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# Biomonitoring of Coral Bleaching - A Glimpse on Biomarkers for the Early Detection of Oxidative Damages in Corals

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Additional information is available at the end of the chapter

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## Abstract

Corals live in a symbiotic life with single-celled algae, zooxanthelle. Anthropogenic threats and natural threat-mediated stress destabilize the photosynthetic electron transport chain resulting in an increased production of reactive oxygen species (ROS) in symbiont algae and causes coral bleaching. In this review, the early warning system and biomarkers for oxidative damages in corals are explained. The review also discusses (1) the mechanism of coral bleaching, (2) the uses of biomarkers to detect the early signs of bleaching, and (3) laboratory and field studies that are carried out on biomarkers and coral bleaching.

**Keywords:** Antioxidant enzymes, oxyradicals, coral bleaching, sym32gene, cytochromeP450

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## 1. Introduction

Coral reefs are among the most productive and diverse ecosystem on earth and support myriad of fish and invertebrate species. The importance of their productivity has prompted the world conservation strategy (UNEP/WWF) to recognize coral reefs as the most essential life support system for food production, health, and other aspects of human survival and sustainable development [1,2]. Coral reefs provide a wide array of food organisms such as fish, mollusks, crabs, shrimps, and algae that are consumed by humans. The destruction of these coral reefs would definitely lead to substantial reduction in supply of animal protein in the diet of coastal population.

In general, the major hazardous threat to coral reefs can be categorized into anthropogenic and natural origin [1]. Bryant et al. [3] developed a risk index based on the impact of anthropogenic threats to the health of coral reef system, namely, coastal development and marine pollution. Under the natural threats, mortality of corals as a result of increased sea temperature is a relatively recent phenomenon that has resulted in the dramatic decline in the number of healthy reefs around the world [4]. Although various numbers of factors are proposed as a threat to coral reefs, the important toxic consequences is oxidative stress, which leads to coral bleaching [5].

The suitable way to assess sub lethal effects of oxidative stress or early detection of coral bleaching is to quantify the physiological and biochemical responses of corals as a biomarker in response to natural and anthropogenic disturbing agents. The measurement of biochemical responses (antioxidant enzymes, oxyradicals, cytochrome P450 isoforms, heat shock protein, and symbiosis-specific genes) in reefs with response to oxidative stress caused by various factors (temperature, UV radiation, and contaminants) will serve as a good biomarker for the early detection of bleaching.

## 2. Coral bleaching

The major reason for global degradation of corals by bleaching is a process whereby corals lose their algal symbiont or the symbionts photosynthetic pigments degrade [6]. The existence of corals is dependent on a mutualistic symbiont relationship between the individual coral polyp and a photosynthetic dinoflagellate such as zooxanthella. Zooxanthellae are intracellular residents of the tissues of coral and provide the coral with energy produced by its photosynthetic activities. In return, the coral effectively fertilizes the zooxanthella, providing nutrients in the form of ammonia and phosphates [1]. The successfully proposed model concerning a possible mechanism of coral bleaching is based on the response to oxidative stress by both components of the symbiont relationship [7]. However, understanding the structure of coral tissues could facilitate readers to know about the mechanism of coral bleaching. Corals are formed of two layers of cells known as epidermis and gastrodermis. Both these layers were covered by mucus layer and connected with porous calcium carbonate skeleton. Tissues of corals contain large populations of eukaryotic algae, bacteria, and archaea as well as numerous viruses. In the beginning of 1883, it has been reported that hard corals were associated with intracellular microscopic algae [8], and further it was identified as dinoflagellates, *Symbiodinium* [9]. *Symbiodinium* supply a large part of the energy requirements of the corals by transferring photosynthetically fixed carbon to the coral [10]. In addition, during photosynthesis, algae produce large amounts of molecular oxygen for the respiration of corals.

As mentioned in the introductory section, anthropogenic and natural threat-mediated stress can destabilize the photosynthetic electron transport chain resulting in an increased production rate of reactive oxygen species (ROS) in symbiont algae. In addition, it is worth to note that the generation of ROS occurs in the chloroplast by various mechanisms associated with an electron transfer catalyzed with photosystem I and photosystem II [11,12]. According to

Mehler reactions, hydrogen peroxide ( $H_2O_2$ ) is generated by oxygen evolving complex, and these oxyradicals can easily diffuse from the algal symbiont in to the coral cytoplasm. When it happens above the threshold level, ROS will cause oxidative damage and bleaching to corals (Figure 1). Bleaching leads to high mortality and is considered as a serious threat to the health of reef ecosystem [13]. Supporting with earlier works, it is suggested that oxidative stress plays a major role in coral bleaching [1,5,14]. Although cellular-based mechanistic models concerning oxidative stress and coral bleaching are not well established, an increasing number of works have been carried out on coral symbiotic oxidative damage in relation to free radicals generated by disturbance of symbionts photosystem [5,14,15]. Hence, an effective management of the health state of coral reefs requires an early detection or biomonitoring of the oxidative stress. The suitable way to assess sublethal effects of oxidative stress or early detection of coral bleaching is to quantify the physiological and biochemical responses of corals in response to natural and anthropogenic disturbing agents.

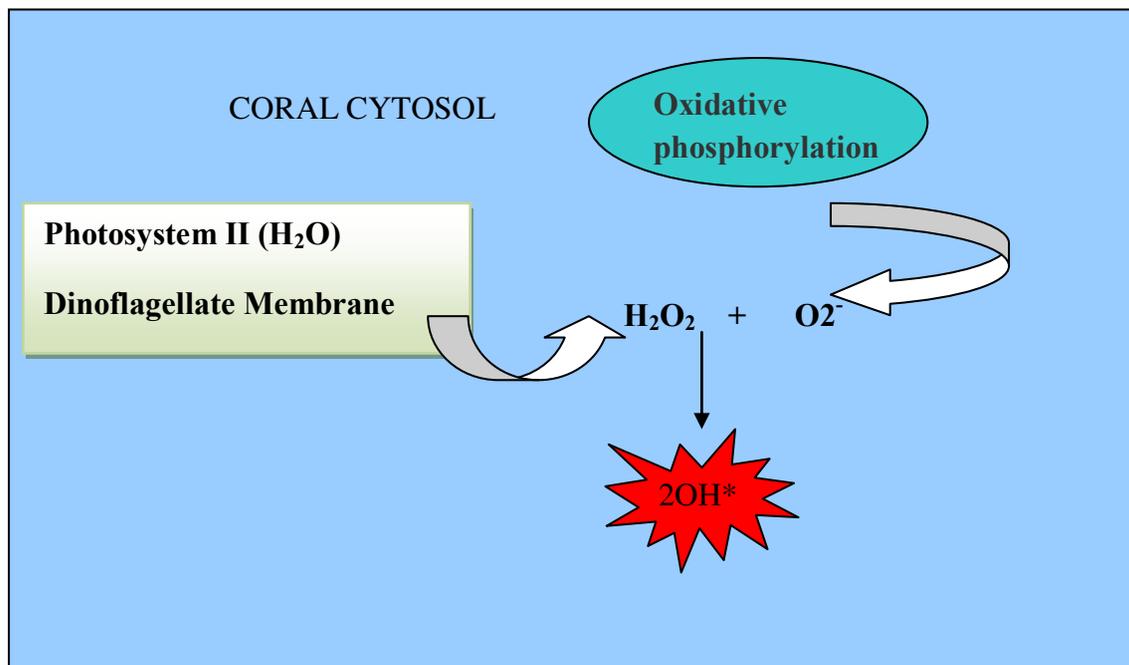


Figure 1. ROS mediated coral bleaching

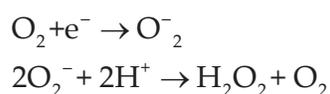
### 3. Biomarkers

The conditions and health state of reefs are unknown since majority of them occur in remote locations [3]. It is very difficult to make a decision about the sustainable use of their resources without having an appropriate data/evidence on their health status. Hence, increased monitoring of reefs is urgently needed. We hope that biochemical responses (antioxidant enzymes, oxyradicals, fluorescent proteins, Cyp 450 isoforms, HSP, and symbiosis-specific genes) on

reefs in response to oxidative stress caused by various factors (temperature, UV radiation, and contaminants) will serve as a good biomarker for the early detection of bleaching.

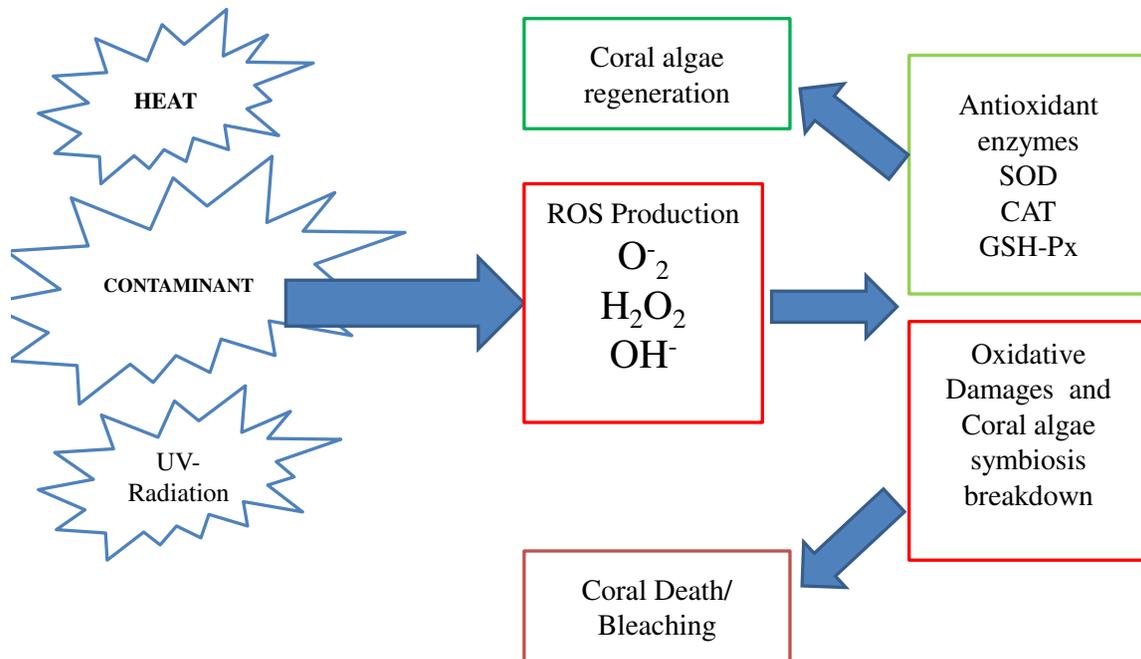
### 3.1. Oxyradicals and antioxidant enzymes

In summer, the elevation of water temperature may affect the cnidarians symbiotic life by generating oxyradicals. Ultraviolet (UV) radiation has also been shown to cause bleaching either alone or by acting synergistically with elevated temperature, wherein they produce active forms of oxygen in the zooxanthellae of corals [16]. The absorption of excitation energy in the presence of oxygen leads to the production of reactive oxygen species, ROS ( $O_2^-$ ,  $H_2O_2$ ), etc.



ROS will further lead to the photoinhibition of photosynthesis in algae and causes bleaching in symbiotic cnidarians. Superoxide dismutase inactivates the superoxide anion by transforming it into hydrogen peroxide ( $H_2O_2$ ). Hydrogen peroxide is then quickly altered by catalase and peroxidases into dioxygen ( $O_2$ ) and water ( $H_2O$ ). Different studies have confirmed that the production of  $H_2O_2$  under the action of SOD is the triggering factor in the natural antioxidant defense mechanisms. SOD therefore seems to be the key enzyme in the natural defense against free radicals. Thus, antioxidant enzyme superoxide dismutase (SOD ;  $2O_2^- + 2H^+ \rightarrow H_2O_2 + O_2$ ), catalase (CAT ;  $2H_2O_2 \rightarrow 2H_2O + O_2$ ), glutathione peroxidase (GSH-Px ;  $2GSH + ROOH \rightarrow GSSG + ROH + H_2O$ ), and ascorbate peroxidase are demonstrated to inactivate the oxyradicals such as  $O_2^-$  and  $H_2O_2$  (Figure 2). In 2004, Mydlarz and Jacobs [17] revealed that  $H_2O_2$  production occurred as an oxidative burst in a physically injured *Symbiodinium* sp. that was isolated from *Pseudopterogorgia elisabethae*. Since  $H_2O_2$  acts as an important signaling molecule between *Symbiodinium*, i.e., zooxanthellae, and their symbiotic host, it is believed that  $H_2O_2$  is the most important ROS associated with coral bleaching [18]. Ross et al. [19] reported that micromolar concentrations of  $H_2O_2$  ( $>10 \mu M$ ) induced cell death in the cyanobacterium *Microcystis aeruginosa*. In 2009, Higuchi et al. [20] studied the response of antioxidant enzymes in the coral *Galaxea fascicularis* against elevated level of  $H_2O_2$ . During short-term  $H_2O_2$  exposure experiment, SOD and CAT activities in zooxanthellae were not significantly altered even at higher  $H_2O_2$  concentration. Similarly, coral bleaching was not observed when exposed to  $H_2O_2$  concentration for a period of 5 days. Both SOD and CAT activities in coral tissue and zooxanthellae were increased with high seawater temperature. It denotes that both  $O_2^-$  and  $H_2O_2$  were formed within the cell by the increased temperature. Further, they opined that high seawater temperature had a greater impact on the SOD and CAT activities of the coral. Anithajothi et al. [21] analyzed antioxidant enzymes (SOD, CAT, and GSH-Px) in selected scleractinian corals such as *Acropora formosa*, *Echinopora lamellosa*, *Favia favius*, *Favites halicora*, *Porites* sp., and *Anacropora forbesi*. They concluded that the assay of these enzymes can be used as biomarkers for identifying the susceptibility of corals towards coral bleaching. Regoli

et al. [22] characterized the antioxidant efficiency of *Petrosia ficiformis* on a monthly basis by combining an analysis of the main antioxidants (superoxide dismutase, catalase, glutathione S-transferases, glutathione reductase, and glutathione peroxidases) with measurements of the total oxyradical scavenging capacity (TOSC). In summer season, significantly increased levels of catalase and TOSC were observed. The greater production of  $H_2O_2$  in the symbioses during this period supports the hypothesis that seawater temperature can significantly modulate the pro-oxidant and antioxidant status in Mediterranean symbioses.



**Figure 2.** Oxyradicals and antioxidant enzymes in Coral Sp.

It is very important to study the stimulation of oxyradical production in corals *in vivo* by water temperature and to what extent the oxyradicals overcome antioxidant defenses to cause oxidative damage. No detailed study has been carried out so far on the direct measurement of oxyradicals generation *in vivo*, but an indication of such process can be obtained by detecting/analyzing the lipid peroxidation products and carbonyl proteins in heat stress exposed corals. The formation of carbonyl groups on amino acid residues as a result of free radical-initiated reactions is well documented [23]. Carbonyl formation is increased by oxidative stress and is a good marker of protein degradation [24,25]. An increased number of works have been carried out on carbonyls [26] and lipid peroxidation products [27], which shows that it could serve as a biomarker for contaminant-stimulated oxidative damage. Downs et al. [7] demonstrated that heat stress causes oxidative damage in corals, which is exacerbated by exposure to light. Later in 2002 [5], they made an attempt to test whether oxidative damage is associated with coral bleaching and examined the levels of protein carbonyl and lipid peroxidation (LPO). Carbonyl protein concentration differed significantly with the exact combination of sampling date and depth and was positively correlated with ocean tempera-

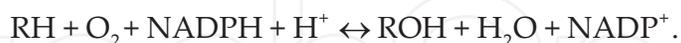
ture. Lipid peroxide (LPO) also showed a similar pattern. The levels of oxidative damage products increased with water temperature and preceded coral bleaching.

### 3.2. Fluorescent proteins

Corals produce fluorescent proteins (FPs) that are similar to the green fluorescent protein (GFP) of jellyfish. Fluorescent protein absorbs high-energy light and protects corals. These proteins are predominantly found in scleractinian corals and constitute up to 14% of the total protein content [28]. These highly conserved molecules contain 238 amino acids that comprise 11 beta sheets and fold to form a cylinder like shape with three amino acids: serine, glycine, and tyrosine forming a posttranslationally modified fluorescent. Although the function of FPs in corals remains unclear, it is believed that it is involved in photoprotection and also acts as an antioxidant [29,30]. Blue light significantly affects corals and their symbionts. Blue light photoreceptors of corals, which are known as cryptochromes, are thought to play a role in coral bleaching during the elevation of seawater temperature. Blue light primarily damages photo system II directly and secondarily inhibits the repair of photo system II through the production of ROS [31]. The GFP of corals maximally absorbs high-energy blue light and provides photoprotection on corals. In 2009, Palmer CV and coworkers [32] found that scleractinian's fluorescent protein scavenges H<sub>2</sub>O<sub>2</sub> and revealed that FPs also act as antioxidant. Carolyn Smith-Keune and Sophie Dove [33] explained that gene expression of host-specific genes such as GFP homologs may act as highly sensitive indicators for the onset of thermal stress within host coral cells. Thus, in future studies, fluorescent protein could be used as a biomarker for the early detection of thermal stress in coral reef, and based on this indication, necessary prevention steps could be taken to prevent coral bleaching.

### 3.3. Cytochrome P450 and monooxygenase system

Cyp 450 and flavoprotein reductase components of the microsomal mixed function oxidase (MFO) system are involved in the formation of ROS in the presence of contaminants



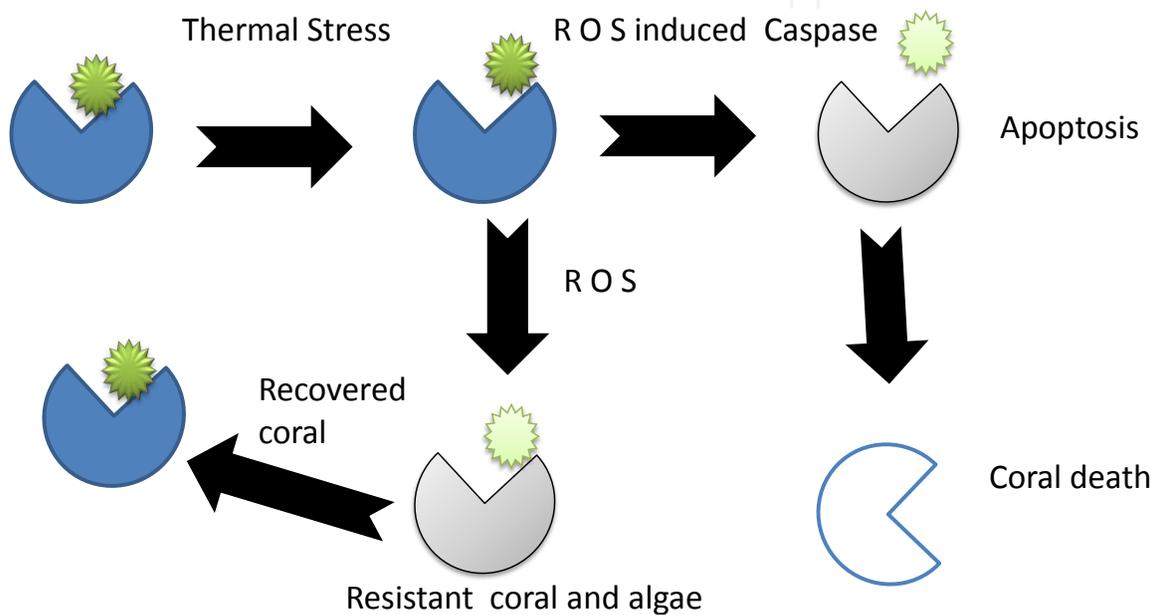
It has been clearly demonstrated that algae have an ability to bioaccumulate and metabolize (via biotransformation) xenobiotic compounds through available detoxifying system such as cytochrome P 450 [34]. Also, the presence of cytochrome P 450-dependent MFO system has been documented in sea anemone and scleractinian coral [35]. CYP-carbon monoxide difference spectra have been detected for the coral species *Favia fragum*, *Siderastrea siderea*, and *Montastraea faveolata* [36,37]. Ramos et al. [38] analyzed the activities of cytochrome P450 and monooxygenase enzymes (CYP450, P420, and NADPH cytochrome c reductase) in corals collected from two different sampling sites (one from least contaminated site and other from contaminated site). An increased content of CYP450, P420, and NADPH cytochrome c reductase was observed in the corals collected from the contaminated site. This difference was attributed to the difference in contamination levels between the two sampling sites. Ben-

zo(a)pyrene-induced CYP gene expression analysis in the scleractinian coral *Montastraea faveolata* [37] revealed that fuel oil exposure [39] induces CYP gene expression. Environmentally induced changes in CYP activity were observed in the coral *Stylophora pistillata* after exposure to hyposaline conditions [10] as well as in *Madracis mirabilis* after exposure to the photosynthesis inhibitor Irgarol [40]. Rosic et al. [41] discovered the presence of three new cytochrome P450 (CYP) genes from the reef-building coral endosymbiont *Symbiodinium*. Alteration in the expression of coral's CYP genes were analyzed during exposed to severe and moderate heat stress experiments. Samples of the scleractinian coral *Acropora millepora* were exposed to two different elevated temperatures (18-h period and 120-h period, i.e., rapid thermal stress and gradual thermal stress). The *Symbiodinium* CYP mRNA pool increased by 30% after 18 h of gradual heating and incubation at 26°C. An increase in the temperature above the average sea temperature (29°C after 72 h) resulted in a two- to fourfold increase in CYP expression. Both rapid thermal stress and gradual thermal stress at 32°C resulted in 50% to 90% decreases in CYP gene. The expression of CYP gene decreased under the enhanced thermal stress conditions at 32°C. These findings indicate that elevated sea temperature may affect the corals and induce the production of chemical stressors that regulate the expression of CYP genes encoding cytochrome P450 monooxygenases. This may alter the mechanism of biotransformation in corals. The studies emphasize that changes in the expression of CYP450 gene in corals could also be acted as a biomarker for the early detection of heat stress-mediated coral bleaching.

### 3.4. Mitochondrial integrity

Changes in environmental conditions destabilizes the symbiotic relationship between cnidarians and their dinoflagellate symbionts, *Symbiodinium* spp. As mentioned earlier, most of the studies have revealed that a breakdown in the symbiosis begins with increased ROS generation within the symbiont due to a decoupling of photosynthesis. Tchernov et al. [42] hypothesized a model for coral bleaching linking dysfunction of mitochondrial integrity to the mortality of the host animal. Mitochondria are known as batteries of the cell, which provides energy in the form of ATP and involves in ROS generation. During thermal stress, algal symbionts produce ROS that exceeds the level threshold. These molecules change the integrity of mitochondria and activate a caspase cascade within the host cell, which leads to the apoptosis and death of the corals. On the other hand, it is found that algal symbiont has the ability to remove or scavenge the ROS and gives protection from coral bleaching. It is noted that varied response was observed in the corals *Seriatopora hystrix* and *S. pistillata* to thermal stress. Although both the corals were bleached, the apoptotic response was elevated in *S. pistillata*, which resulted in the death of corals. On the contrary, apoptotic response was decreased in *S. hystrix*, which indicates that the response of corals against thermal stress is species specific and the algal symbiont of *S. hystrix* is strongly involved in scavenging ROS. However, in the case of *S. pistillata* corals, elevated ROS level induced the changes in mitochondrial integrity and further caused death (Figure 3). Dunn et al. [43] corroborate with the above said mechanism by evaluating the changes of mitochondrial integrity of host cnidarians in response to thermal stress. They assessed the overall morphology of host mitochondria associated symbionts under an experimental thermal stress using confocal and electron microscopy. It is noted that thermal

stress degraded the integrity of cnidarian host mitochondria. Further, the potential sites of host mitochondrial disruption were confirmed by measuring changes in the expression of genes associated with electron transport and ATP synthesis using quantitative RT-PCR. They believed that the primary site of degradation appeared to be downstream of complex III of the electron transport chain with a significant reduction in host cytochrome *c* and ATP synthase expression. Hence, it is believed that this reduction may affect the ability of the host to remove ROS and cellular energy supplies. This finding may give us a clue on the importance of host/coral response to thermal stress and in symbiosis dysfunction that has significant implications for understanding how coral reefs will survive during the climate changes.



**Figure 3.** Thermal stress mediated coral death and recovery of ROS resistant coral Sp.

### 3.5. Heat Shock Proteins (HSP)

Heat stress in coral reef affects both corals and their symbionts, which further lead to bleaching of corals. Coral bleaching occurs due to the dissociation of the coral–algal symbiosis [44]. The sensitivity of coral and symbiont bond to heat stress is not well understood. However, it is believed that photosynthesis system can be impaired by heat stress [45,46]. Understanding the basic mechanism of corals against heat stress is crucial in knowing the reason of coral bleaching in response to changes in sea temperature. Heat shock protein (HSPs) represents a class of molecular chaperones that are well known for their quick response to environmental stresses [47]. Thus, alterations in coral's HSPs may serve as biological marker for heat stress. Heat shock proteins are involved in the thermotolerance of oxidative phosphorylation. Several studies demonstrate that oxidative phosphorylation is correlated with the induction of HSP. It is interesting to note that inhibitors of electron transport or inhibitors of complex I act as an inducer of HSP [48]. The mitochondrial low molecular weight HSP is usually produced only in response to environmental stress [49]. It was successfully demonstrated that chloroplast

HSP protects photosynthetic electron transport during heat stress [50], which revealed that HSPs are an important adaptation to heat stress and function as a protective molecular chaperones. Smith et al. [18] found a threefold increase in the level of HSP70 protein in host coral colony at 33°C. Chow et al. [51] also demonstrated a robust transient induction of Hsp60 in response to both light and heat stress in laminar coral. So far, the works carried out on HSP of corals provided a new insight into changes occurring in coral endosymbionts under heat stress. Further research works related to the utilization of HSP as a biomarker to thermal stress is needed.

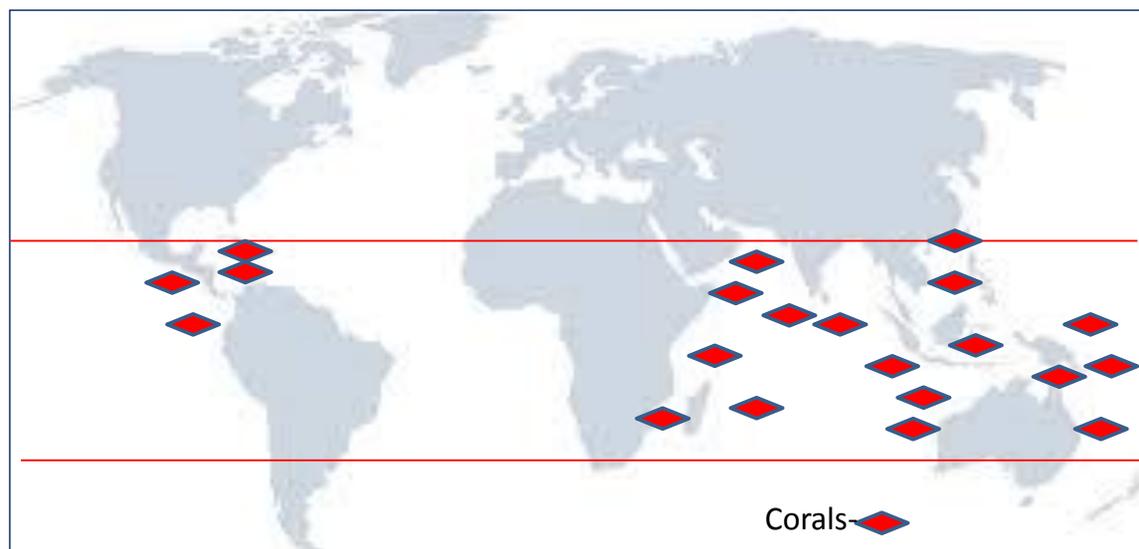
### 3.6. Symbiotic-specific genes

Coral bleaching, defined as loss of color in corals, occurs due to the breakdown of the symbiosis with algae. Recently, cnidarian genes that are expressed as a function of the symbiotic state have been characterized in the sea anemone for studying cnidarian algal symbiosis [52]. They found that *sym32* gene is involved in the regulation of the symbiosis by mediating cell–cell interactions. Mitchelmore et al. [53] characterized several genes responsible for the regulation of cnidarians and their symbiotic interaction. Temperate sea anemone *Anthopleura elegantissima* has been used as a model species, and a symbiosis-specific gene, *Sym32*, was identified from the host genome. RT-PCR studies also suggested that the expression of *Sym32* was correlated with the presence of host algae. No changes in algal numbers were observed on the exposure of cadmium to anemones under laboratory condition. However, they observed the downregulation of *sym 32* compared to controls. This indicates that a difference in the expression of *sym32* may act a biomarker of cnidarians–algal symbiosis breakdown.

### 3.7. Field and lab observations/applications of biomarkers

Corals generally grow well in clean water with a temperature between 20°C and 30°C. The optimum temperature for the growth of coral is 24°C. Coral reefs are found in great quantity in the Indian Ocean, Southeast Asia, Central Pacific, Southwest Pacific, and Caribbean regions. The largest coral reef is the Great Barrier Reef in Australia. The second largest coral reef can be found off the coast of Belize, in Central America. Coral reefs are also found in Hawaii, the Red Sea, and other areas in tropical oceans. The presence of corals in the ocean is depicted in Figure 4.

Corals and their algal endosymbionts cannot move from their habitats when they face unwanted environmental conditions such as increased seawater temperature and solar radiation. Hence, they have to develop molecular mechanisms to acclimatize and live in those unwanted conditions. Numbers of works have been carried out on coral bleaching that occurs around the world. According to the information provided by the World Resource Institute (WRI), about 370 observations were made on coral bleaching globally between 1980 and 1997. Interestingly, more than 3,700 observations were made between 1998 and 2010. This increased numbers of reports indicate the increase in awareness among researchers to monitor the health of corals and communicate about the bleaching events to the public. The suitable way to assess early detection of coral bleaching is to quantify the physiological and biochemical responses of corals as a biomarker. As mentioned in this review, changes in the biochemical parameters



**Figure 4.** The presence of coral reefs in Ocean

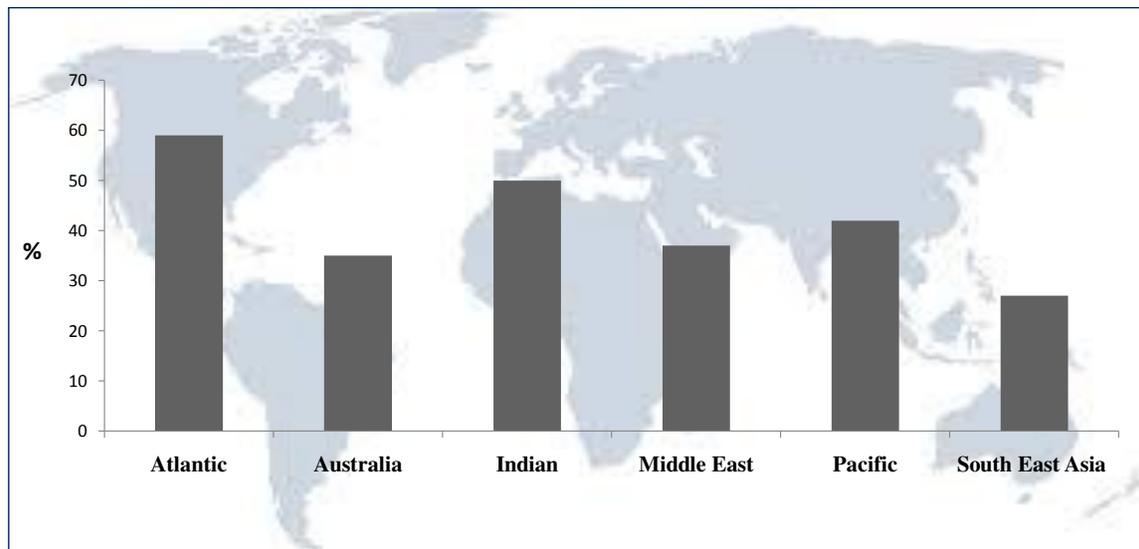
(antioxidant enzymes, oxyradicals, cytochrome P450 isoforms, heat shock protein, and symbiosis-specific genes) of coral reefs with response to increased seawater temperature may serve as a good biomarker for the early detection of coral bleaching. Numbers of laboratory and field studies have been carried out on these biomarkers. Some of the works relating to coral biomarkers and field applications are given in Table 1.

Location	Biomarkers	Coral host	Authors
Parque Nacional Morrocoy, Venezuela	Cytochrome-P450, Antioxidant enzymes and NADPH-C reductase	<i>Siderastrea siderea</i>	Ramos et al. (2011) [38]
Heron Island	Heat Shock Protein 70	<i>Porites cylindrica</i> and <i>Stylophora pistillata</i>	Fitt et al. (2009) [54]
Australia	Catalase	<i>Acropora millepora</i>	Krueger et al. (2015) [55]
South East Coast of India	Antioxidant enzymes	<i>Acropora formosa</i> , <i>Echinopora lamellosa</i> , <i>Favia favaus</i> , <i>Favites halicora</i>	Anithajothi et al. (2014) [21]
France	Catalase	<i>Anemoniaviridis</i>	Merie et al. (2007) [56]
Florida	Antioxidant enzymes	Coral reef	Downs et al. (2002) [5]
USA	Fluorescence protein	<i>Acroporayongei</i>	Roth and Deheyn (2013) [57]
Great Barrier Reef	Green Fluorescence protein	Scleractinia and Alcyonacea corals	Palmer et al. (2010) [58]
Australia	Green Fluorescence protein	<i>Acroporamillepora</i>	Smith-Keune and Dove S (2008) [33]
Australia	Cytochrome P450	<i>Acropora millepora</i>	Rosic et al. (2010) [41]

Location	Biomarkers	Coral host	Authors
Honolulu, USA	Cytochrome P450	<i>Stylophora pistillata</i>	Downs et al. (2009) [10]
Italy and Maldives	Mitochondrial HSP60	<i>Seriatopora hystrix</i> , <i>Montipora monasteriata</i> , and <i>Acropora echinata</i>	Seveso et al. (2014) [59]
NJ, USA	Mitochondrial integrity	Zooxanthellate corals	Tchernov et al. (2011) [42]
USA	Heat shock protein	<i>Montastrea annularis</i>	Hayes and King (1995) [60]
Red Sea	Heat shock protein	<i>S. pistillata</i> and <i>Turbinaria reniformis</i>	Chow et al. (2009) [51]
USA	Heat shock protein	<i>Xestospongia muta</i>	López-Legentil et al. (2008) [61]
USA	Heat shock protein and breakdown in symbiosis between coral and zooxanthellae	<i>Montastraea faveolata</i>	DeSalvo et al. (2008) [62]
USA	Symbiosis-specific gene	<i>Anthopleura elegantissima</i>	Mitchelmore et al. (2002) [53]

**Table 1.** Corals and biomarkers

In the year of 2011, World Resource Institute furnished data on thermal stress affected coral reefs, which is represented in Figure 5. From the data, it can be understood that more than 40% of the corals were affected by thermal stress in Atlantic and Indian Ocean, which is higher when compared to the other regions. On viewing the earlier research works relating to biomonitoring of coral bleaching, it can be understood that only few research works were carried out in the Indian Ocean. Since corals available in this region are believed to face thermal stress, it is important to concentrate on avoiding coral bleaching in Indian Ocean. Similarly, a large volume of works has been done only on coral antioxidant enzymes and their response against climate change or thermal stress. However, an increased number of works are needed in the aspect of host symbiosis breakdown, coral's mitochondrial integrity, and cytochrome P450 protein as a biomarker of thermal stress. This may give us a better idea about coral bleaching and the utilization of biomarkers for early detection of oxidative damages. In recent days, the early prediction of thermal stress in Ocean has been proposed as the best biomarker for coral bleaching. It is very interesting to know that a computer-based model could assess sea temperature every week and predict the changes in sea temperature and warn us to take precautionary efforts to avoid temperature-mediated coral bleaching [63]. The National Oceanic and Atmospheric Administration's (NOAA) Coral Reef Watch (CRW) and the National Centers for Environment Prediction (NCEP) carried out an excellent research work to predict thermal stress that causes mass coral bleaching. In this regard, a statistical climate model to produce the first seasonal bleaching outlook system was released in 2008 at the 11th International Coral Reef Symposium. This kind of work is another milestone in this field.



(Source: World Resource Institute (1998-2007))

Figure 5. Data on thermal stress affected coral reefs

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## References

- [1] Souter D, Obura D, Linden O. Coral Reef Degradation in the Indian Ocean: Status Report 2000. CORDIO/SAREC Marine Science, Sweden.
- [2] UNEP. Co-operation for Environmental Protection in the Pacific [report]. UNEP Regional Seas Reports and Studies No. 97; 1998.
- [3] Bryant D, Burke L, McManus J, Spalding M. Reefs at Risk: A Map-Based Indicator of Threats to the World's Coral Reefs. Washington, DC, World Resource Institute [WRI]; 1998; 56 p.
- [4] Wilkinson CR. Global and local threats to coral reef functioning and existence: review and predictions. *Marine and Freshwater Research*. 1999;50(8):867–878.

- [5] Downs CA, Fauth JE, Halas JC, Dustan P, Bemiss J, Woodley CM. Oxidative stress and seasonal coral bleaching. *Free Radical Biology and Medicine*. 2002;33:533–543.
- [6] Brown, BE. Coral bleaching: causes and consequences. *Coral Reefs*. 1997;16(sup):129–138.
- [7] Downs CA, Mueller E, Phillips S, Fauth JE, Woodley CM. A molecular biomarker system for assessing the health of coral (*Montastraea faveolata*) during heat stress. *Marine Biotechnology*. 2000;2:533–544.
- [8] Brandt K. Über die morphologische und physiologische Bedeutung des Chlorophylls bei Tieren. *Mitt Zool Stat Neapol*. 1983;4:191.
- [9] Klebbs, G. Ein kleiner Beitrag zur Kenntnis der Peridineen. *Bot Z*. 1984;10:46–47.
- [10] Downs CA, Kramarsky-Winter E, Woodley CM, Downs A, Winters G, Loya Y, Ostrander GK. Cellular pathology and histopathology of hypo-salinity exposure on the coral *Stylophora pistillata*. *Science of the Total Environment*. 2009;407(17):4838–4851.
- [11] Mehler, AH. Studies on reactions of illuminated chloroplasts. I. Mechanisms of the reduction of oxygen and other Hill reagents. *Archives of Biochemistry and Biophysics*. 1951;33:65–77.
- [12] Richter M, Rühle W, Wild A. Studies on the mechanism of photosystem II photoinhibition II. The involvement of toxic oxygen species. *Photosynthesis Research*. 1990;24(3):237–243.
- [13] Brown BE, Dunne RP, Goodson MS, Douglas AE. Bleaching patterns in reef corals. *Nature*. 2000;404(6774):142–143.
- [14] Lesser MP. Oxidative stress causes coral bleaching during exposure to elevated temperatures. *Coral Reefs*: 1997;16:187–192.
- [15] Warner ME, Fitt WK, Schnid GW. Damage to photosystem II in symbiotic dinoflagellates: a determinant of coral bleaching. *Proceedings of the National Academy of Sciences of the United States of America*. 1999;94(14):8007–8012.
- [16] Lesser MP, Stochal WR, Tapley JDW, Shick JM. Bleaching in coral reef anthozoans: effects of irradiance, ultraviolet radiation and temperature on the activities of protective enzymes against active oxygen. *Coral Reefs*. 1990;8:225–232.
- [17] Mydlarz LD, Jacobs RS. Comparison of an inducible oxidative burst in free-living and symbiotic dinoflagellates reveals properties of the pseudopterosins. *Phytochemistry*. 2004;65:3231–3241.
- [18] Smith APR, Henson RNA, Rugg MID, Dolan RJ. Modulation of retrieval processing reflects accuracy of emotional source memory. *Learning and Memory*. 2005;12:472–479.

- [19] Ross C, Santiago-Vázquez L, Paul V. Toxin release in response to oxidative stress and programmed cell death in the cyanobacterium *Microcystis aeruginosa*. *Aquatic Toxicology*. 2006;78(1):66–73.
- [20] Higuchi T, Fujimura H, Arakaki T, Oomori T. Activities of antioxidant enzymes (SOD and CAT) in the coral *Galaxea fascicularis* against increased hydrogen peroxide concentrations in seawater. In: *Proceedings of the 11th International Coral Reef Symposium*. Ft. Lauderdale, Florida; 2009; pp. 926–930.
- [21] Anithajothi R, Duraikannu K, Umagowsalya G, Ramakritinan CM. The presence of biomarker enzymes of selected Scleractinian corals of Palk Bay, southeast coast of India. *BioMed Research International*. 2014;684874:1–6.
- [22] Regoli F, Cerrano C, Chierici E, Chiantore MC, Bavestrello G. Seasonal variability of prooxidant pressure and antioxidant adaptation to symbiosis in the Mediterranean demosponge *Petrosia ficiformis*. *Marine Ecology Progress Series*. 2004;275:129–137.
- [23] Stadtman ER. Metal ion-catalyzed oxidation of proteins: biochemical mechanism and biological consequences. *Free Radical Biology and Medicine*. 1990;9(4):315–325.
- [24] Grant AJ, Jessup W, Dean RT. Accelerated endocytosis and incomplete catabolism of radical-damaged protein. *Biochimica et Biophysica Acta*. 1992;1134(3):203–209.
- [25] Grant AJ, Jessup W, Dean RT. Inefficient degradation of oxidized regions of protein molecules. *Free Radic Res Commun*. 1993;18(5):259–267
- [26] Grant AJ, Jessup W, Dean RT.: Enhanced enzymatic degradation of radical damaged mitochondrial membrane components.: *Free Radical Research Communications*. 1993;19(2):125–134.
- [27] Halliwell B, Gutteridge JMC. *Free Radicals in Biology and Medicine*. Oxford University Press, 1999.
- [28] . Leutenegger A, D'Angelo C, Matz MV, Denzel A, Oswald F, Salih A, Nienhaus GU, Wiedenmann J. It's cheap to be colorful. Anthozoans show a slow turnover of GFP-like proteins. *FEBS Journal*. 2007;274(10):2496–505.
- [29] Kawaguti S. On the physiology of reef corals VI. Study on the pigments. *Palao Tropical Biological Station Studies*. 1944;2:617–673.
- [30] Salih A, Larkum A, Cox G, Kuhl M, Hoegh-Guldberg O. Fluorescent pigments in corals are photoprotective. *Nature*. 2000;408:850–853.
- [31] Nishiyama Y, Allakhverdiev SI, Murata N. A new paradigm for the action of reactive oxygen species in the photoinhibition of photosystem II. *Biochimica et Biophysica Acta*. 2006;1757:742–749.
- [32] Palmer CV, Roth MS, Gates RD. Red fluorescent protein responsible for pigmentation in trematode-infected *Porites compressa* tissues. *Biological Bulletin*. 2009;215:68.

- [33] Smith-Keune C, Dove S. Gene expression of a green fluorescent protein homolog as a host-specific biomarker of heat stress within a reef-building coral. *Marine Biotechnology*. 2008;10(2):166–180.
- [34] Kirso U, Irha N. Role of algae in fate of carcinogenic polycyclic aromatic hydrocarbons in the aquatic environment. *Ecotoxicology and Environmental Safety*. 1998;41(1):83–89.
- [35] Heffernan LM, Winston GW. Distribution of microsomal CO-binding chromophores and EROD activity in sea anemone tissues. *Marine Environmental Research*. 2000;50(1–5):23–27.
- [36] Garcia E, Ramos R, Bastidas C. Presence of cytochrome P450 in the Caribbean corals *Siderastrea siderea* and *Montastraea faveolata*. *Ciencias Marinas*. 2005;31:23–30.
- [37] Ramos R, Garcia E. Induction of mixed-function oxygenase system and antioxidant enzymes in the coral *Montastraea faveolata* on acute exposure to benzo(a)pyrene. *Comparative Biochemistry and Physiology. Part C: Toxicology and Pharmacology*. 2007;144:348–355.
- [38] Ramos R, Bastidas C, Debrot D, García E. *Phase I and II biotransformation and antioxidant enzymes in the coral Siderastrea siderea act as biomarkers for reproductive condition and habitat quality*. *Marine Biology Research*. 2011;7(4):398–406.
- [39] Rougee L, Downs CA, Richmond RH, Ostrander GK. Alteration of normal cellular profiles in the scleractinian coral (*Pocillopora damicornis*) following laboratory exposure to fuel oil. *Environmental Toxicology and Chemistry*. 2006;25:3181–3187.
- [40] Downs C, Downs A. Preliminary examination of short-term cellular toxicological responses of the coral *Madracis mirabilis* to acute Irgarol 1051 exposure. *Archives of Environmental Contamination and Toxicology*. 2007;52:47–57.
- [41] Rosic NN, Pernice M, Dunn S, Dove S, Hoegh-Guldberg O. Differential regulation by heat stress of novel cytochrome P450 genes from the dinoflagellate symbionts of reef-building corals. *Applied Environmental Microbiology*. 2010;76(9):2823–2829.
- [42] Tchernova D, Kvitta H, Haramaty L, Thomas S, Bibby TS, Gorbunov MY, Rosenfeld H, Falkowski PG. Apoptosis and the selective survival of host animals following thermal bleaching in zooxanthellate corals. *Proceedings of the National Academy of Sciences of the United States of America*. 2011;108(24):9905–9909.
- [43] Dunn SR, Pernice M, Green K, Hoegh-Guldberg O, Dove SG. Thermal stress promotes host mitochondrial degradation in symbiotic cnidarians: are the batteries of the reef going to run out? *PLoS One*. 2012;7(7):e39024.
- [44] Hoegh Guldberg O. Climate change, coral bleaching and the future of the world's coral reefs. *Marine and Freshwater Research*. 1999;50(8):839–866.
- [45] Iglesias-Prieto R, Matta JL, Robins WA, Trench RK. The photosynthetic response to elevated temperature in the symbiotic dinoflagellate *Symbiodinium microadriaticum* in

- culture. Proceedings of the National Academy of Science of USA; 1992. 89: 10302–10305.
- [46] Lesser MP. Elevated temperatures and ultraviolet radiation cause oxidative stress and inhibit photosynthesis in symbiotic dinoflagellates. *Limnology and Oceanography*. 1996;41(2):271–283.
- [47] Sørensen JG, Kristensen TN, Volker Loeschcke V. The evolutionary and ecological role of heat shock proteins. *Ecology Letters*. 2005;6(11):1025–1037.
- [48] Ashburner M, Bonner JJ. The induction of gene activity in drosophila by heat shock. *Cell*. 1979;17(2):1241–1254.
- [49] Chen Q, Vierling E. Analysis of conserved domains identifies a unique structural feature of a chloroplast heat shock protein. *Molecular Genetics and Genomics*. 1991;226(3):425–431.
- [50] Heckathorn SA, Downs CA, Sharkey TD, Coleman JS. The small, methionine-rich chloroplast heat-shock protein protects photosystem II electron transport during heat stress. *Plant Physiology*. 1998;116(1):439–444.
- [51] Chow AM, Ferrier-Pagès C, Khalouei S, Reynaud S, Brown IR. Increased light intensity induces heat shock protein Hsp60 in coral species. *Cell Stress Chaperones*. 2009;14(5):469–476.
- [52] Reynolds WS, Schwarz JA, Weis VM. Symbiosis-enhanced gene expression in cnidarian–algal associations: cloning and characterization of a cDNA, sym32, encoding a possible cell adhesion protein. *Comparative Biochemistry and Physiology A*. 2000;126(1):33–44.
- [53] Mitchelmore CL, Schwarz JA, Weis VM. Development of symbiosis-specific genes as biomarkers for the early detection of cnidarian–algal symbiosis breakdown. *Marine Environmental Research*. 2002;54(3–5):345–349.
- [54] Fitt WK, Gates RD, Hoegh-Guldberg O, Bythell JC, Jatkar A, Grottoli AG, Gomez M, Fisher P, Lajuenesse TC, Pantos O, Iglesias-Prieto R, Franklin DJ, Rodrigues LJ, Torregiani JM, Woesik RV, and Lesser MP. Response of two species of Indo-Pacific corals, *Porites cylindrica* and *Stylophora pistillata*, to short-term thermal stress: the host does matter in determining the tolerance of corals to bleaching. *Journal of Experimental Marine Biology and Ecology*. 373;2009:102–110.
- [55] Krueger T, Hawkins TD, Becker S, Pontasch S, Dove S, Hoegh-Guldberg O, Leggat W, Fisher PL, Davy SK. Differential coral bleaching—contrasting the activity and response of enzymatic antioxidants in symbiotic partners under thermal stress. *Comparative Biochemistry and Physiology A*. 2015;23:190:15–25.
- [56] Merle PL, Sabourault C, Richier S, Allemand D, Furla P. Catalase characterization and implication in bleaching of a symbiotic sea anemone. *Free Radical Biology and Medicine*. 2007;42(2):236–246.

- [57] Roth MS, Deheyn DD. Effects of cold stress and heat stress on coral fluorescence in reef-building corals. *Scientific Reports*. 2013;3:1421.
- [58] Palmer CV, Bythell JC, Willis BL. Levels of immunity parameters underpin bleaching and disease susceptibility of reef corals. *FASEB Journal*. 2010;24(6):1935–1946.
- [59] Seveso D, Montano S, Strona G, Orlandi I, Galli P, and Vai M. The susceptibility of corals to thermal stress by analyzing Hsp60 expression. *Marine Environmental Research*. 2014;99:69–75.
- [60] Hayes RL, King CM. Induction of 70-kD heat shock protein in scleractinian corals by elevated temperature: significance for coral bleaching. *Molecular Marine Biology and Biotechnology*. 1995;4(1):36–42.
- [61] López-Legentil S, Song B, McMurray SE, Pawlik JR. Bleaching and stress in coral reef ecosystems: hsp70 expression by the giant barrel sponge *Xestospongia muta*. *Molecular Ecology*. 2008;17(7):1840–1849.
- [62] DeSalvo MK, Voolstra CR, Sunagawa S, Schwarz JA, Stillman JH, Coffroth MA, Szmant AM, Medina M. Differential gene expression during thermal stress and bleaching in the Caribbean coral *Montastraea faveolata*. *Molecular Ecology*. 2008;17(17):3952–3971.
- [63] Liu G, Matrosova LE, Penland C, Gledhill DK, Eakin CM, Webb RS, Christensen TRL, Heron SF, Morgan JA, Skirving WJ, Strong AE. NOAA Coral Reef Watch Coral Bleaching Outlook System. Proceedings of the 11th International Coral Reef Symposium, Ft. Lauderdale, Florida; July 2008; 7–11.

