturable bacteria isolated from the mucus of coral *Fungia echinata* and found bacteria within the gamma proteobacteria cluster, they also detected antibiotic resistance genes in many of the studied bacteria. Kannapiran and Ravindran, 2012³⁸ studied phosphate producing bacteria and inorganic phosphate stabilizing bacteria associated with the corals of GoM. Chellaram *et al.*, 2011⁴² investigated on corals *Acropora formosa* and *Favia palida* from Tuticorin for antagonistic activity of associated bacteria against commonly occurring bacteria including human pathogens and found that many of the coral-associated bacteria have antagonistic or inhibitory effects against many human pathogens. Ravindran *et al.*, 2001⁴³ found that fungi are a regular part of the coral with a potential role as bioeroders of calcium carbonate skeletons.

Now briefly visiting the dark side of microbes, emerging coral diseases are one of the serious threats implicated in extensive reef deterioration. Most of the world's coral reefs have been experiencing unprecedented increases in coral diseases since the 1980s. Rohwer and Youle, 2010⁴⁴ suggested that direct (nutrient enrichment, overfishing) and indirect (global climate change associated bleaching) anthropogenic problems are lowering disease resilience in corals. Looking at Indian reefs, as early as the 1990s, Raghukumar & Raghukumar, 1991⁴⁵ reported necrotic patches in five out of seven coral species examined in Andaman islands; caused by a fungal pathogen, identified as *Scolecobasidium* sp. Thinesh *et al.*, 2011⁴⁶ reported coral disease prevalence in PB (21%) is higher than GoM (8.9%), in PB, the spreading rate of Black Band Disease (BBD) was found to be 3.0 cm/ month and author suggested that it was linked with sewage waters and dumping of unwanted trash directly into the reef environment. Ravindran and Raghukumar, 2002⁴⁷ reported occurrences of Pink Line Syndrome (PLS) in the *Porites lutea* from the

Kavaratti reef, caused partial mortality and has affected about 10% of the colonies where the dead patches were found to have colonised by a cyanobacterium identified as *Phormidium valderianum*. Babu *et al.*, 2004⁴⁸ did molecular identification of bacteria, isolated from the coral tissues from GoM by using 16S rRNA sequences. More recently, Raj *et al.* 2016⁴⁹ noted mass mortality of *Montipora digitata* (Scleractinia) in Vaan Island, GoM by Black band disease (BBD) caused by a consortium of cyanobacterium (*Phormidium corallyticum*) and other bacteria. Knowing the fact that a vast number of microbes in an environment, the majority of them cannot be cultured at all under lab conditions. Hence, powerful and revolutionary techniques such as metagenomics, DGGE (Denaturing gradient gel electrophoresis), stable isotope probing, FISH (Fluorescent in-situ hybridisation) should be applied in most of the investigations attempting to understand diversity, distribution, and roles in the reef ecosystem. However, considering the imminent threat of coral disease outbreaks worldwide by climatic stressors and pollution, Indian corals are not in exception of the high risk of disease susceptibility by frequent bleaching event and local human activity, research on coral disease microbiology is still sparse and should be set as priority for prevention of disease impact.

Coral reef fauna such as soft corals, sponges, ascidians, molluscs, and bryozoans are the source of plentiful and structurally unique bioactive products with the potentiality of medical and industrial applications⁵⁰. Steroids are among the various classes of secondary metabolites produced by a range of hard and soft corals⁵¹. Marine fungi isolated from soft corals and sponges, collected from Mandapam coast (Tamil Nadu) were screened for protease activity – an enzyme having wider industrial applications⁵². Parvatkar *et al.*,⁵³ isolated and studied butenolides secondary metabolites, Aspernolides A & B from the marine fungus *Aspergillus terreus* which was collected from a soft coral *Sinularia kavarattiensis* from Mandapam coast and reported that Aspernolide A is acytotoxic and anticancer agent. Devi *et al.*,⁵⁴ tested eleven species of soft corals collected from the Lakshadweep and the coast of Mandapam for antispasmodic, anti-arrhythmic and oxytocin activity and reported that many of those showed antispasmodic and oxytocin like activity. Mol *et al.*,^{55,56} extracted a

sesquiterpene bioactive compound from *Simularia kavartiiensis*, and *Cladiella krempfi* abundant in the GoM and Lakshadweep Islands and was reported as anti-inflammatory and was found to have antifouling properties as it inhibited larval settlement and moderately inhibited the growth of biofilm producing bacteria and barnacles' larvae. Raghukumar *et al.*, 2006⁵⁷ screened marine fungus NIOCC#312 from decaying seagrass from Lakshadweep for removal of polycyclic aromatic hydrocarbons from the aqueous culture medium. Chellaram *et al.*, 2011⁵⁸ found antagonistic activity of bacterial strains against the pathogens isolated from *Acropora formosa* and *Favia palida* from Tuticorin. Sarma *et al.*, 2009⁵¹ reviewed researches on marine metabolites extraction from soft corals, and acknowledged contribution of Indian researchers (for detailed information Sarma *et al.*, 2009 and references herein). Although, it is challenging to transform this understanding into feasible technology, that can reproducibly yield secondary metabolites of therapeutic use⁵⁰. Although there are a few reports on extraction of the bioactive compound from corals and associated biota from India, however, research on coral reef biotechnology is in a relatively undeveloped state and should be a priority for future research.

Climate change and reefs in crisis

Globally, coral reefs throughout the tropics have been progressively damaged in the last century by a broad range of intrinsic and extrinsic factors, like direct human perturbation, overexploitation of resource, physical damage, pollution, terrigenous sediment and nutrients input from agricultural and urbanized coastline and coastal development^{1, 6, 7}. Additionally, the recent decades have observed worsened ways of climate-change phenomena, i.e. increased seawater temperature, ocean acidification and intensifying extreme weather events that swelled frequency and magnitude of mass coral bleaching.

Coral Bleaching

Coral reefs are highly sensitive and vulnerable to thermal stress, resulting in 'bleaching' events (loss of symbiotic algae) when sea surface temperatures (SST) rise above a threshold⁵⁹. Coral bleaching is 'whitening of coral tissue' because of the partial or complete riddance of zooxanthellae symbiont algae population⁶⁰. Stressors like elevated sea surface temperatures,

higher irradiance, decreased salinity and metal pollution etc. can cause bleaching; nevertheless, the widely concerned prime cause is the elevated sea surface temperatures triggered by increased global warming⁶¹. The number of stress (bleaching) episodes has increased in recent decades which have contributed to the widespread loss of live coral cover. There are several major bleaching events with the associated coral mortality since 1997, affecting more or less all the reefs around the world. Furthermore, the bleaching event of 1997-98 was unprecedented and worst of ever recorded mass bleaching event, affecting almost all reefs of the world including very remote ones⁶¹. In the context of bleaching in Indian reefs, Arthur 2002⁶³ reported 11% coral bleaching with no apparent bleaching-related mortality from GoK, 82% coral bleaching and 26% bleaching related mortality from Lakshadweep and 89% coral bleaching, and 23% bleaching related mortality from GoM; during April to July 1998. Even after four years of the bleaching event, Arthur *et al.*, 2005⁶³ found relatively low live coral cover on most atolls in Lakshadweep. Harithsa *et al.*, 2005⁶⁴ noted temperatures beyond the bleaching threshold in the region of Kavaratti atoll, Lakshadweep during April-May 2002 with consequent coral bleaching. Ajith Kumar and Balasubramanian, 2012⁶⁵ reported an average of 76.5% coral bleaching Agatti reefs during May to June 2010. Ravindran *et al.*, 2012⁶⁶ studied how coral bleaching prevalence in combination with other stressors are destroying reefs of PB at an alarming rate. They reported that elevated sea surface temperature in combination with increased irradiance caused coral bleaching in PB during April 2010. Marimuthu *et al.*, 2013⁶⁷ and Krishnan *et al.*, 2013⁶⁸ reported severe bleaching events in the Andaman Islands during the same bleaching event of 2010 due to elevated sea surface temperature. PB witnessed extensive bleaching (~50-60%) in April-June 2002 possibly due to elevated SST and failure of South-West monsoon winds during this period⁶⁹. Coral reefs in GoM and PB were again devastated by another round of bleaching in April-May, 2010 leading to 85.1 % and 87.2% bleaching respectively⁷⁰. According to Adhavan *et al.*, 2014⁷¹, GoK witnessed bleaching in 2014-2015 possibly due to combined influence of elevated SST, sedimentation, and delayed monsoon. De *et al.*, 2015⁷² reported the occurrence of coral bleaching in the Malvan marine sanctuary (MMS) due to elevated sea

surface temperatures (SST). It is expected that SST to increase by 1-2°C over the next century and even this much of change in global climate may increase the incidences of mass coral bleaching like 1998 one⁶¹. There is little evidence of recovery of corals in South Andaman Islands, following the bleaching event of 2010⁶⁷. Based on satellite-derived SST data, Indian National Centre for Ocean Information Services (INCOIS), has launched the Coral Bleaching Alert System (CBAS) for major Indian coral reefs since 2011, which would aid the concern stakeholders for better management paradigm during or after coral bleaching events (for details kindly find <http://www.incois.gov.in/portal/coralwarning>). Meanwhile, 2015-2016 has been reported as global coral bleaching year, and bleaching phenomena were observed in most of the coral reefs around the globe due to the extreme El Niño, in the context of Indian reefs, primary observation on coral bleaching is reported from A&N during April 2016 by INCOIS⁷³. It is pitiful to realize that in spite of having around 3000 km² of coral reef area and knowing the fact that Indian reefs are severely impacted by coral bleaching⁷⁴, only a handful study could be found from Indian reefs that have investigated the impact of coral bleaching on reef ecosystem, recovery rate and resilience of Indian reefs.

Ocean acidification

Human activities have increased atmospheric concentrations of carbon dioxide (CO₂) by 36% and the pH of ocean surface waters has already declined by about 0.1 units, 8.2 to 8.1, since the beginning of the industrial era⁷⁵. The CO₂ taken up by the ocean decreases the pH and concentration of carbonate ions, leads to a combination of chemical changes collectively known as ocean acidification⁷⁶. The effect of elevated pCO₂ on coral has received particular interest^{77,78} because calcification rates in corals (which secrete a form of Calcium carbonate, known as aragonite) decline under increased pCO₂ environment. It may result in declining future coral cover and degradation of the reef biodiversity⁷⁸. Langdon *et al.*⁷⁹ predicted that coral calcification rates may decrease by 21–40% over the period 1880–2065 in response to changes in atmospheric CO₂ concentrations. Based on the amount of coral reef that has died in the Caribbean in the past few years, studies predicted that over 60% of the earth's coral reefs will be lost by the next thirty years if global

warming continues unchecked⁸⁰. Therefore, it is critical to understand how the air-sea exchange of CO₂ and seawater carbonate chemistry regulates calcification and potential dissolution of coral and associated calcifying organisms. Unfortunately, till now very little is known about the impact of ocean acidification on Indian coral reef systems and there is an urgent need to improve large gap in our knowledge on the impact of acidification on reef ecosystem structure and functioning.

Threats, conservation, and management

On a global scale, overall diminishing of coral reef ecosystems is appalling. Therefore, raising concern for the coral reef is thrusting the need for an intensive study to ensure successful conservation management all over the world. Like other parts of the world, Indian reefs are also in huge peril. Not only consumerist anthropogenic impacts on coral reefs have augmented dramatically for various reasons since the last century, but the global climate change is also scratching in Indian coral reefs as well. By the end of the previous century, except reefs of the A&N Islands, hardly any reefs of mainland India were pristine. However, islands of A&N are also facing multiple challenges to protect their natural resources and for resilience. Therefore, immediate identification, understanding and proper addressing of the current threats is needed for protection and better management of this fragile ecosystem.

Coral disease: Emergence of different epidemic diseases including 'White plague', 'White pox', 'White band', and 'Black band' causes extensive damage to the reef. Recently, a prevalence of white band, white pox, white plague, pink line, pink spot, yellow band, fungal blotch, black band, narcotic patches were reported from GoM, and Lakshadweep Islands⁸¹. Ramesh *et al.*, 2014⁸² reported occurrences of yellow spot disease, pink line syndrome, white line syndrome, white plague and black band diseases during a survey in Andaman Islands. Recently, Abey *et al.*⁸³ recorded the first occurrence of coralline lethal orange disease (CLOD) from GoM, pathogenesis of this disease yet to be studied. Hussain *et al.*, 2016⁸⁴ first time reported skeletal tissue growth anomalies in foliose coral *Turbinaria mesenterina* from the Malvan marine sanctuary and emphasised on the further etiological study of this disease.

Reef fishing: Illegal and destructive fishing practices are also responsible for such type of

damage. Many banned malpractices like blast fishing are still going on in many coral reef regions like the GoM which is believed to be massively damaged and destroyed reef region of India²². Overfishing cause the removal of herbivorous fishes that encourages excessive algal growth in the absence of these grazers. In such a way coral reef ecosystem is shifted to algal dominated barren without any fish and corals. As a result, there is a recent report on the dominance of fleshy macro-algae and loss of live coral cover in GoM⁸⁵. Therefore, if the present scenario persists unchanged many Indian known and unknown reefs may shift into algal dominated barren.

Extreme natural events: There is a range of natural calamities causing the immense destruction of corals includes cyclone, local tectonic upheavals, tsunami. After the 26th December 2004 tsunami, Ramachandran *et al.*, 2005⁸⁶ recorded 41-100% damage in Nicobar Islands and Kumaraguru *et al.*, 2005⁸⁷ reported severe coral damage in GoM and PB. Therefore, updated study needed to understand present status and recovery of corals after such natural perturbation.

Bio-invasion: Introduction of invasive species in Indian reefs is another emerging threat to indigenous reef biodiversity. Bio-invasion of macroalgae *Kappaphycus alvarezii* and its detrimental impact on reef corals in the GoM has been reported by several studies^{88, 89} and recent reports on bio-invasion of snowflake octocoral *Carijoa riisei* from different part Andaman and Nicobar Island, GoK, GoM and Goa (Venkataraman *et al.*, 2016⁹⁰ and references herein) heighten urgent need for more investigation on impact of invasive species in Indian reefs.

Pest, predator, and competitor: Outbreak of coral eating Crown of Thorns Starfish *Acanthaster planci* reported from Andaman Islands⁹¹. Also, overgrowth of bio-eroding coral boring sponges recorded in GoM⁹², and in MMS (personal observation).

Reef tourism: Uncontrolled tourism may cause major problem responsible for degradation of Indian reefs. Tourists hanging out, swimming, snorkeling and diving in unmanaged areas results in significant damage to shallow water corals by unintentionally or intentionally trampling and breaking coral fragments. Additionally, there is a finding on severe reef damage from Andaman Islands by tourist

activity⁹¹. Furthermore, anchoring of tourist boats can also cause coral damage (Fig. 3, personal observation in MMS). Hence, regular impact assessment of recreation activity on reef ecology is needed to adopt sustainable tourism practice.



Fig 2: Damage coral *Turbinaria mesenterina* by recreational dive boat anchoring

Illegal harvesting: The illegal collection of shells for souvenir hunting, uncontrolled harvesting, smuggling various exotic marine organisms and products derived from the reef is still major problem for Indian reefs. Jeyabaskaran *et al.*, 2007⁹¹ mentioned poaching as a severe problem in A&N coral reefs. In past, coral mining for cement industries affected different reefs in GoM⁹³, still illegal fishing, the collection of shells and sea cucumbers continue from these reef⁹⁴.

Other human impacts that arise through land runoff/siltation, waste disposal, shipping and other pollution related activities is of pollution which is a widespread and well-known problem for coral reefs globally and therefore, studies are necessary on these aspects.

Conservation of Indian coral reefs is enforced under the Wild Life (Protection) Act (WLPA) 1972, Marine Fishing Regulation Act (MFRA) 1983, 2000 and the Coastal Regulation Zone (CRZ) Notification, 2011; under which coral reefs of India are protected by law. There are total 31 Marine Protected Areas (MPAs) in India among them five coral reef regions have been surveyed and identified for protection. Pillai, 1996¹¹ recommended halting all human intervention and malpractices that are responsible for mechanical damage and removal of corals and bringing numerous marine organisms except for scientific research.

Recent research on implementation of environmental engineering approaches of the ontogeny of artificial reef restoration methods such as transplantation and underwater silviculture has been widely heightened as a management practice in damaged or degraded coral reefs⁹⁵. To replenish the degraded coral reef regions in the Lakshadweep Islands, Venkatesh *et al.*, 2008⁹⁶ successfully accomplished transplantation of *Acropora* spp. and *Pocillopora* spp. on artificial metal frames placed on a sandy bottom in the degraded lagoon. They noted 90% survival and the establishment of associated fauna such as fish along those transplants. Based on this experience, they suggested that such re-introduction of species is the practical and cost effective strategy for conserving the degraded areas. Raj *et al.*, 2015⁹⁷ reported enhanced live coral cover and reproduction success after the coral transplantation in 2004 in the Vaan Island, GoM. Moreover, these success stories of coral transplantation for rehabilitation of degraded coral sites should be carried forward in coming years.

No doubt, the focus, particularly in developing countries is in food production and economic growth whereas conservation of biodiversity is either ignored or is not the priority. Likewise, most of the outcomes of several scientific events on management and conservation Indian coral reefs remain in paper only⁹⁸. Fortunately, realizing this problem; efforts have been put forward for conservation and management of rich coral resources by different agencies of Govt. of India, research institutes, universities, and non-profit organizations (NGO). Implementation of robust laws, appropriate management approaches, pursue of conservation strategies, and sustainable exploitation of biological resources, modern technology, expert marine biologists and indispensable further scientific research are crucial in fulfilling this goal. Acknowledging the gigantic impact of immediate remediless global climate change on coral reefs, management scheme should be focused to put utmost effort to curb local anthropogenic perturbation like overexploitation and pollution of the reef systems. However, long-term conservation policies with a goal of awareness creation through educational experience and sense of ownership may be the most impactful and can bestow on the local population.

Conclusion

Intensive studies on the ecology of Indian coral reef is the need of the hour not only to avoid extreme risks of destruction by different stressors of these fascinating ecosystem but, to sustain the aimed economic growth of millions of people and industries which depend on the coral reef ecosystem. However, there are many challenges, political back up, scientific knowledge, integration and positive alliance among the central government organization, state departments, NGOs, scientists, educators are essential for the betterment of the situation. Hopefully, since last few years' encouragement by different agencies of Govt. of India with research grants and as well as immense interest among students and scientific community promising a ray of light on coral reef research. Research on coral reefs in India increased significantly over the last three decades which is definitely a bright sign in spite of all the hardships. Future directions should be set up accordingly to meet these challenges. Thus, the revival of the National Coral Reef Research Institute in the A&N, and a dedicated National Level 'Coral Reef Research' program with a well thought objective could provide a platform for young and enthusiastic researchers to study and manage this vital natural resource.

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References

1. Ove Hoegh-Guldberg, Coral reef ecosystems and anthropogenic climate change, *Reg. Environ. Chang.*, 11 (2011), 215-227.
2. Cantin, N.E., Cohen, A.L., Karnauskas, K.B., Tarrant, A.M., McCorkle, D.C., Ocean warming slows coral growth in the central Red Sea, *Science*, 329 (2010), 322-325.
3. Albright, R., Mason, B., Langdon, C., Effect of aragonite saturation state on settlement and post-settlement growth of *Porites astreoides* larvae, *Coral Reefs*, 27 (2008), 485-490.
4. Pratchett, M. S., Hoey, A. S., Wilson, S. K., Reef degradation and the loss of critical ecosystem goods and services provided by coral reef fishes, *Curr. Opin. Environ. Sustain.*, 7 (2014), 37-43.
5. Gardner, T. A., Côté, I. M., Gill, J. A., Grant, A., Watkinson, A. R., Long-term region-wide declines in Caribbean corals, *Science*, 301 (2003), 958-960.
6. Côté, I.M., Gill, J.A., Gardner, T.A., Watkinson, A.R., Measuring coral reef decline through meta-

- analyses, *Phil. Trans. R. Soc. B. Biol. Sci.*, 360 (2005), 385–395.
7. De'ath, G., Fabricius, K.E., Sweatman, H., Puotinen, M., The 27-year decline of coral cover on the Great Barrier Reef and its causes, *Proc. Natl. Acad. Sci. USA*, 109 (2012), 1795–1799.
 8. Bahuguna, A., Ray Chaudhury, N., Bhattji, N., Ajai, Navalgund, R. R., Spatial inventory and ecological status of coral reefs of the Central Indian Ocean using Resourcesat-1, *Indian J. Mar. Sci.*, 42 (2013), 684-696.
 9. SAC., *Coral Reef Atlas of the World. Vol. I Central Indian Ocean.* (SAC-ISRO, Govt. of India), 2010
 10. Nair, R.R., Qasim, S.Z., Occurrence of a bank with living corals off the south-west coast of India; short communication, *Indian J. Mar. Sci.*, 7 (1978), 55-58.
 11. Pillai, C.S.G., Coral reefs of India, their conservation and management, in: *Marine Biodiversity: Conservation and management*, edited by N. G. Menon, C. S. G. Pillai, (CMFRI, Cochin) 1996, 16-31.
 12. Qasim S.Z., Wafer M.V.M., Occurrence of living corals at several places along the west coast of India, *Mahasagar*, 12 (1979), 53-58.
 13. Vora K.H., Almeida F., Submerged reef systems on the central western continental shelf of India, *Mar. Geol.*, 91 (1990), 255-262.
 14. Manikandan, B., Ravindran, J., Mohan, h., Periasamy, R., Mani Murali R., Ingole, B. S., Community structure and coral health status across the depth gradient of Grande Island, Central west coast of India, *Reg. Stud. Mar. Sci.*, 7 (2016), 150-158.
 15. Zacharia, P. U., Krishnakumar, P. K., Dineshbabu, A. P., Vijayakumar, K., Rohit, P., Sujitha Thomas, S., Sasikumar, G., Kaladharan, P., Durgekar, R. N., Mohamed, K. S., Species assemblage in the coral reef ecosystem of Netrani Island off Karnataka along the southwest coast of India, *J. Mar. Biol. Ass. India*, 50 (2008), 87 – 97.
 16. Ingole BS et al, Monograph of Coral and Associated fauna from the Angrai Bank, Tech, Rep,2016 Ramaiyan, V., Adiyapatham, S., Studies on the systematics of coral fishes from Porto Novo. In: Proceedings of the 5th International Coral Reef Congress, edited by C Gabriele, J L Toffart & B Salvat (Antenne Museum-EPHE, Tahiti, French Polynesia), 1985, 314.
 17. CMFRI, 2015. Annual Report 2014-15. Central Marine Fisheries Research Institute, Cochin, pp 206, Retrieve on 11 December 2016 from <http://eprints.cmfri.org.in/10461/1/CMFRI%20Annual%20Report%202014-15.pdf>.
 18. Annon, 2016, Remotely operated vehicle (ROV) developed by National institute of Ocean Technology (NIOT), Ministry of Earth Sciences maps the coral reef in Andaman and Nicobar Islands. http://moes.gov.in/writereaddata/files/Andaman_Coral_reefs_mapping_with_ROV_one_page_wri-teup-for_PIB.pdf, accessed on 01.08. 2016.
 19. Rink, H. J. *Die Nikobarischen Inseln. Eine geographische Skizze, mit spezieller Berücksichtigung der Geographie.* (Kopenhagen: H.G. Klein) 1847.
 20. Venkataraman K., Raj Kumar R., Stayanarayan Ch., *Fauna of the ecosystem of India: Coral Reefs*, (Zoological Survey of India, Kolkata) 2012, 1-30.
 21. Venkataraman K., Satyanarayana Ch, Alfred JRB, Wolstenholme J., *Handbook on Hard Corals of India*, (Zoological Survey of India, Kolkata) 2003, 1-266.
 22. Raghuraman R, Raghunathan C, Venkataraman K, Present Status of Coral Reefs in India. In: *Ecology and Conservation of Tropical Marine Faunal Communities*, edited by K. Venkataraman, C. Sivaperuman, C. Raghunathan, (Springer-Verlag Berlin Heidelberg) 2013, 351-379.
 23. Raghuraman R., Sreeraj C R, Raghunathan C, Venkataraman K, Scleractinian coral diversity in Andaman Nicobar Island in comparison with other Indian reefs, in: *Marine Biodiversity: One Ocean- Many worlds of life*, (Uttar Pradesh State Biodiversity Board, Lakhnow) 2012, 75-92.
 24. Rodrigues, C., *Taxonomic and Ecological survey of the Lakshadweep for Perumal Par Marine Park - Project Completion Report*, Goa University, 1996.
 25. Edward J K P, Mathews G, Patterson J, Ramkumar R., Wilhelmsson D, Tamellander J, Linden O, Status of Coral Reefs of the Gulf of Mannar, South eastern India, in: *Ten years after bleaching facing the consequences of climate change in the Indian Ocean. CORDIO Status Report*, edited by D O Obura, J, Tamellander & O Linden, (Coastal Oceans Research and Development in the Indian Ocean/Sida-SAREC. Mombasa) 2008.
 26. Rajan P T., Sreeraj C R, Fish fauna of Andaman and Nicobar Islands: a review, in: *Ecology and Conservation of Tropical Marine Faunal Communities*, edited by K. Venkataraman, C. Sivaperuman & C. Raghunathan, (Springer Berlin Heidelberg) 2013, pp 231-243
 27. Kumar J S, Geetha S, Sornaraj R, Diversity and Distribution of Reef Fishes in Gulf of Mannar Islands, India, in : *Ecology and Conservation of Tropical Marine Faunal Communities*, edited by K. Venkataraman, C. Sivaperuman & C. Raghunathan, (Springer Berlin Heidelberg) 2013, 297-310.
 28. Thomas, S., Sreeram, M.P., Kakati, V.S., Manisseri, M.K., George, R.M., Coral fish diversity in Netrani waters off Murudeshwar, Karnataka, south India, *Indian J. Fish*, 58 (2011), 45-51.
 29. Koren, O., Rosenberg. E., Bacteria associated with mucus and tissues of the coral *Oculina patagonica* in summer and winter, *Appl. Environ. Microbiol.*, 72 (2006), 5254–5259.
 30. Ritchie K B., Smith G W, Microbial communities of coral surface mucopolysaccharide layers, in: *Coral health and disease*, edited by Rosenberg E & Loya Y, (Springer, New York) 2004, 263–269.
 31. Ceh, J., Keulen, M.V., Bourne, D.G., Coral associated bacterial communities on Ningaloo Reef, Western Australia. *FEMS Microbiol. Ecol.*, 75 (2011) 134–144.

32. Sweet, M.J., Croquer, A., Bythell, J.C., Bacterial assemblages differ between compartments within the coral holobiont, *Coral Reefs*, 30 (2011), 39–52.
33. Rypien, K.L., Ward, J.R., Azam, F., Antagonistic interactions among coral-associated bacteria, *Environ. Microbiol.*, 12 (2010), 28-39.
34. Hunt, L.R., Smith, S.M., Downum, K.R., Mydlarz, L.D., Microbial regulation in Gorgonian corals, *Mar. Drugs*, 10 (2012), 1225-1243.
35. Olson, N.D., Ainsworth, T.D., Gates, R.D., Takabayashi, M., Diazotrophic bacteria associated with Hawaiian *Montipora* corals: Diversity and abundance in correlation with symbiotic dinoflagellates, *J. Exp. Mar. Biol. Ecol.*, 371 (2009), 140–146.
36. Raina, J.B., Dinsdale, E.A., Willis, B.L., Bourne, D.G., Do the organic sulphur compounds DMSP and DMS drive coral microbial associations? *Trends Microbiol.*, 18 (2009), 101-108.
37. Kannapiran, E., Ravindran, J., Dynamics and diversity of phosphate mineralizing bacteria in the coral reefs of Gulf of Mannar, *J. Basic Microbiol.*, 52 (2012), 91–98.
38. Chandramohan, D., Recent advances in marine microbiology: The Indian scenario, *J. Mar. Biotechnol.*, 5 (1997), 73-81.
39. Feby, A., Nair, S., Sponge-associated bacteria of Lakshadweep coral reefs, India: resource for extracellular hydrolytic enzymes, *Adv. Biosci. Biotechnol.*, 1 (2010), 330-337,
40. Badhai, J., Kumari, P., Krishnan, P., Ramamurthy, T., Das, S.K., Presence of SXT integrating conjugative element in marine bacteria isolated from the mucus of the coral *Fungia echinata* from Andaman Sea, *FEMS Microbiol. Lett.*, 338 (2013), 118–123.
41. Chellaram, C., Shreenivasan, S., Anand, T.P., Kumaran, S., Kesavan, D., Priya, G., Antagonistic bacteria from live corals, Tuticorin coastal waters, southeastern India, *Pak. J. Pharm. Sci.*, 24 (2011), 175-181.
42. Ravindran, J., Raghukumar, C., Raghukumar, S., Fungi in *Porites lutea*: Association with healthy and diseased corals, *Dis. Aquat. Organ.*, 47 (2001), 219-228.
43. Rohwer, F., Youle, M., Coral reefs in the microbial seas, in: *The influence of fishing, nutrients, bacteria, viruses & climate change on nature's most wondrous constructs*, Illustrated by Derek Vosten (Plaid Press, USA) 2010.
44. Raghukumar, C., Raghukumar, S., Fungal invasion of massive coral P.S.Z.N.I., *Mar. Ecol.*, 12 (1991), 251-260.
45. Thinesh, T., Mathews, G., Patterson Edward, J.K., Coral disease prevalence in the Palk Bay, south-eastern India – with special emphasis to black band, *Indian J. Geo Mar. Sci.*, 40 (2011), 813-820.
46. Ravindran, J., Raghukumar, C. Pink line syndrome (PLS) in the scleractinian coral *Porites lutea*, *Coral Reefs*, 21 (2002), 252.
47. Babu T G, Nithyanand P, Kannapiran E, Ravi A V, Pandian S K, Molecular identification of bacteria associated with the coral reef ecosystem of Gulf of Mannar Marine Biosphere Reserve using 16S rRNA sequences, in: *Proceedings of MBR 2004 National Seminar on New Frontiers in Marine Bioscience Research*, 2004, 47-53.
48. Raj, K. D., Mathews, G., Bharath, M. S., Edward, J. K.P., Mass mortality of *Montipora digitata* (Scleractinia) in Vaan Island, Gulf of Mannar, southeast India, *Curr. Sci.*, 110 (2016), 1407-1408.
49. Radjasa, O.K., Vaske, Y. M., Navarro, G., Vervoort, H.C., Tenney, K., Linington, R.G., Crews, P., Highlights of marine invertebrate-derived biosynthetic products: Their biomedical potential and possible production by microbial associates, *Bioorg. Med. Chem.*, 19 (2011), 6658 -6674.
50. Sarma, N.S., Krishna, M.S., Pasha, S.K.G., Prakash, Rao, T.S., Venkateswarlu, Y., Parameswaran, P.S., Marine Metabolites: The Sterols of Soft Coral, *Chem. Rev.*, 109 (2009), 2803-2828.
51. Karnat, T., Rodrigues, C., Naik.C.G., Marine-derived fungi as a source of proteases, *Indian J. Mar. Sci.*, 37 (2008), 326-328.
52. Parvatkar R.R., D'Souza, C., Tripathi, A., Naik, C.G., Aspermolides A, B, butenolides from a marine-derived fungus *Aspergillus terreus*, *Phytochemistry*, 70 (2009), 128-132.
53. Devi, P., Jayasree, V., Naik, C.G., Effects of soft Coral Extracts on Isolated Tissues, in: *Proceedings of the National Seminar on New Frontiers in Marine Bioscience Research*, 2004, 41-45.
54. Limna Mol, V.P., Raveendran, T.V., Parameswaran, P.S., Kunnath, R.J., Rajamohan, P.R., (–)-6a-Hydroxy polyanthellin A — A novel antifouling diterpenoid from the Indian soft coral *Cladiella krempfi* (Hickson), *Canadian J. Chem.*, 89 (2010), 57 – 60.
55. Limna Mol, V.P., Raveendran, T.V., Parmeshvaran, P.S., Kunnath, R.J., Sathyan, N., Antifouling Sesquiterpene from the Indian Soft Coral, *Sinularia kavasattienensis* Alderslade & Prita, *Indian J. Mar. Sci.*, 39 (2010) 270-273
56. Raghukumar, C., Shailaja, M.S., Parameswaran, P.S., Singh, S.K., Removal of polycyclic aromatic hydrocarbons from aqueous media by the marine fungus 33 NIOCC#312: involvement of lignin-degrading enzymes and exopolysaccharides, *Indian J. Mar. Sci.*, 35(2006), 373-379.
57. Chellaram, C., Sreenivasan, S., Anand, T. P., Kumaran, S., Kesavan, D., Priya, G., Antagonistic bacteria from live corals, Tuticorin coastal waters, Southeastern India, *Pak. J. Pharm. Sci.*, 24(2011), 175–181.
58. Brown, B.E., Coral bleaching: causes and consequences, *Coral Reefs*, 16 (1997), 129–138.
59. Douglas, A.E., Coral bleaching – how and why? *Mari. Pollt. Bull.*, 46 (2003), 385-392,
60. Hoegh-Guldberg O., Climate change, coral bleaching and the future of the worlds' coral reefs, *Mar. Freshwater res.*, 50 (1999), 839-866,
61. Arthur, R., Coral bleaching and mortality in three Indian reef regions during an El Niño southern oscillation event, *Curr. Sci.*, 79 (2002), 1723-1729.
62. Arthur, R., Done, T. J., Marsh H., Benthic recovery four years after an El Niño-induced

- coral mass mortality in the Lakshadweep atolls, *Curr. Sci.*, 89 (2005), 694-699.
63. Harithsa, S., Raghukumar, C., Dalal, S.G., Stress response of two coral species in the Kavaratti Atoll of the Lakshadweep Archipelago, India, *Coral reefs*, 24 (2005), 463-474.
 64. Ajith Kumar, T. T. and Balasubramanian, T., Bleaching of Corals in Agatti Lakshadweep, India: A window view, in: *Proceedings of the 12th International Coral Reef Symposium*, Cairns, Australia, 2012.
 65. Ravindran, J., Kannapiran, E., Manikandan, B., Murali, R.M., Joseph, A., Bleaching and secondary threats on the coral of Palk Bay: A survey and proactive conservation needs, *Indian J. mar. Sci.*, 41 (2012), 19-26.
 66. Marimuthu, N., Wilson, J.J., Vinithkumar, N.V., Kirubakaran, R., Coral reef recovery status in South Andaman Islands after the bleaching event 2010, *Ocean. Coast. Sea Res.*, 12 (2013), 91-96.
 67. Krishnan P, George G, Immanuel T, Malakar B, Anand A, Studies on the Recovery of Bleached Corals in Andaman: Fishes as Indicators of Reef Health, in: *Ecology and Conservation of Tropical Marine Faunal Communities*, edited by K. Venkataraman, C. Sivaperuman, C. Raghunathan (Springer-Verlag Berlin Heidelberg) 2013, 395-407.
 68. Kumaraguru, A.K., Jayakumar, K., Ramakritinan, C.M., Coral bleaching 2002 in the Palk Bay, southeast coast of India, *Curr. Sci.*, 85 (2003), 1787-1793.
 69. Manikandan, S., Ganesapandian, S., Singh, M., Anand, M., Kumaraguru, A.K., Impact of climate change induced coral bleaching in the Northern part of Gulf of Mannar and Palk Bay, Southeast Coast of India, *J. Biol. Sci.*, 14 (2014), 276-283.
 70. Adhavan, D., Kamboj, R. D., Marimuthu, N., Bhalodi, M. M., Seasonal variation and climate change influence coral bleaching in Pirotan Island, Gulf of Kachchh Marine National Park, Gujarat, *Curr. Sci.*, 107 (2014), 1780-1781.
 71. De, K., Sautya, S., Mote, S., Tsering, L., patil, V., Nagesh, R., Ingole, B., Is climate change triggering coral bleaching in a tropical coral reef at Malvan Marine Sanctuary, west coast of India? *Curr. Sci.*, 109 (2015), 1379-1380.
 72. INCOIS 2016. Coral bleaching status in Andaman. Available on http://www.incois.gov.in/WEBSITE_FILES/CoralReef/CB_Andaman.pdf, accessed on. 26 July 2016
 73. Bhandhari, R.R., Sharma, P.K., UV-B radiation and high light induced oxidative damage in *Phormidium corium* may cause bleaching to associated coral reefs, *Indian J. Mar. Sci.*, 39(3) (2010), 423-428.
 74. Caldeira, K., Wickett, M.E., Anthropogenic carbon and ocean pH, *Nature*, 425 (2003), 365.
 75. Orr, J. C., Fabry, V.J., Aumont, O., Bopp, L., Doney, S.C., Feely, R.A. *et al.*, Anthropogenic ocean acidification over the twenty-first century and its impacts on calcifying organisms, *Nature*, 437 (2005), 681-686.
 76. Marubini, F., Atkinson, M. J., Effects of lowered pH and elevated nitrate on coral calcification, *Mar. Ecol. Prog. Ser.*, 188 (1999), 117-121.
 77. Kleypas, J.A., Buddemeier, R.W., Gattuso, J.P., The future of coral reefs in an age of global change, *Int. J. Earth Sci.*, 90 (2001), 426-437.
 78. Langdon, C., Broecker, W.S., Hammond, D.E., Glenn, E., Fitzsimmons, K., Nelson, S.G., Peng, T.-H., Hajdas, I., Bonani, G., Effect of elevated CO₂ on the community metabolism of an experimental coral reef, *Global Biogeochem. Cycles*, 17 (2003), 1-14.
 79. Cesar, H., Burke L., Pet-Soede, L. The Economics of Worldwide Coral Reef Degradation. 2003. Accessed on 21 December 2016 from https://www.wwf.or.jp/activities/lib/pdf_marine/coral-reef/cesardegradationreport100203.pdf.
 80. Thangaradjou, T., Machendiranathan, M., Ranith, R., Senthilnathan, L., Sasamal, S.K., Choudhury, S.B. Coral disease prevalence in Gulf of Mannar and Lakshadweep Islands, *Indian J. Mar. Sci.*, 45 (2016), 1755-1762.
 81. Ramesh, C.H., Mohanraju, R., Murthy, K. N., Karthick, P., Preliminary survey of diseases in the coral reefs of Burmanallah coast, Andaman's, *Indian J. Mar. Sci.*, 43 (2014), 1972-1976.
 82. Aeby, G. S., Raj, K. D., Mathews, G., Bharath, M. S., Edward, J. K. P., First record of coralline lethal orange disease (CLOD) in the Indian Ocean, *Coral Reefs*, 34 (2015), 1177.
 83. Hussain, A., De, K., Thomas, L., Nagesh, R., Mote, S., Ingole, B., Prevalence of skeletal tissue growth anomalies in Scleractinian coral: *Turbinaria mesenterina* of Malvan Marine Sanctuary, Eastern Arabian Sea, *Dis. Aquat. Org.*, 121 (2016), 79-83.
 84. Machendiranathan, M., Senthilnathan, L., Ranith, R., Saravanakumar, A., Thangaradjou, T., Choudhry, S.B., Sasamal, S. K. Trend in coral-algal phase shift in the Mandapam group of islands, Gulf of Mannar Marine Biosphere Reserve, India, *J. Ocean Univ. China*, 15 (2016), 1080.
 85. Ramachandran, S., Anitha, S., Balamurugan, V., Dharanirajan, K., Vendhan, K.E., Marie Irene Preeti, Divien, Senthil, A. V., Hussain, S.I. Udayaraj, A. Ecological impact of tsunami on Nicobar Islands (Camorta, Katchal, Nancowry and Trinkat), *Curr. Sci.*, 89(2005), 195-200.
 86. Kumaraguru, A. K., Jayakumar, K., Wilson J. J., Ramakritinan, C. M., Impact of the tsunami of 26 December, 2004 on the coral reef environment of Gulf of Mannar and Palk Bay in the southeast coast of India, *Curr. Sci.*, 89 (2005), 1729-1741.
 87. Pereira, N., Verlecar, X. N., Is Gulf of Mannar heading for marine bioinvasion? *Curr. Sci.*, 89 (2005), 1309-1310.
 88. Chandrasekaran, S., Nagendran, N. A., Pandiaraja, D., Krishnankutty, N. and Kamalakannan B., Bioinvasion of *Kappaphycus alvarezii* on corals in the Gulf of Mannar, India, *Curr. Sci.*, 94 (2008), 1167-1172.
 89. Venkataraman, K., Raghunathan, C., Satyanarayana, Ch., Rajkumar, R., Invasion of Snowlake coral, *Carijoa riisei* (Duchassaing and Michelotti, 1860), in Indian seas: threats to coral reef ecosystem. *Indian J. Mar. Sci.*, 45 (2016), 1403-1408.

90. Jeyabaskaran R, Venkataraman K, Alfred J R B, Implications for Conservation of Coral Reefs in the Andaman and Nicobar Islands, India. in: *Proceedings of Third International Tropical Marine Ecosystem management symposium (ITMEMS3)*, Mexico, 2006. Retrieved on 11 November 2015 from http://eprints.cmfri.org.in/6858/1/IB_ITMEMS_3_paper.pdf.
91. Thinesh, T., Jose, A.P., Saqib Hassan, S., Selvan, M.K., Selvin, J., Intrusion of coral-killing sponge (*Terpios hoshinota*) on the reef of Palk Bay, *Curr. Sci.*, 109 (2015), 1030-1032.
92. Venkataramanujam K, Santhanam R, Sukumaran N, Coral resources of Tuticorin (S. India) and method of their conservation, in: *Proceedings of the 4th International Coral Reef Symposium*, edited by E D Gomez, C E Birkeland, RW Buddemeier, R E Johannes, J A Marsh, Jr., R T Tsuda, (Marine Science Center, University of the Philippines, Manila, Philippines) 1981, 259-262.
93. Rajan, R., Satyanarayana, C., Raghunathan, C., Koya, S. S., Ravindran, J., Manikandan, B., Venkataraman, K., Status and review of health of Indian coral reefs, *J. Aqua. Bio Fish.*, 3 (2015), 1-14.
94. Horoszowski-Fridman, Y.B., Brêthes, J.C., Rahmani, N., Rinkevich, B. Marine silviculture: Incorporating ecosystem engineering properties into reef restoration acts. *Ecol. Eng.*, 82 (2015), 201-213.
95. Venkatesh M, Koya S I, Wafar M, Re-introduction and supplementation of species of *Acropora* and *Pocillopora* into the lagoons of Lakshadweep Islands, India, in: *Global re-introduction perspectives, re-introduction case-studies from around the globe*, edited by P Soorae, (IUCN.SSC Re-introduction specialist group, Abu Dhabi) 2008, 1-3.
96. Raj, K.D., Mathews, G., Malleshappa, H., Edward, J.K.P. Reproductive success of restored coral colonies in Vaan Island, Gulf of Mannar, Southeastern India. *Indian J. Mar. Sci.*, 44 (2015), 589-598.
97. George R M, Jasmine S, Scleractinian coral diversity in Indian reefs, their threats and conservation, in: *Summer School on Recent Advances in Marine Biodiversity Conservation and Management*, (CMFRI, Kochi, India) 2015, 33-37, Retrieve on 15 December 2016 from http://eprints.cmfri.org.in/10411/1/06_Rani_Mary_George.pdf