International Journal of Ecology and Environmental Sciences 49: 327-340, 2023
ISSN: 2320-5199 (Online); https://doi.org/10.55863/ijees.2023.2717



*Review*

# Coral Bleaching: Causes, Mechanism, Consequences, Resilience and Preventive Strategies for Mitigation

**TANUSHRI SAXENA[1], ARUNIMA SAHGAL[2,*], RENU GUPTA[2], NEERA MEHRA[1] AND RAJNI ARORA[1]**

[1]*Department of Zoology, Swami Shraddhanand College, University of Delhi, Alipur, Delhi, 110036, India*
[2]*Department of Zoology, Ramjas College, University of Delhi, Delhi, 110007, India*

E-mail: tanushrisaxena@ss.du.ac.in, arunima.sahgal@ramjas.du.ac.in, renu.gupta@ramjas.du.ac.in, neeramehra@ss.du.ac.in, rajniarora@ss.du.ac.in

***Corresponding Author**

**ABSTRACT**

Coral reefs, like the rainforests, are one of the richest ecosystems in terms of diversity of life since they support an estimated quarter of all marine fauna on the Earth. The foundation of this ecosystem is formed of both soft & hard corals besides other invertebrate (sponges, crustaceans, molluscs) and vertebrate (fishes, sea turtles, sharks, dolphins) fauna. However, coral reefs are under constant threat due to anthropogenic climate change, resulting from global warming, causing mass bleaching events all over the World. Coral bleaching is a phenomenon in which the coral polyps expel the symbiotic photosynthetic zooxanthellae present in their tissues and turn white in colour which affects their growth and reproduction. It further proves to be disastrous for marine wildlife across interconnected ecosystems as well as human populations residing near the coastal regions who are dependent on coral reef ecosystems for food, protection and income. This review study aims at determining the hazards of coral bleaching and examining its major causes and consequences. The preventive strategies needed to restore this endangered ecosystem are also explored. Currently, coral restoration efforts involve coral farming, coral relocation and micro fragmentation. There is an urgent need to make a climate change pledge. Attempts should hence be made to decarbonize the economy worldwide and eliminate pollution of all kinds besides adopting sustainable fishing practices. In fact, every stakeholder must be engaged closely in prudent planning so that the reefs can be protected from extinction.

**Key words:** Climate change, Coral reefs, Mass bleaching, Zooxanthellae

## INTRODUCTION

Coral reefs are one of the most diverse and rich ecosystems on the Earth, despite constituting only 1% of total ocean floor. Often called the "Tropical Rainforests of the Sea", coral reefs are ancient and unique ecosystems on the planet exhibiting a rich diversity of marine life. The hard corals, known as hermatypic corals responsible for the formation of coral reefs, predominantly belong to the class Anthozoa. Their existence is generally restricted between 30°N and 30°S latitudes, in tropical and subtropical clear waters and upto a depth of 100 metres only. The optimum temperature range which results in maximum coral growth is 26-28°C. These reefs form a stable biosphere for algae, sponges, crustaceans, molluscs, fish, sea turtles, sea birds etc. About 25% of all known marine species are dependent on the coral reefs for food, habitat and reproduction (Baswapoor and Irfan 2018).

Coral reefs are a marvel of nature and are of immense importance to mankind due to the products and services they offer to human society (Costanza et al. 2014). They provide some of the most essential oceanic services viz., they prevent erosion and flooding; provide habitat, shelter, breeding ground and food to a myriad of marine organisms; supply essential nutrients to marine organisms; fix carbon and nitrogen as well as recycle carbon dioxide between the sea and atmosphere; help in assessing climate change and pollution of coastal areas; and act as "nurseries" for about 25% of marine fishes, a major source of protein (Baswapoor and Irfan 2018). Moreover, they also render many economic services like fishing industry and eco-tourism. A research model estimated annual contribution of USD 36 billion per annum by reefs to global economy, with a net benefit of USD 19 billion from actual "on-reef" tourism and another USD 16 billion from "reef-adjacent" tourism (Brumbaugh 2017). It has been reported that The Great Barrier Reef also generates more than AUD 6.4 billion per annum for the Australian economy along with providing jobs to around 69,000 people (Deloitte Access Economics, 2017). Additionally, corals play an important role in medicinal industry and are used for developing drugs against arthritis, cancer, HIV etc., as bone substitutes in reconstructive bone surgery. They are also a source of raw material for semi precious stones used in jewellery and in construction and cement industry.

However, coral reefs are subjected to constant damage and destruction by both natural and anthropogenic activities. Several factors, such as overfishing and destructive fishing, pollution, global warming, changing ocean chemistry and invasive species, etc. are taking a huge toll on their survival. This destruction is still continuing unabated. According to the World Resources Institute Report 2021, by 2030, most coral reefs are projected to undergo coral bleaching at least twice per decade and possibly every year by 2040. (Burke and Wood 2021) .Another study estimated that 90% of the reefs will be facing this risk by 2030 and nearly all will be wiped out by 2050 (Baswapoor and Irfan 2018). This grave situation warrants immediate attention and action of the entire world.

Among various causes of destruction of reefs, losing zooxanthellae by the corals resulting in their bleaching and thus affecting their growth and reproduction, is considered as one of the primary reasons and an indicator of ailing coral reef. With this backdrop, studying the concept of coral bleaching, its causes, consequences and mitigation assumes great importance and hence prompted us to take up this subject as the objective of the present paper.

Worldwide, coral reefs are present in around 100 countries and territories (Fig. 1). Among these, maximum proportion of reef area is present in Indonesia (18%), Australia (17%), the Philippines (9 %) and Asia and Oceania possess over 80% of the world's coral reefs.

## Mechanism of coral bleaching – A global phenomenon

Coral reefs are subjected to several environmental adversities that can lead to their severe destruction. Among these, coral bleaching is considered one of the major and serious threats where they lose their pigments or symbiotic algae. It is well established that the majority of corals live in a symbiotic

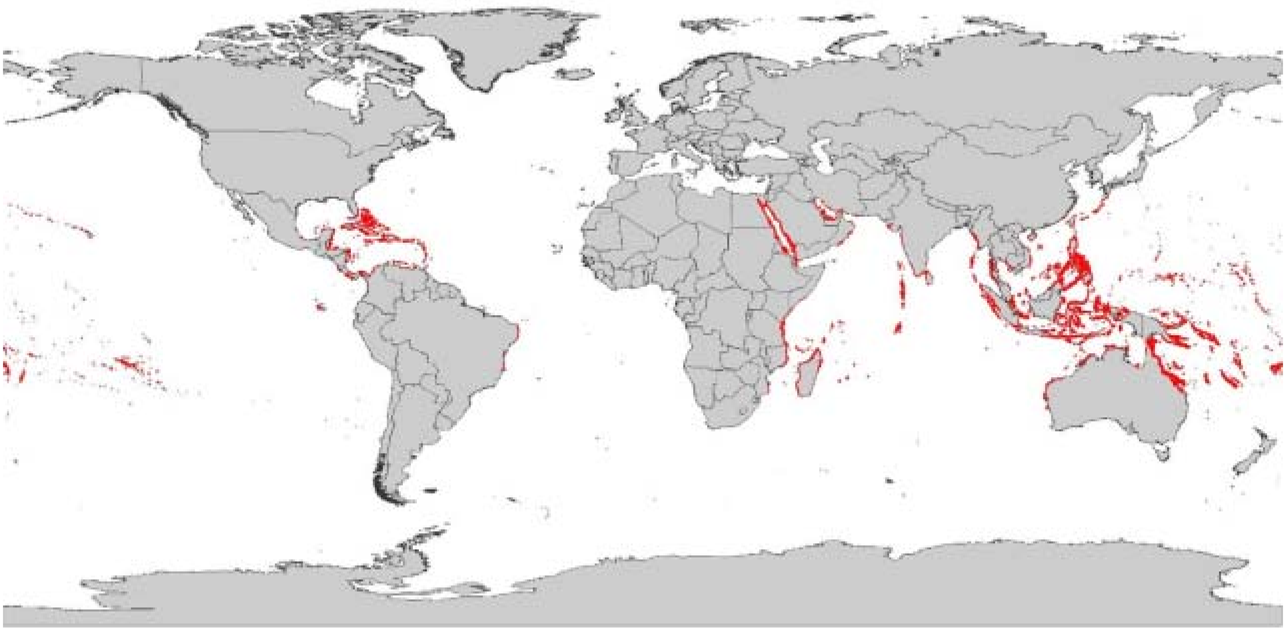

Figure 1. Distribution of coral reefs at the global level (Source: Teh et al. 2013).

relationship with unicellular, dinoflagellate algae of the genus *Symbiodinium*, the zooxanthellae. These microscopic algae impart distinct colour to the corals as well as provide nutrition through photosynthetic process. Other microbiota of coral reefs includes bacteria, fungi, a few protists and viruses.

It has been observed that degradation of the algal pigments due to some physiological stress, especially photo-oxidative stress, exposes the white calcium carbonate skeleton, making the corals appear white or "bleached". Nevertheless, occasional pastel shades of blue, yellow or pink; a phenomenon known as "colourful bleaching"; has also been recorded in bleached corals which is ascribed to the augmented protein synthesis in the absence of zooxanthellae (Dove et al. 2001). According to the oxidative theory of coral bleaching, the damaged photosynthetic machinery in the symbiont produces reactive oxygen species (ROS) which leak into the host cell, affects the antioxidant system and damages the host tissue (Downs et al. 2002).

It has been reported that microbial imbalance and their unhealthy state in the reefs can disrupt their photosynthetic activity and nutrient exchange between corals and their biome partners which interrupts the photosymbiosis causing bleaching (Morrow et al. 2018). The microbial dysbiosis and resultant disruption in the metabolic network can occur quickly even before the appearance of distinctive bleaching symptoms (Bourne et al. 2008). The role of holobiont dysbiosis has been reviewed in coral bleaching proposing three stages (Boilard et al. 2020). According to them, holobionts (Corals with associated microbiota) can change from eubiosis (healthy state) to dysbiosis (unhealthy or disruptive state) depending upon the environmental conditions. They proposed succession of three holobiont stages in coral bleaching, where the microbiota can either

a) Help to maintain holobiont **homeostasis** during stress and/or
b) Promote **adaptive dysbiosis** by employing temperature-resistant Symbiodiniaceae species to fight coral bleaching or
c) Enter a disruptive **dysbiosis state** leading to coral death as a result of breakdown of the cushioning capacity of both the partners under extreme environmental stress. Consequently, dysbiosis can occur when the host (coral) either expels the dinoflagellate partner or by the host's immune system through cell apoptosis, autophagy, exocytosis or necrosis.

Such kind of bleaching, if persists for an extended period, can result in starvation and death of the corals (Fig. 2). Consequent reduction in the surviving corals, initiates a struggle for reproduction leading to the gradual deterioration and collapse of the entire reef ecosystem.

**Coral bleaching events – A global review**

Coral bleaching is a relatively "modern" phenomenon. Prior to 1980, it was barely visible in the world and was considered to be a localised problem due to local stressors. Since then, the intensity of bleaching, in both frequency and severity has increased steadily. The percentage of corals damaged all over the world due to bleaching, has spiraled from 8% per annum in the 1980s to around 31% in 2016. According to National Institute of Oceanography (NIO), moderate to severe damage has been observed in more than 40 countries (Baswapoor and Irfan 2018) (Fig. 3).

The first global coral bleaching event or mass bleaching was reported in 1997-98 during a strong El Niño (Southern Oscillation), followed by an equally strong La Niña phenomenon.It was the longest and most destructive mass bleaching event (Wilkinson 2004). Globally, 16% of reefs were destroyed in the year 1998 itself (Goldberg and Wilkinson 2004). It was succeeded by the next event in 2006, followed by another one in 2015 and since then it has continued unabated. Over the course of this period, more than 70% of the coral reefs throughout the globe, have been hit adversely and are expected to disappear by 2050. (Elias 2018) Further, the gap between one mass bleaching event and the next is also reducing which is a serious cause for concern too.

The classical case of mass bleaching event in the Great Barrier Reef occurred in the years 1998, 2002, 2006, 2016 and 2017 and now a sixth mass bleaching event has been reported as recent as in 2020 (newsday.co.tt/2022/03/24/mass-bleaching-on the great-barrier-reef). Global Coral-Bleaching Database (GCBD) has compiled 34,846 coral bleaching records from 1980–2020 reported from 14,405 sites in 93 countries (van Woesik and Kratochwill 2022).

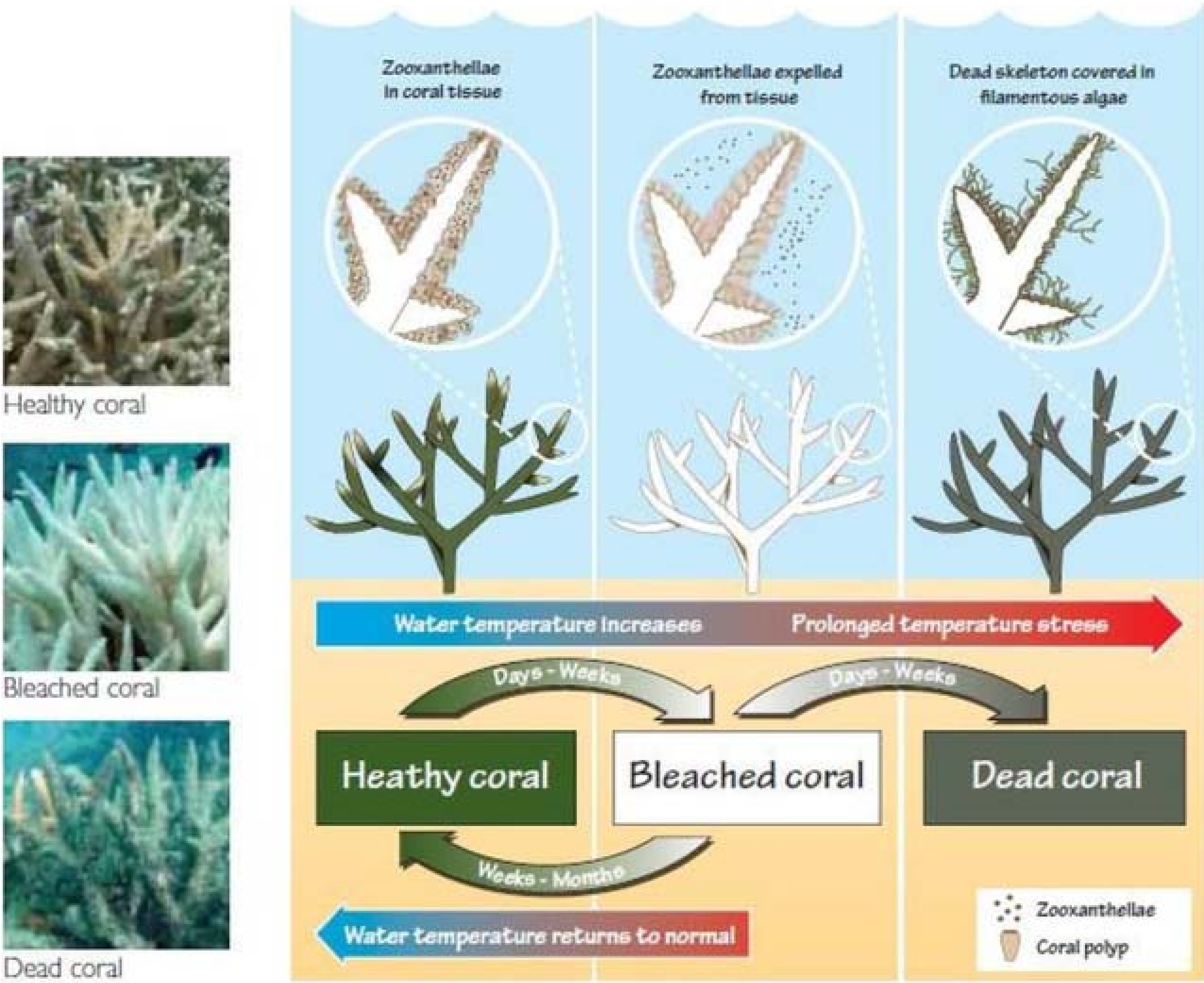


Figure 2. Stages in coral bleaching (Source: Marshall and Schuttenberg 2006).

It provides significant information about the site exhibiting coral bleaching, the site exposure, along with physical parameters such as distance to land, mean turbidity, cyclone frequency, and sea-surface temperature. In 2020, coral bleaching events have been observed around the Hainan Island and the Beibu Gulf from South China Sea spreading over the fringing reef along the Chinese mainland (Lyu et al. 2022). They surveyed 74 sites out of which 81.08% sites were found bleached with 51.14% average bleaching percentage.

The World Resources Institute has observed that about 75% of coral reefs in the Caribbean are also facing grave danger by anthropogenic activities and coastal development. Similar observations have been recorded in Indonesia, Philippines etc. Coral bleaching has also been pronounced in regions viz. South Asia, East Asia, The Pacific, the Western Indian Ocean, The Gulf and Gulf of Oman. Thus, such events have not spared any part of the World. According to the Indian National Centre for Ocean Information Services (INCOIS) 3 mass coral bleaching events have transpired in India; in 1998 and 2010 in Andaman, Nicobar and Gulf of Kutch regions, and in 2016 in Lakshadweep and Gulf of Munnar regions (Arora et al. 2019).

**Causes of coral bleaching – Stress conditions**

Multiple reef stressors, such as erosion, solar radiation, climate change leading to rise in sea surface temperature, presence of pollutants, sedimentation due to deforestation and construction, predation, variable salinity, infections, outbreak of disease and rise in virulence as well as overfishing and destructive fishing etc., have been associated with loss of symbiotic algae by corals leading to

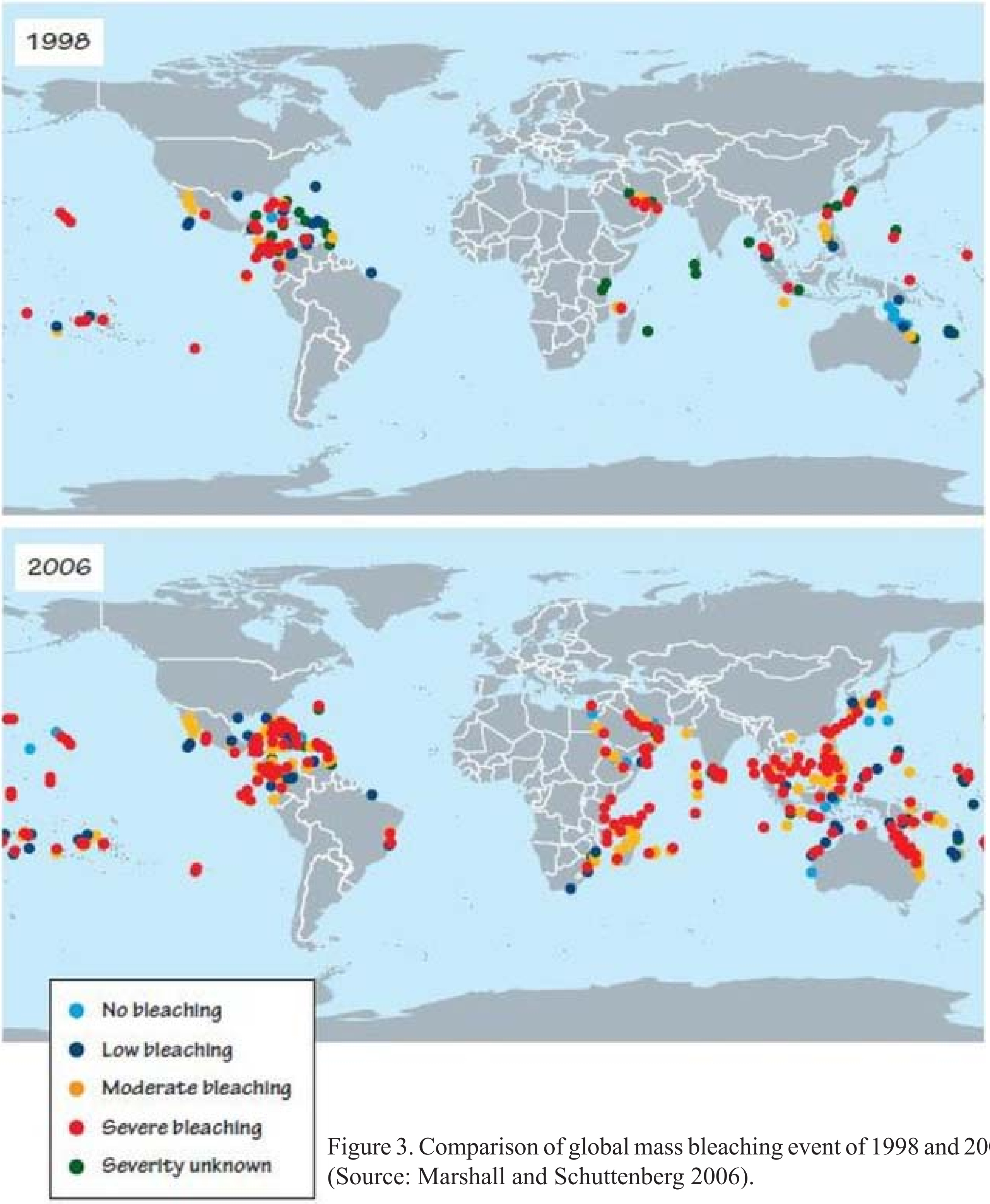


Figure 3. Comparison of global mass bleaching event of 1998 and 2006 (Source: Marshall and Schuttenberg 2006).

bleaching. However, climate change is considered the major cause of coral bleaching. The following factors have been suggested to cause coral bleaching:

*Temperature:*

The occurrence of coral bleaching has been recorded by temperature fluctuations due to rise or drop in temperature of sea surface (Trapido-Rosenthal et al. 2005, IPCC 2018). Increased sea surface temperature accounts for the mass coral bleaching events observed throughout the globe (Fig. 4). Since coral polyps can tolerate only a narrow range of temperature, rise of only 1-2$^{o}$C is sufficient to initiate mass bleaching events. Rising temperature interferes

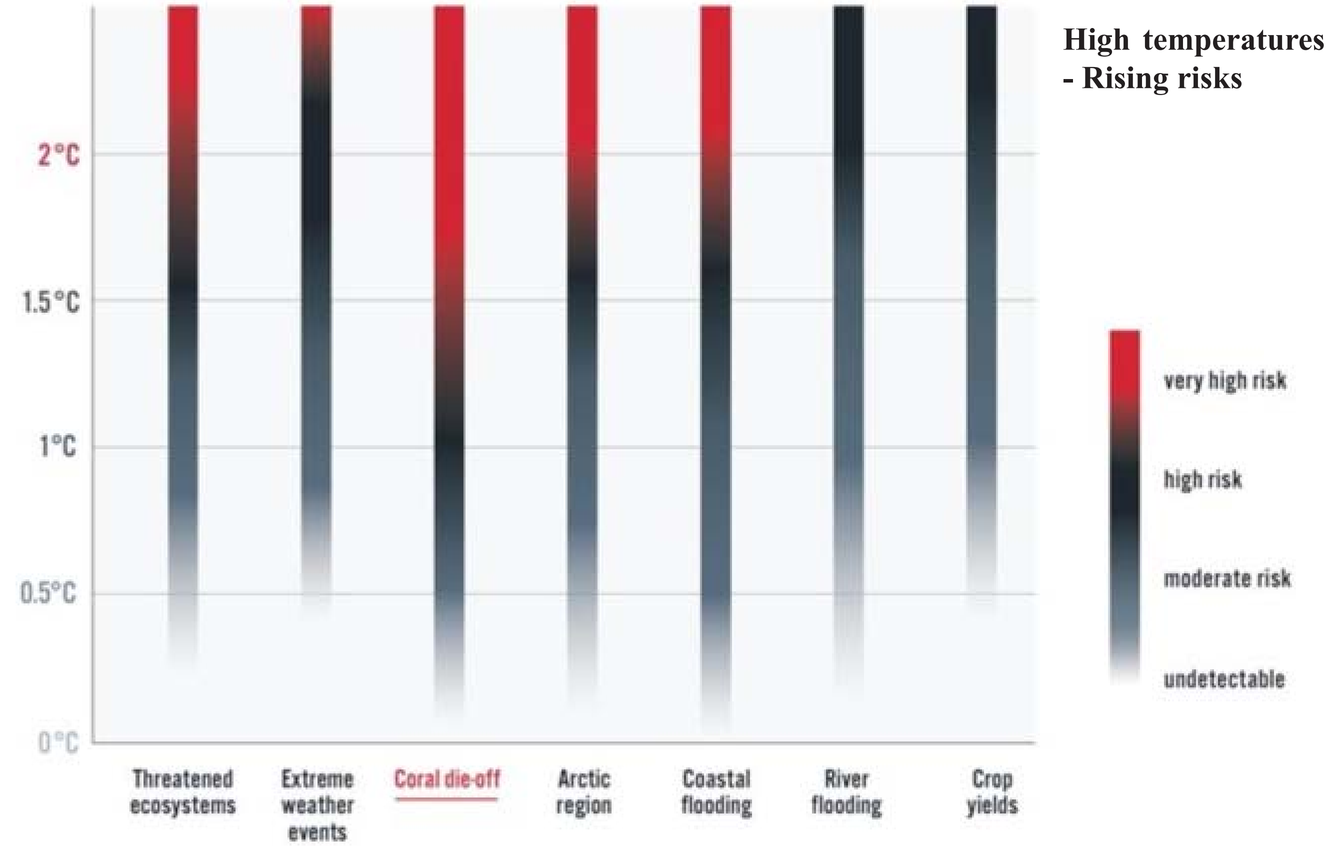


Figure 4. Assessment of level of risk in multiple climate change affected sectors (Source: IPCC 2018).

with the photosynthetic ability of zooxanthellae to process light resulting in the production of reactive oxygen radicals that damage cells and tissues (Takahashi et al. 2004, IPCC 2022). Since corals cannot endure the increased concentration of these poisonous compounds, they get rid of zooxanthellae to prevent destruction of their cells and tissues.

*Turbidity:*

High turbidity in water due to deposit of silt and contaminants reduces the amount of light available to coastal coral reefs, making them more vulnerable to damage and bleaching. Not only this, global warming has also induced threat to the reefs by increased rainfall and changing ocean circulation (Rafferty 2022).

*Rise in sea level*:

Rise in sea level caused by global warming is another reef stressor pushing the corals to deeper water. Consequently, corals do not receive an adequate amount of sunlight required for photosynthesis leading to retarded growth.

Tropical cyclones:

The adverse effects of high frequency tropical cyclones and storms has been recorded on the coral reefs causing their destruction and death by breakage of the coral branches into smaller pieces and even uprooting them.

*Ocean acidification*:

Increase in acidification of ocean due to absorption of more $CO_2$ from atmosphere is also a major cause of coral reef destruction. Consequent formation of carbonic acid dissolves calcium from the reef's skeleton, making them weaker and hence more prone to diseases and destruction.

*Depletion of Ozone layer*:

It has been demonstrated that depletion of ozone layer exposes all the marine organisms to greater amount of atmospheric UV radiations, which is also a causative factor of extensive damage to corals present in shallow waters (Baswapoor and Irfan 2018).

Interestingly, a synergistic association between temperature and light in causing coral bleaching has been demonstrated, indicating a positive correlation between the thermal damage to corals and the intensity of light. It has been observed that while bleaching is reduced in shaded reef systems, it is more pronounced in the areas exposed to elevated light conditions.

*Anthropogenic Stressors*

There are also several anthropogenic stress conditions for coral reefs that may cause local bleaching, such as, indiscriminate fishing, sedimentation from land clearing and flooding, nutrient wash -off and pollution from agriculture and sewage resulting in eutrophication, damage from ships and eco- tourism etc. which can disrupt this ecosystem.

Sully et al. (2019) observed coral bleaching and its patterns during 1998-2017 at 3351 sites located in 81 countries. They deduced that common occurrence of coral bleaching was associated with the thermal-stress anomalies taking place at high frequency and high intensity. On the contrary, the phenomenon was significantly less common in areas which had a high variance in sea-surface temperature anomalies (Fig. 5). They suggested that current onset of coral bleaching at significantly higher sea-surface temperature than earlier may be because of the decline in thermally susceptible genotypes inducing higher thermal threshold in rest of the corals for bleaching.

**Consequences of coral bleaching – A major distress**

Coral reefs furnish food and shelter to a myriad of living creatures including humans. They also shield the oceans from the action of waves by forming natural barricades. The phenomenon of bleaching not only causes tissue necrosis in them but also decreases their nutrient reserves, reproductive fitness and growth affecting their longevity and survival as well as of their predators. Therefore mortality of coral reefs results in the multitude of consequences involving all round deterioration of ecosystem as well as economies.

*Ecological consequences*:

The major consequence observed due to bleaching is its multifaceted effect on biodiversity leading to their depletion (Palumbi et al. 2014). Since corals are sensitive to high temperature, coupled with their limited power of adaptation as well as acclimatization, they have increasingly become vulnerable to mass bleaching events. This eventually results in coral reefs with less live coral cover as well as associated marine fauna. The most notable example here is that of fast growing and visually dominant *Acropora* which shows noticeable decline in abundance with far reaching impact on aesthetics and extent of habitat for many reef-dependent species (Mercado-Molina and Hernandez-Delgado 2020). Since coral species exhibit dissimilar sensitivity to thermal stress, a change in community composition has been demonstrated. In Lakshadweep Islands, India, massive corals viz. *Porites* have replaced staghorn *Acropora* which were dominant members before 1998 mass bleaching event (Wooldridge et al. 2005, Saravanan et al. 2017). Besides this, many other species which are strongly dependent on reef ecosystem for food and shelter are also threatened. This is particularly true for obligate corallivores who face maximum risk! Sadly, due to 1998 bleaching in reefs surrounding Okinawa, Orange spotted filefish (*Oxymonacanthus longirostris*) has vanished from this area (Kokita and Nakazono 2001, National Geographic 2018). Thus hard corals are giving way to low diversity, low cover reef communities, reducing ecosystem services upon which humans depend.

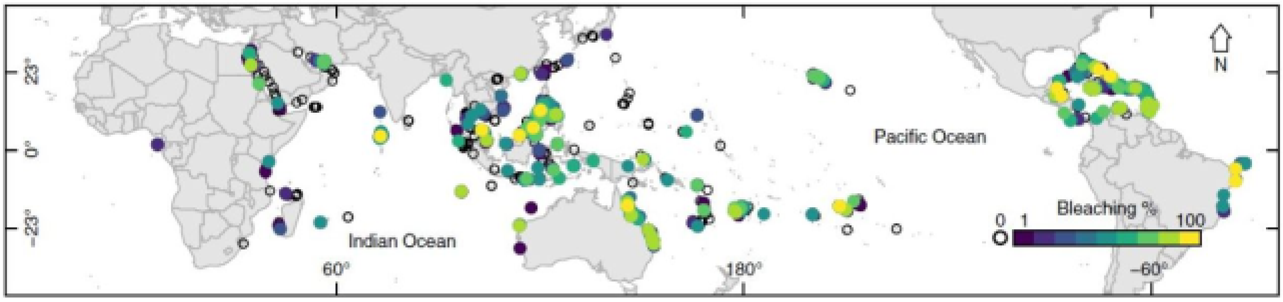


Figure 5. Distributive bleaching of coral. Measured at 3351 sites in 81 countries between 1998 and 2017, the prevalence of coral bleaching is shown as a percentage of the coral assemblage that bleached during the survey. No bleaching is indicated by white circles. Colored circles show bleaching levels from 1% (blue) to 100% (yellow) (Source: Sully et al. 2019).

*Economic impact on Fisheries*:

Another important influence of mass bleaching is reflected in its widespread effects on fisheries, especially small-scale and subsistence fisheries. A distinct change in fish species constitution and possibly diminished fisheries catches has been observed due to bleaching. Also, degradation of coral reef ecosystems, brought about by coral bleaching, greatly impacts fisheries, since corals provide nutrition and habitat for a number of fish species as well as other reef-associated marine fauna. The damsel fish species (Family: Pomacentridae) strongly associated with branching corals on a reef at Pulau Pemanggil, Malaysia are adversely impacted by the destruction and death of corals due to bleaching. Population of larger species, in turn, the important predators of these fishes, have also reduced drastically in these reefs (Muthiga and McClanahan 2020). These impacts have hit hard the coastal communities living in tropics, practising coral reef-based fisheries, by loss of their livelihood, income, and safety. This, in turn, has a spiralling impact on rich industrialised nations dependent on seafood from coral reef ecosystems.

*Tourism*:

The phenomenon of coral bleaching has also affected tourism with a detrimental impact on many regional and national economies along with the diverse wild life. Since the vibrant colours of coral reefs impart aesthetic beauty and attract tourists, hence, small scale reef-oriented businesses, *viz*. eco-tourism based on snorkeling, scuba diving, fishing tours etc., are adversely affected by deterioration in reef conditions in Philippines, Indonesia, etc. (Doshi et al. 2012, National Geographic 2022).

*Other factors*:

The coastlines too have become more susceptible to damage, due to mass coral bleaching events in the tropical regions during last 10 years. They also exert far reaching effects on oceanic currents (changes in strength and direction of current), frequency and severity of storms, hurricanes and cyclones, greater virulence of diseases, rise in sea level with consequent increase in deposit of sediments and pollutants from the flooded coastal areas, reduced calcification in reef - building, changes in salinity, insufficient absorption of carbon dioxide - leaving it more in the atmosphere, ocean acidification etc.

Thus, empirical results show that the loss in global coral reef value under climate change ranges from US $3.4 billion to US$ 23.78 billion annually. (Chen et al. 2015, coast.noaa.gov/states/fast-facts/coral reefs.html)

## Resilience to bleaching in corals – An adaptive phenomenon

Like other organisms, corals have also adapted to the challenge of bleaching by developing the ability to defy bleaching (Resistance), withstand the bleached state (tolerance) and bounce back after bleaching (recovery). Understanding these factors will help to potentially manage actions in handling the threat of bleaching.

The corals exhibit various degrees of resistance to bleaching. While some show visible signs of bleaching only after 1-2 weeks at temperature 1.5$^{o}$C above normal, the others at the same location do not experience bleaching until more than 4-6 weeks. Such a hierarchy of resistance is seen in coral assemblages of Western Pacific and Indian Oceans (Fig. 6). A strong relationship between the vulnerability to bleaching in corals exists with the compactness of tissues (LaJeunesse et al. 2003). Typically, the feeble and weak polyps with slow growth rate and well linked structural framework are more prone to damage than the strong, huge, compact corals showing sluggish development. It has been demonstrated by the occurrence of higher susceptibility in pocilloporid and many acroporids as well as hydrocoral *Millepora* to possible bleaching than the porits, faviids and mussids which may be attributed to the shading of zooxanthellae by thicker tissues.

Another possible cause of bleaching resilience in corals is the influence of intrinsic factors like acclimatisation and genetic variations in zooxanthellae enabling corals to withstand thermal stress and bleaching. The acclimatized corals alter their physiology and metabolism in order to survive better at high temperatures and endure harsh environmental conditions *viz*., high intensity of light and thermal stress. They are found to be better adapted to bleaching stress even in future. However, acclimatization does not provide them with long term protection against mass bleaching events. Thus, the type of zooxanthellae present within the host, play a

| RESISTANCE | GROWTH FORM | CORAL FAMILY | EXAMPLES |
|---|---|---|---|
| LOW | Fine branching | Pocilloporidae | *Seriatopora*<br>*Stylophora*<br>*Pocillopora* |
| | Branching, tabulate, encrusting/foliose | Acroporidae | *Acropora*<br>*Montipora* |
| MEDIUM | Massive, brain | Faviidae | *Favia*<br>*Favites*<br>*Leptoria*<br>*Goniastrea*<br>*Platygyra* |
| | Massive, boulder | Poritidae | *Porites*<br>*Goniopora* |
| HIGH | Various | Various | *Turbinaria*<br>*Cyphastrea* |

Figure 6. An overall ranking of coral bleaching susceptibility (Source: Marshall and Schuttenberg 2006).

pivotal role in resistance to coral bleaching (van-Oppen et al. 2015). Recently, Phillip Cleves and his colleagues suggested the use of CRISPR-Cas 9 gene editing tool to modify coral reef genes (Hunt 2019). Diverse forms of zooxanthellae exhibit divergent levels of endurance to high temperature. It indicates that the corals harbouring eurythermic algae may be more resistant to bleaching (Baker 2003, Bay et al. 2016). According to the Adaptive Bleaching Hypothesis, the corals may manifest novel symbiosis with more heat-resistant algae in response to altered temperature regime to improve their thermal tolerance (Pratte and Richardson 2018). This was originally proposed by Buddemeier and Fautin (1993). The corals of a species inhabiting Galapagos Island, though may have a threshold of only 28$^{o}$C, yet it may be 34$^{o}$C in the Persian Gulf due to adaptive phenomenon. This is because of the selection of more tolerant genotypes contributing more to the successive generations of corals while less resistant ones are annihilated. This evolutionary process of adaptation, however, relies on several causes including the intensity of bleaching, heritability of heat endurance and genetic structure of coral populations (van Oppen et al. 2015). The mechanism of resistance and resilience involving shifts in microbial gene expression, modification in taxonomic composition of algae and "switching and shuffling" is known as **metagenomic plasticity** (van Oppen et al. 2018). Hence, the proposed mechanism for coral health and resilience are (i) selection of phenotypes manifesting increased survival and resilience- the **probiotics** (Peixoto et al. 2017) and (ii) modification of genotypes of microbiota associated with corals to withstand climate change more efficiently – the **microbiome engineering** (Epstein et al. 2019).

Nevertheless, corals that survive bleaching events are still vulnerable and show several sub-lethal impacts exhibiting reduced rate of growth, diminished reproduction and low immunity to pathogens causing increased susceptibility to diseases. It has been reported that expulsion of the energy providing zooxanthellae induces a phase of hunger or "famine" in the damaged corals. The retrieval from this starvation (recovery) depends upon several factors *viz.*, the health of individual coral colonies measured by its nutrient reserves, because a coral with adequate energy reserves will be able to survive the starvation phase by using surplus nutrient stores as a buffer during periods of low energy supply. Similarly, heterotrophy i.e. feeding on minute floating organisms and other organic-material present in the ambient water body provides an alternative source of energy to the corals and hence they are more likely to endure the loss of algae. Herbivory in oceans by grazing fishes is another crucial factor in the recovery of coral reefs. The depletion of the herbivory, due to disease or overfishing, results in a switch from domination of corals to that of algae in the reef, largely due to the increased levels of nutrients available to algae in absence of herbivorous fishes.

**Conservation and mitigation of Coral Bleaching**

Several initiatives for restoration of coral health have been undertaken to rescue the coral reefs from onslaught of bleaching. Understanding the involvement of pigment granules present within the coral tissue (Fluorescent Pigment Granules - FPGs) in coral health restoration is an emerging field of study. The high concentrations of these pigments have been reported to optimize the availability of light to zooxanthellae and thus shelter them from light stress. This, in turn, helps to reduce coral bleaching rendering them more resistant to bleaching (Tappert 2016).

In 2020, a novel restoration project of the coral reefs was taken up by the scientists of Zoological Survey of India (ZSI) in Gulf of Kachchh, Gujarat, India. Since this area is subjected to tides of high amplitude, they used Bio-rock or mineral accretion technology in which an anode and a cathode are located at the bottom of the sea, followed by the passing of an electric current through them (Fig. 7). It results in combining of calcium ions with carbonate ions forming calcium carbonate, which adheres to the cathode. Coral larvae, in turn, attach to the calcium carbonate and grow quickly without spending their own energy. This technique is advocated to protect the corals along with the highly vulnerable branching forms from the risks of rise in sea temperature. (https://www.thehindu.com/sci-tech/science/india-begins-coral-restoration-in-gulf-of-kachchh/article 30645770.ece/amp/)

Larval recruitment has a critical role to play in the process of "recovery" (Bostrom-Einarsson et al. 2020). This process utilizes the availability of "original" pool of reefs to supply new larvae, their production, successful settlement, survival and growth. However, the larval recruitment is adversely affected by poor ambient environmental conditions, such as, degraded quality of water.

It is believed that recovery of coral reefs can be best achieved by the coral farming or propagation which involves the process of micro-fragmentation (Fig. 8). The technique involves breaking down of large corals collected from the local farms into miniature polyps with their numbers ranging from 1 to 5. This triggers the growth of corals forming clones 25 to 50 times bigger than the original forms. These clone pieces, then, recognize their replica and join each other to form large colonies. On maturation after 4-12 months, they are put back into the ocean or the restoration site.

It is considered to be most viable remedy to prevent widespread destruction of corals by stimulating proliferation and biodiversity. This remarkable feat is achieved by using unique cultivation technology to stimulate genetic diversity (https://www.concrete-online.co.uk/benefits -of coral-farming/). Nowadays several low-cost coral farming methods have been employed worldwide to restore corals (Fig. 9).

Hence a "multi- omics" strategy involving ecological rehabilitation, establishment of MPAs, keeping a record of stringent physico-chemical parameters of ocean water, collaboration among

Figure 7. Electrification of reef in Indonesia by Bio-rock Technology (Source: https://en.wikipedia.org/wiki/Biorock)

Figure 8. Coral Transplantation in Indonesia (Source: https://en.wikipedia.org/wiki/Aquaculture_of_coral)

various countries and maintenance of coral health database is required to halt the current unprecedented deterioration of coral reefs.

## CONCLUSIONS

Coral reefs are exquisite, diverse and rich ecosystems, providing various ecosystems and economic services to mankind. However, they are facing major existential threat due to natural and anthropogenic climate change. To solve this issue of coral bleaching we must address climate change - limit deforestation, curb burning of fossil fuels and switch to renewable energy, check global warming thus removing excess carbon dioxide from the atmosphere and guide governments towards climate-smart policies geared towards long term sustainability. Besides this, curbs should be imposed on unlawful and unregulated fishing practices. Steps

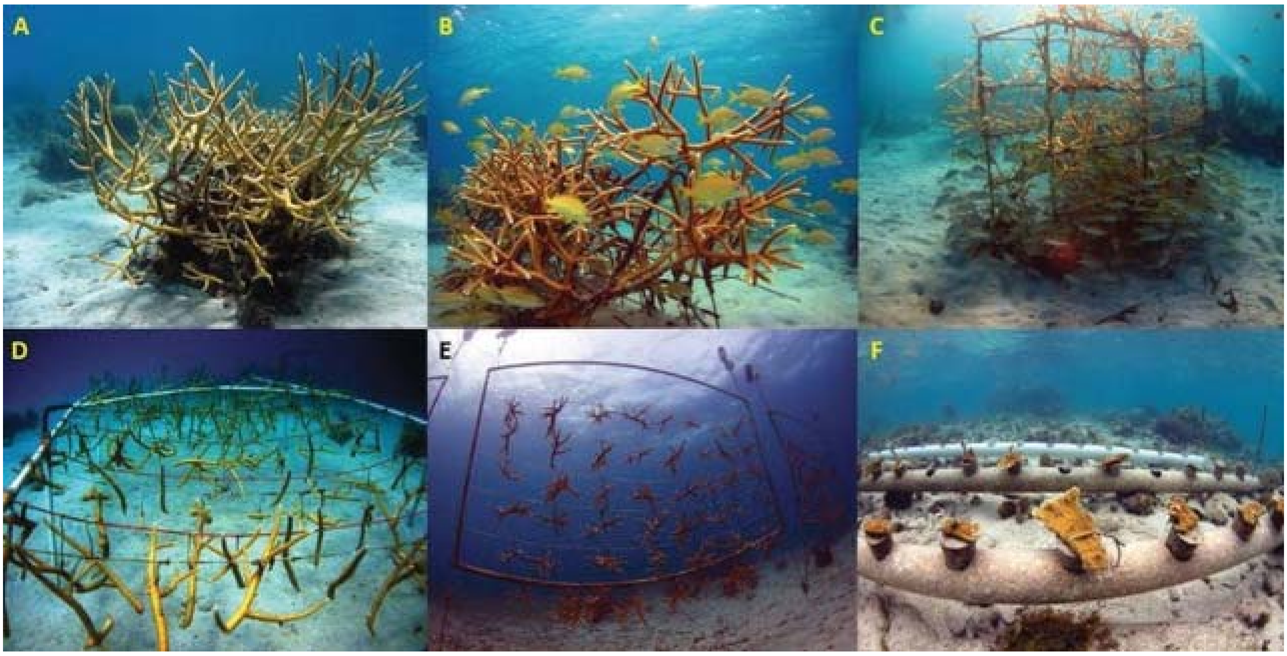


Figure 9. Coral farming methods employed in Puerto Rico, (A) to (E) used with *Acropora cervicornis* and *Acropora prolifera*; (A) plastic-covered wire mesh; (B) large wire mesh; (C) Condominium PVC unit; (D) horizontal line nursery; (E) floating underwater coral array; and (F) benthic underwater coral array used for *Acropora palmata*.

should be taken to reduce water pollutants such as agricultural pesticides, industrial and household waste water, oil and chemical spillage etc. A reef-friendly approach should be practised by tourists to avoid unnecessary future damage to these reefs. Attempts to stretch Marine protected areas (MPAs) to 30% of the oceans should be undertaken. Thus, there is an urgent need to save the world's coral reefs from bleaching before it is too late, and all stakeholders must work in unison to plan for the protection of the reefs.

Coral bleaching is not just the outcome of abuse of the ocean only but also to the environment *per se*. Hence, some of the measures which we can adopt to benefit the environment as a whole and in turn, play our role in combating coral bleaching are : recycling the waste, going plastic free, volunteering to participate in the ocean clean up, using natural or organic fertilizers, following more environment friendly and sustainable habits viz. using bicycle or public transport instead of private vehicles, avoiding use of sunscreens, consuming sustainable sea food as well as conserving energy, following fishing regulations, supporting MPAs (Marine Protected Areas) in key conservation sites and not using corals as souvenirs. These small steps will go a long way in protecting coral reefs and reducing its bleaching.

**Authors' contribution:** All authors contributed equally

**Conflict of interest:** The authors declare no conflict of Interest.

## REFERENCES

Arora, M., Chaudhury, N.R., Gujrati, A. and Patel, R.C. 2019. Bleaching stress on Indian coral reef regions during mass coral bleaching years using NOAA OISST data. Current Science, 117(2), 242-250.

Baker, A.C. 2003. Flexibility and specificity in coral-algal symbiosis: diversity, ecology, and biogeography of Symbiodinium. Annual Review of Ecology, Evolution, and Systematics, 34, 661-689.

Baswapoor, S. and Irfan, Z.B. 2018. Current status of coral reefs in india: Importance, rising threats and policies for its conservation and management (No. 2016-175). Madras School of Economics, Chennai. 31 pages.

Bay, L.K., Doyle, J., Logan, M. and Berkelmans, R. 2016. Recovery from bleaching is mediated by threshold densities of background thermo-tolerant symbiont types in a reef-building coral. Royal Society Open Science, 3(6), 160322.

Boilard, A., Dubé, C. E., Gruet, C., Mercière, A., Hernandez-

Agreda, A. and Derome, N. 2020. Defining coral bleaching as a microbial dysbiosis within the coral holobiont. Microorganisms, 8(11), 1682.

Boström-Einarsson, L., Babcock, R.C., Bayraktarov, E., Ceccarelli, D., Cook, N., Ferse, S.C., Hancock, B., Harrison, P., Hein, M., Shaver, E. and Smith, A. 2020. Coral restoration–A systematic review of current methods, successes, failures and future directions. PloS one, 15(1), e0226631.

Bourne, D., Iida, Y., Uthicke, S. and Smith-Keune, C., 2008. Changes in coral-associated microbial communities during a bleaching event. The ISME Journal, 2(4), 350-363.

Brumbaugh, R. 2017. Protecting million dollars reefs is key to sustaining global tourism. The Nature Conservancy, https://www.nature.org/en-us/what-we-do/our-insights/perspectives/protecting-million-dollar-reefs/, Accessed on June 29, 2022

Buddemeier, R.W. and Fautin, D.G. 1993. Coral bleaching as an adaptive mechanism. Bioscience, 43(5), 320-326.

Burke, L. and Wood, K. 2021. Decoding Coral Reefs: Exploring their Status, Risks and ensuring their future. wri.org/insights/decoding-coral-reefs

Chen, P.Y., Chen, C.C., Chu, L. and McCarl, B. 2015. Evaluating the economic damage of climate change on global coral reefs. Global Environmental Change, 30, 12-20.

Costanza, R., DeGroot, R. and Sutton, P. 2014. Changes in the global value of ecosystem services. Global Environmental Change, 26(1): 152-158.

Deloitte Access Economics. 2017. At what price? The economic, social and icon value of the Great Barrier Reef. Brisbane, Australia, https://www2.deloitte.com/content/dam/Deloitte/au/Documents/Economics/deloitte-au-economics-great-barrier-reef-230617.pdf, Accessed on June 29, 2022.

Doshi, A., Pascoe, S., Thébaud, O., Thomas, C.R., Setiasih, N., Hong, J.T.C., True, J., Schuttenberg, H.Z. and Heron, S.F. 2012. Loss of economic value from coral bleaching in SE Asia. In: Proceedings of the 12th International Coral Reef Symposium 22D-1:1-5.

Dove, S.G., Hoegh-Guldberg, O. and Ranganathan, S. 2001. Major colour patterns of reef-building corals are due to a family of GFP-like proteins. Coral Reefs, 19(3),197-204.

Downs, C.A., Fauth, J.E., Halas, J.C., Dustan, P., Bemiss, J. and Woodley, C.M., 2002. Oxidative stress and seasonal coral bleaching. Free Radical Biology and Medicine, 33(4), 533-543.

Elias, S. 2018. Loss of coral reefs. In: Encyclopedia of the Anthropocene; Elsevier: Amsterdam, The Netherlands, 245-258.

Epstein, H.E., Smith, H.A., Torda, G. and van Oppen, M.J. 2019. Microbiome engineering: Enhancing climate resilience in corals. Frontiers in Ecology and the Environment, 17, 100–108.

Goldberg, J. and Wilkinson, C. 2004. Global threats to coral reefs: coral bleaching, global climate change, disease, predator plagues and invasive species. Status of Coral Reefs of the World, 2004, 67-92.

htpps://www.concrete-online.co.uk/benefits -of coral-farming/ 10/03/2020

https://www.thehindu.com/sci-tech/science/india-begins-coral-restoration-in-gulf-of-kachchh/article 30645770.ece/amp/ (24/01/2020)

Hunt, K. 2019. Innovative ways to save the coral reefs. Greenmatters.com/news/2018/06/12/z2011R7/scientists-fight-coral-reef-bleaching.

IPCC. 2018. AR5 Climate Change 2018: Impacts, Adaptation and Vulnerability

IPCC. 2022. AR6 Climate Change 2022: Impacts, Adaptation and Vulnerability

Kokita, T. and Nakazono, A. 2001. Rapid response of an obligately corallivorous filefish *Oxymonacanthus longirostris* (Monacanthidae) to a mass coral bleaching event. Coral Reefs, 20(2), 155-158.

LaJeunesse, T.C., Loh, W.K., Van Woesik, R., Hoegh Guldberg, O., Schmidt, G.W. and Fitt, W.K. 2003. Low symbiont diversity in southern Great Barrier Reef corals, relative to those of the Caribbean. Limnology and Oceanography, 48(5), 2046-2054.

Lyu, Y., Zhou, Z., Zhang, Y., Chen, Z., Deng, W. and Shi, R., 2022. The mass coral bleaching event of inshore corals form South China Sea witnessed in 2020: insight into the causes, process and consequence. Coral Reefs, 41(5), 1351-1364.

Marshall, P.A. and Schuttenberg, H.Z. 2006. A reef manager's guide to coral bleaching. Great Barrier Reef Marine Park Authority, Australia (ISBN 1-876945-400). IUCN.

Mercado- Molina, A.E. and Hernandez-Delgado, E.A. 2020. Advances in Marine Biology, sciencedirect.com/topics/agricultural-and-biological-sciences/

Morrow, K., Muller, E. and Lesser, M. 2018. How does the coral microbiome cause, respond to, or modulate the bleaching process? Pp. 153–188. In: Coral Bleaching. Springer; Berlin, Germany.

Muthiga, N.A. and McClanahan, T.R. 2020. Sea Urchin: Biology and Ecology. In: developments in aquaculture and fisheries science. scienedirect.com/topics/agricultural-and-biological-sciences/damselfish.

National Geographic. 12/05/2022.www.national geographic.com>magazine> article.

National Geographic. 24/05/2018. prezi.com > 5qpqxhhmpolf > orange-spotted-filefish.

newsday.co.tt/2022/03/24/mass-bleaching-on the great-barrier-reef

Peixoto, R.S., Rosado, P.M., Leite, D.C.D.A., Rosado, A.S. and Bourne, D.G. 2017. Beneficial microorganisms for corals (bmc): Proposed mechanisms for coral health and resilience. Frontiers in Microbiology, 8, 341.

Palumbi, S.R., Barshis, D.J., Traylor-Knowles, N. and Bay, R.A. 2014. Mechanisms of Coral reef resistance to future climate change. Science, 344, 895-898.

Pratte, Z.A. and Richardson, L.L. 2018. Microbiome dynamics of two differentially resilient corals. Diseases of Aquatic Organisms, 131, 213-226.

Rafferty, J.P. 2022. Coral Bleaching. Britannica.com/science/coral bleaching

Saravanan, R., Ranjith, L., Jasmine, S. and Joshi, K.K. 2017. Coral bleaching: Causes, consequences and mitigation. Marine Fisheries Information Service; Technical and Extension Series, 231, 3-9.

Sully, S., Burkepile, D.E., Donovan, M.K., Hodgson, G. and Van Woesik, R. 2019. A global analysis of coral bleaching over the past two decades. Nature communications, 10(1), 1-5.

Takahashi, S., Nakamura, T., Sakamizu, M., Woesik, R.V. and Yamasaki, H. 2004. Repair machinery of symbiotic photosynthesis as the primary target of heat stress for reef-building corals. Plant and Cell Physiology, 45(2), 251-255.

Tappert, S. 2016. Fluorescent pigments: What Purpose do they Serve? 2016. acrooptics.com/fluorescent-pigments-purpose/

Teh, L.S., Teh, L.C. and Sumaila, U.R. 2013. A global estimate of the number of coral reef fishers. PLoS One, 8(6), e65397.

Trapido-Rosenthal, H., Zielke, S., Owen, R., Buxton, L., Boeing, B., Bhagooli, R. and Archer, J. 2005. Increased zooxanthellae nitric oxide synthase activity is associated with coral bleaching. The Biological Bulletin, 208(1), 3-6.

van Oppen, M.J., Bongaerts, P., Frade, P., Peplow, L.M., Boyd, S.E., Nim, H.T. and Bay, L.K. 2018. Adaptation to reef habitats through selection on the coral animal and its associated microbiome. Molecular Ecology, 27, 2956–2971.

van Woesik, R. and Kratochwill, C. 2022. A global coral-bleaching database, 1980–2020. Scientific Data, 9(1), 1-7.

Van-Oppen, M.J., Oliver, J.K., Putnam, H.M. and Gates, R.D. 2015. Building coral reef resilience through assisted evolution. Proceedings of The National Academy of Sciences, 112(8), 2307-2313.

Wilkinson, C.R. 2004. Status of Coral Reefs of the World. Vol. 1. Australian Institute of Marine Science. IUCN-2004-074, (1), 301

Wooldridge, S., Done, T., Berkelmans, R., Jones, R. and Marshall, P. 2005. Precursors for resilience in coral communities in a warming climate: a belief network approach. Marine Ecology Progress Series, 295, 157-169.

World Resources Institution Report. 2011. Decision making in a changing climate. Washington, USA, 1-184. https://files.wri.org/d8/s3fs-public/pdf/world_resources_report_2010-2011.pdf. Accessed on June 10, 2022.

*Received: 20th September 2022*
*Accepted:27th December 2022*