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THE IMPACTS OF OCEAN ACIDIFICATION ON CORAL REEFS IN THE RED SEA AND WAYS TO ADDRESS IT - A REVIEW

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ABSTRACT: Ocean acidification (OA) is an escalating environmental challenge that poses significant threats to marine ecosystems, especially coral reefs. The Red Sea, characterized by its distinct marine biodiversity and climatic conditions, is becoming increasingly susceptible to the effects of (OA). This review investigates the impact of ocean acidification on coral reefs in the Red Sea, emphasizing physiological, ecological, and socio-economic consequences. Alterations in seawater chemistry, notably a reduction in pH and the availability of carbonate ions, impede coral calcification, disrupt symbiotic relationships, and contribute to coral bleaching. The review also highlights the vulnerability of coral species in the Red Sea, which is further exacerbated by local stressors such as temperature variations, pollution, and overfishing. Additionally, it examines various strategies to mitigate these impacts, including active coral reef restoration, genetic adaptation research, the creation of marine protected areas, and the mitigation of local environmental stressors. Addressing ocean acidification in the Red Sea necessitates a combination of global and regional initiatives aimed at reducing (CO_2) emissions, alongside local conservation measures to enhance the resilience of coral reef ecosystems. This review highlights the critical need for interdisciplinary research and cooperative efforts to protect the future of coral reefs in the region.

Key words: Ocean acidification (OA), Red Sea, coral reefs, coral bleaching

INTRODUCTION

Human-induced disturbances in marine environments across the globe have significantly disrupted the natural dynamics of ecosystems due to both global stressors, such as climate change, and local stressors such as from coastal development, agricultural runoff, over-exploitation, and habitat degradation. Coral reefs, in particular, have suffered some of the most severe adverse effects worldwide. After such disturbances, new substrates may become available for colonization and the subsequent growth of new organisms on the reefs. Turf and macroalgae frequently emerge as early colonizers of these bare substrates, attributed to their rapid growth and high dispersal capabilities. In a healthy reef ecosystem, the natural succession typically advances from the growth of turf algae to the colonization of crustose coralline algae (CCA) and other algal crusts, which subsequently facilitate the settlement of a diverse array of invertebrate communities, including stony corals **(Hulver *et al*., 2022).**

Consequently, these so-called 'pioneer communities' are crucial for the biological succession and restructuring of reefs following disturbances **(Roth *et al*., 2014).** The species composition and settlement sequence can serve as indicators for the future configuration of the reef, potentially leading to either a thriving, coral-dominated ecosystem or a shift towards an algal-dominant environment in nutrient-rich reefs. Additionally, pioneer communities contribute comparable amounts of fixed carbon to the reef as healthy coral populations through

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elevated rates of photosynthesis, thereby supporting the trophodynamics of coral reefs in the aftermath of coral decline **(Hulver *et al*., 2022).**

In a significant review examining the potential effects of various IPCC scenarios on oceans and their ecosystem services, **Gattuso *et al*. (2015)** revealed that coral reefs are the most vulnerable marine ecosystems, regardless of the IPCC scenario (RCP2.6/RCP8.5), and currently represent the most endangered ecosystems worldwide. Coral reef ecosystems exemplify the intricate connections among biology, ecology, human societies, and global changes. Consequently, it was appropriate for the theme of the 4th Workshop in the series to concentrate on the biodiversity and ecosystem services provided by coral reefs, particularly in light of 2018 being designated as the International Year of the Reefs. Like previous workshops, this event aimed to explore innovative and interdisciplinary solutions from the Natural, Economic, and Social Sciences. Thus, the workshop's objective was to identify science-based solutions at both global and regional levels that could enhance the resilience of coral reefs facing threats from ocean acidification and other global or local stressors.

Aim of the Study

The objective of researching the impacts of ocean acidification (OA) on coral reefs in the Red Sea is to gain insights into the particular vulnerabilities of these ecosystems as they respond to rising atmospheric CO_2 concentrations. The Red Sea, characterized by its distinct environmental conditions, acts as a vital natural laboratory for exploring the relationship between acidification and coral health. This study aims to assess the physiological and ecological consequences of (OA) on the coral reefs in this area, with the goal of pinpointing potential risks to coral biodiversity, reef integrity, and the overall health of marine ecosystems.

Furthermore, the research seeks to evaluate the effectiveness of different approaches to tackle these issues, such as local conservation initiatives, coral restoration methods, and the possibilities for coral adaptation to acidic environments. The primary objective is to offer insights that can inform effective policy and management strategies aimed at safeguarding coral reefs in the Red Sea, while also contributing to wider efforts to alleviate the global effects of ocean acidification on marine ecosystems.

Research Problem

The research problem is to identify the impact of ocean acidification (OA) on coral reefs in the Red Sea focuses on identifying the specific and often distinct vulnerabilities of these ecosystems to the ongoing alterations in seawater chemistry. As global CO_2 levels rise, a substantial amount of this gas is absorbed by the oceans, resulting in lower pH levels and reduced availability of carbonate ions, which are essential for coral calcification. The Red Sea, characterized by its unique environmental conditions—such as elevated temperatures, high salinity, and low nutrient availability—provides a distinctive context for examining how these factors interact with (OA) to affect coral reef ecosystems.

This research issue is of paramount importance, as the coral reefs in the Red Sea play a vital ecological role by providing habitat for a wide array of marine species and supporting the livelihoods of millions through tourism, fisheries, and coastal protection. The study aims to investigate the effects of combined stressors, including ocean acidification, thermal stress, pollution, and overfishing, on the health, resilience, and biodiversity of these coral reefs. Additionally, gaining insights into the responses of these reefs to ocean acidification will inform conservation initiatives and management strategies, ultimately helping to alleviate the effects of acidification and enhance the adaptive capacity of these ecosystems.

Furthermore, this research endeavor seeks to investigate possible solutions to mitigate the adverse impacts of ocean acidification (OA), including coral restoration efforts, studies on genetic resilience, the establishment of marine protected areas, and the alleviation of local human-induced stressors. The objective is to develop a framework for sustainable management practices aimed at protecting coral reefs in the Red Sea from the escalating challenges posed by ocean acidification.

The Biological and Ecological Importance of Coral Reefs

Coral reefs are complex biological structures primarily built by Scleractinian corals, which are often referred to as "Ecosystem Engineers" **(Jones *et al*., 1994).** These reef-building corals produce a calcium carbonate skeleton, and over millions of years, the accumulation of this material leads to the formation of coral reefs. These reefs represent the largest constructions made by living organisms; for instance, the Great Barrier Reef, located off the northeast coast of Australia, stretches for 2,600 kilometers and covers an area of approximately 344,000 square kilometers, while the New Caledonia barrier reef extends 1,600 kilometers. The annual growth rate of coral reefs is typically around 4 kilograms of ($CaCO_3$) per square meter **(Smith and Kinsey, 1976)**, with some branched corals exhibiting linear growth rates exceeding 10 centimeters annually. The largest known colony of massive corals, dubbed "Big Momma," has a diameter of 12 meters and a height of 7 meters; it is a giant Porites located in the National Marine Sanctuary of the Samoa Archipelago in the Pacific **(Brown *et al*., 2009)**.

Coral reefs first appeared approximately 450 million years ago, with the "modern" varieties originating during the Triassic period, around 237 million years ago **(Stanley, 2003; Hoegh-Guldberg, 2014)**. Currently, they are predominantly found between latitudes 30°N and 30°S, within the tropical and subtropical regions surrounding the equator. Typically, these reefs develop at depths ranging from 0 to 30 meters, although they can extend beyond 100 meters in certain locations, known as Mesophotic Reefs. Their distribution is primarily influenced by factors such as light availability (photic zone) and water temperature **(Spalding *et al*., 2001)**.

Currently, coral reefs cover an estimated area ranging from 284,300 km² **(Spalding *et al*., 2001)** to 600,000 km² (Smith, 1978), representing approximately 0.08% to 0.16% of the ocean's surface. Indonesia and Australia lead in reef area, accounting for 17.95% and 17.22% of the world's reefs, respectively, followed by the Philippines at 8.8%. Interestingly, despite this limited area, coral reefs are home to around 30% of all described marine species, totaling 93,000 species within the reefs out of 274,000 known marine species **(Porter and Tougas, 2001)**. This includes 25% of marine fish species **(Allsopp *et al*., 2009)**, highlighting that coral reefs possess nearly 400 times the species diversity found in other oceanic regions, making them comparable to large rainforests in terms of species richness per square kilometer **(Reaka-Kudla, 1997)**.

This intriguing phenomenon of an oasis amidst an expansive oceanic desert was first described by Darwin in 1842 and later referred to as the "Darwin Paradox" **(Stoddart, 1976; Crossland, 1983)**. Tropical waters are notably deficient in nutrients, characterizing them as oligotrophic environments, which poses challenges for sustaining life. The thriving existence of coral reefs is attributed to a crucial biological interaction: the symbiosis between corals and unicellular algae, known as zooxanthellae, which reside within coral cells (for a comprehensive review, see **Furla *et al*., 2005; Stambler, 2011**). These algae are primarily found within the endodermal cells of coral tissue, with a density reaching approximately 1 million zooxanthellae per cm² of coral. The process of photosynthesis performed by these microalgae generates photosynthates (sugars), with the majority—up to 95% **(Muscatine, 1990; Stambler, 2011)**—being transferred to the coral host. This transfer provides the coral with most of its nutritional needs, although the coral is still capable of capturing prey and absorbing dissolved nutrients **(Houlbrèque and Ferrier-Pagés, 2009)**.

Symbionts play a crucial role in supplying the oxygen required for coral respiration, while the coral host offers a secure habitat for these symbionts, protecting them from grazing. In exchange, the symbionts gain access to nitrogen and phosphorus through the recycling of the host's metabolic waste **(Furla *et al*., 2005)**, thereby minimizing waste in an environment that is low in nutrients. Nutrients that are not utilized for coral metabolism are released into the reef environment as mucus at a significant rate, approximately 5 liters per square meter of reef annually **(Wild *et al*., 2004)**. This process facilitates the connection between the coral/zooxanthellae symbiosis and the nutritional dynamics of the reef, while also promoting waste recycling. It addresses Darwin's paradox, which highlighted the richness of coral reefs despite the scarcity of food in tropical oceans. Consequently, this symbiotic relationship is fundamental to the establishment of the coral reef ecosystem **(Allemand and Furla, 2018**).

Coral reefs, a Threatened Sentinel Ecosystem

The health of reef ecosystems worldwide is currently under significant threat. Research conducted by **De'ath *et al*. (2009).** on 328 massive corals from the Great Barrier Reef indicates that reef growth has been declining at a rate of 14.2% since 1990, following a period of stability that lasted for 400 years. As part of the "Tara Pacific" expedition, which took place from 2016 to 2018, the schooner Tara is conducting a comprehensive analysis of Pacific Ocean reefs to assess, among other factors, the changes in growth rates over the past century. However, projections from the Intergovernmental Panel on Climate Change (IPCC) in their October 2018 report, "Global warming at 1.5 °C," forecast a potential loss of 90% of reef-building corals by the end of this century with a temperature increase of 1.5 °C, and an almost complete loss (over 99%) with a 2 °C rise **(IPCC, 2018)**.

While these forecasts may seem particularly grim, it is evident that even if corals do not entirely vanish, the structure of coral reefs will undergo significant alterations **(Hughes *et al*., 2018; Moritz *et al*., 2018)**. It is also important to recognize that the methods used to identify coral species can yield varying results; for instance, the quadrat method enables a more detailed examination of smaller and more cryptic coral species that may be overlooked by less precise techniques **(Jokiel, 2015)**.

There are two categories of threats: local and global. Local threats primarily include overfishing, the use of destructive fishing methods such as dynamite or cyanide, unsustainable tourism practices, the development of coastal infrastructure, pollution from agricultural fertilizers and pesticides, wastewater discharge, sedimentation, the spread of Acanthaster starfish, and the utilization of coral skeletons in construction **(Burke *et al*., 2011).** These locally manageable threats compromise the health of coral reefs, diminishing their ability to withstand global pressures **(Carilli *et al*., 2009)**.

There are two kinds of global threats:

• Physical Modification: Water Worming

This phenomenon represents the most urgent and significant global threat to coral reefs **(Hughes *et al*., 2017)**. A mere increase of 1 °C above the typical summer sea surface temperature can disrupt the symbiotic relationship between corals and their zooxanthellae, leading to its deterioration. Consequently, corals expel their zooxanthellae, resulting in the loss of the vibrant colors they provide, which exposes the underlying white skeleton through the transparent coral tissue. This process is commonly referred to as "coral bleaching." The cellular mechanisms responsible for the breakdown of this symbiosis remain a topic of ongoing debate **(Weis, 2008; Roth, 2014; Bieri *et al*., 2016)**, as do the specific roles of both the host and the symbionts **(Hoegh-Guldberg *et al*., 2019)**. Bleaching can impact a reef spanning several square kilometers within just a few hours, making it a highly visible manifestation of global warming.

Although the first instances of coral bleaching were noted as early as the early 20th century, it was not until the 1980s that this phenomenon became a recurring issue, marked by three significant episodes **(Brown, 2015; Donner *et al*., 2017).** The first episode occurred between 1997 and 1998, resulting in the loss of 16% of the world's coral reefs, predominantly in the Indian Ocean. The second episode took place in 2010 and affected reefs globally. The most recent event, occurring from 2015 to 2016, stands as the longest, largest, and most destructive occurrence for coral reefs to date. Notably, certain regions of the Great Barrier Reef, despite being distant from direct human influence, experienced bleaching rates of up to 99%, leading to mortality rates of 30%, and in some areas like Lizard Island, as high as 90% **(Hughes *et al*., 2017).** During this event, it is estimated that 29% of shallow-water coral cover was lost across the Great Barrier Reef Marine Park (2017). The death of centuries-old coral colonies underscores the extraordinary nature of this phenomenon, with mortality rates reaching 80% recorded in Kiribati **(Ezzat and Courtial, 2016)**.

Coral bleaching events seem to be intensifying and occurring with greater frequency. According to **Hughes *et al*. (2017),** the duration during which surface water temperatures surpass the summer average has lengthened from 1998 to 2016, correlating with rising temperatures. Projections indicate that, in the foreseeable future, bleaching occurrences may become an annual phenomenon, with over 90% of the world's reefs likely to be impacted by 2050 **(Frieler *et al*., 2012; Kwiatkowski *et al*., 2015)**.

In 2008, a report from the Global Coral Reef Monitoring Network indicated that 19% of coral reef surfaces had vanished, with an additional 15% facing imminent threats **(Wilkinson, 2008)**. By 2011, this figure had escalated, with 60% of reefs identified as being at risk in the short term **(Burke *et al*., 2011)**. As of 2018, limited regional data continued to reflect a global decline. For instance, in the Caribbean, the average coral cover across 88 sites decreased from 34.8% in 1970 to 16.3% in 2011, although significant variability was noted among different locations **(Jackson *et al*., 2014)**. The bleaching event of 2005 resulted in 80% of the Caribbean's reef surface experiencing bleaching, leading to the death of 40% of the reefs **(Eakin *et al*., 2010)**. Over the past three years, 21 out of 29 reefs listed as World Heritage sites have suffered from severe and recurrent bleaching, particularly affecting four notable reefs: the Great Barrier Reef (Australia), Papahānaumokuākea (Hawaii, USA), the Lagoons of New Caledonia (France), and Aldabra Atoll (Seychelles). Nevertheless, a recent global assessment of Pacific reefs revealed that the average live coral cover remained relatively stable from 1990 to 2016, although shifts in species composition were noted, with a decline in Pocillopora spp. and an increase in Porites spp. **(Moritz *et al*., 2018)**. This suggests that while there is a semblance of stability, the coral community is slowly transitioning from branched to massive coral forms. It is also important to highlight that conventional metrics used to assess ecosystem health and population status may not effectively capture significant, albeit subtle, changes in community composition **(Bellwood et al., 2006)**.

Predictions are overall pessimistic, and the latest IPCC report estimates, with very high confidence, that bleaching will cause coral mortality in the order of 50% resulting in a reduction in the equivalent reef area **(Wang *et al* ., 2014)**

Chemical Modification: Ocean Acidification Induced by Carbon Dioxide. The phenomenon known as 'ocean acidification' results from the dissolution of carbon dioxide in oceanic waters causing a decrease in the pH of the seawater according to the reaction: $CO_2+H_2O \rightarrow HCO_3^{-}+H^{+}$ (reaction 1) (where HCO_3^{-} is bicarbonate and H^{+} is the acidic hydrogen ion).

While this phenomenon may provide short-term benefits to humanity by mitigating the greenhouse effect and consequently lowering the rise in Earth's average surface temperature, it has also resulted in a 30% increase in ocean acidity since the onset of this era, with a decrease in pH from 8.2 to 8.1. Projections suggest that pH levels could drop to 7.8 by the end of this century **(Lerman *et al*., 2011)**, despite remaining stable for the past 300 million years. The acidification of the oceans alters the chemical composition of seawater, particularly affecting carbonate chemistry, which is a complex system crucial for maintaining pH equilibrium in seawater and all biological fluids, including plasma, as well as in the formation of sedimentary rocks.

The carbonate ion (CO_3^{-2}) is vital for the construction of shells and skeletons of invertebrates, including corals, as it reacts with calcium to produce calcium carbonate ($CaCO_3$ or limestone) through the following reaction: $CO_3^{-2} + Ca^{+2} \rightarrow CaCO_3$ (reaction 2). As seawater acidity increases, excess protons (H^{+}) will interact with the carbonate ion, as shown in reaction 3: $H^{+} + CO_3^{-2} \rightarrow HCO_3^{-}$ (reaction 3). This process leads to a reduction in carbonate concentration in seawater. Such chemical changes have significant biological consequences, affecting the availability of carbonate needed for skeleton formation and altering pH, which is a critical factor in physiological processes **(Comeau *et al*., 2017)**. The pH level influences numerous cellular functions, including the activity of various proteins. Nevertheless, further research is essential to comprehensively understand the full effects of ocean acidification on coral reefs **(Hilmi *et al*., 2013a, Hilmi *et al*., 2013b; see also Hoegh-Guldberg *et al*., 2019)**.

Ocean acidification impacts a diverse range of species, including corals, bivalves, and finfish. Among the various biological consequences of ocean acidification are diminished calcification, interference with essential physiological functions such as reproduction and nutrition, and alterations in behavior. Research indicates significant variability in the sensitivity of different organisms. For instance, studies conducted on coral reefs exposed to natural carbon dioxide sources, such as CO_2 vents in Papua New Guinea, reveal that massive corals can withstand conditions down to a pH of 7.7, while branched corals exhibit high sensitivity **(Fabricius *et al*., 2011)**. It appears that in a more acidic environment, some species may thrive while others decline, leading to substantial disruptions in reef structure and ecology, characterized by reduced coral biodiversity and increased algal proliferation **(Fabricius *et al*., 2011)**. Furthermore, laboratory investigations suggest that while certain coral species may show resilience to acidification, their growth in length remains unaffected; however, these colonies experience increased porosity, resulting in more fragile branches **(Tambutté *et al*., 2015; Rippe *et al*., 2018)**, indicating a troubling future for coral reefs.

As of now, the immediate consequences of warm water bleaching events continue to represent the most significant and devastating threat to coral reefs. However, the prolonged effects of ocean acidification further weaken the ability of reef ecosystems to withstand these events. A key issue under discussion is the adaptability of these systems, which has become a focal point in current debates **(refer to Allemand *et al*., 2017**) for a comprehensive overview).

What Are the Solutions for Reefs?

The only sustainable approach to counteracting ocean acidification and its synergistic effects with increasing sea surface temperatures is to reduce atmospheric CO_2 levels. This involves striving to keep global warming "well below 2 °C compared to pre-industrial levels" and, if feasible, to "continue efforts to limit the rise in temperatures to 1.5 °C," as articulated during the COP21 in Paris **(UNFCCC, 2015)**. It is evident that implementing this solution will require considerable time, and the consequences of climate change may have already resulted in irreversible damage, as the effects of global change on coral reefs have been observable for nearly four decades. Consequently, it is imperative to devise strategies that can mitigate the impacts of ocean acidification and elevated sea surface temperatures in the interim.

This interdisciplinary workshop convened 62 experts in economics, social sciences, and natural sciences from various disciplines, including marine biology, physiology, ecology, zoology, oceanography, genomics, biogeochemistry, macro- and microeconomics, blue finance, anthropology, marine policy, and sociology, along with leaders from NGOs and policymakers, representing 22 countries. The purpose of the three-day event was to foster a global dialogue regarding the ecological and socio-economic challenges facing coral reefs across six distinct regions worldwide. This dialogue yielded both local and global solutions. The solutions identified during the workshop are categorized below according to the four classifications proposed by **Gattuso *et al*. (2015)** (Fig. 1):

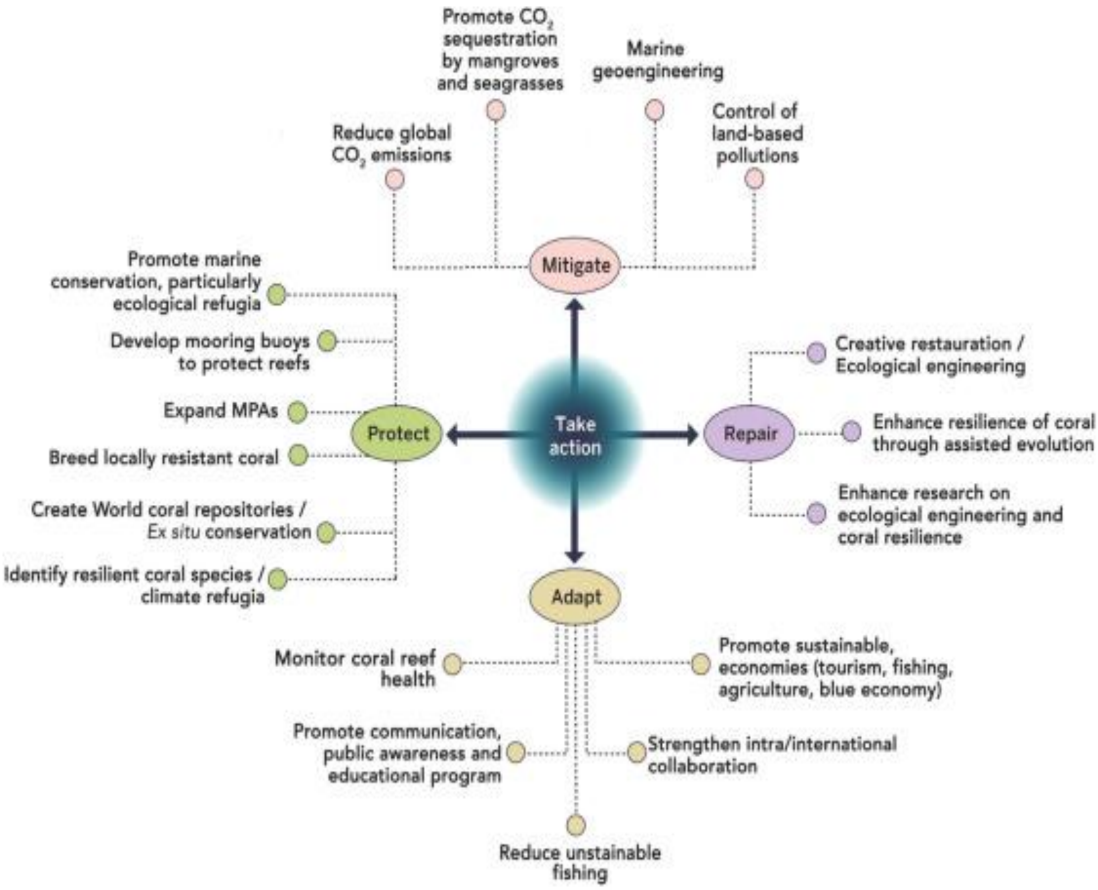

Fig. 1. Solutions for coral reefs against climate. The diagram is based on the four clusters of actions against climate change proposed by **Gattuse *et al*.,(2015)** and adapted for specific solutions for coral reefs.

4.1 Mitigation: Mitigation strategies aim to stabilize greenhouse gas levels by tackling the root causes of climate change, such as lowering carbon dioxide emissions **(IPCC 2018)**. Many of these approaches, which are not exclusively focused on coral reefs, involve the restoration or cultivation of marine phanerogam meadows (seagrass) and the replanting of mangroves. These ecosystems serve as highly effective "CO_2 sinks," helping to alleviate the decrease in pH associated with ocean acidification **(Howard *et al*., 2017)**. The development of phanerogam meadows can also contribute to a reduction in bacterial pathogens **(Lamb *et al*., 2017)**. Additionally, marine geoengineering techniques have been suggested, such as the introduction of alkaline substances into seawater (for a comprehensive review, see **(Hilmi *et al*., 2015)** or the application of biodegradable biopolymers on the water's surface to limit light penetration.

4.2 Protection: Regulations at local, regional, or national levels, along with market incentives and social awareness campaigns, can play a significant role in mitigating localized pollution that undermines coral reef ecosystems, thereby diminishing their resilience to climate change **(Carilli *et al*., 2009)**. The establishment of marine protected areas (MPAs) has been frequently recommended as an effective strategy to alleviate local stressors and enhance resilience to global changes **(Hilmi *et al*., 2015)**. The contribution of MPAs to the mitigation, adaptation, and safeguarding of coral reefs is well-documented in various scientific studies **(Lamb *et al*., 2015; Roberts *et al*., 2017)**.

However, it is noteworthy that less than 6% of coral species are adequately safeguarded by MPAs, which corresponds to less than 10% of their distribution range **(Mouillot *et al*., 2016)**.

Furthermore, MPAs do not offer complete protection against global changes; for instance, the northwestern region of the Great Barrier Reef, which is protected and distanced from direct human impact, experienced a significant bleaching event exceeding 90% during 2015–2016 **(Hughes *et al*., 2017)**. One potential solution is to prioritize the protection of "refuge" areas where corals exhibit greater resilience compared to typical environments, such as the Persian Gulf **(Coles and Riegl, 2013)**, the Red Sea or the mesophotic zone at depths between 30 and 150 meters **(Osman *et al*., 2017**. Additionally, the establishment of coral repositories has been suggested to conserve coral species for future reef restoration efforts or scientific research (Zoccola D., pers. comm.), alongside the advancement of studies focused on coral resilience **(Conservation Physiology, see Wikelski and Cooke, 2006).** The coral conservatory could also facilitate the selection of resilient strains through assisted evolution techniques **(van Oppen *et al.*, 2015)** and artificial breeding methods **(West and Salm, 2003).**

Adaptation

A crucial aspect of adaptation strategies for reef areas involves the promotion of 'blue' economies—such as tourism, fisheries, and agriculture—that adhere to sustainability principles. In various regions, alleviating the pressure of tourism on reefs can be achieved by regulating diving activities **(Hasler and Ott, 2008)** or by establishing artificial reefs that can initially be explored by novice divers **(Kotb, 2016)**. The establishment of the Underwater Museum of Art (MUSA) in Cancún, Mexico, which opened in 2010 and features 450 underwater sculptures, exemplifies this approach, as does the implementation of ecological mooring buoys **(ICRI, 2017).**

The workshop also emphasized the importance of enhancing both intra- and international collaboration, particularly in regions like the Red Sea, to develop coral reef health monitoring programs and to foster communication, educational initiatives, and public awareness. Additionally, policy and governance measures can be employed to facilitate the adaptation of fisheries and aquaculture, such as adjusting fishing pressures to sustainable levels and promoting more resilient fish species, including pelagic varieties **(see Shelton, 2014)**.

Repair

The final category focuses on the repair and restoration of damaged reef ecosystems. This can be achieved by utilizing colonies sourced from "refuge" areas, such as the Persian Gulf **(refer to Coles and Riegl, 2013)**, or through (i) ex situ live coral repositories that utilize asexually-produced coral fragments (World Coral Conservatoire) **(Leal *et al*., 2014)**, (ii) juveniles obtained via sexual reproduction **(Nakamura *et al*., 2011)**, or (iii) in situ cultivation **(Kotb, 2016; Rinkevich, 2005; Rinkevich, 2014)**. During the cultivation process, resilient coral strains may be "selected" through an "assisted evolution" approach **(van Oppen *et al*., 2015)**. These researchers advocate for the "evolution" of corals to enhance their resilience. They propose four strategies: the first involves artificially inducing resistance through laboratory stress, retaining only the surviving colonies (pre-conditioning acclimatization). This process is influenced by epigenetic mechanisms, as recently shown during laboratory acidification stress **(Liew *et al*., 2018)**. The second strategy recommends actively modifying the coral-associated microbiota to select for the most beneficial community **(Peixoto *et al*., 2017).**

The third approach advocates for selective breeding to create resistant phenotypes. The final strategy involves the artificial evolution of the algal component within the coral holobiont through mutation and genetic selection of zooxanthellae, followed by the inoculation of these resistant strains into corals **(Hume *et al*., 2015)**. Subsequently, corals can be relocated to natural substrates or artificial reefs. The Reef Ball Foundation, a non-profit organization, has established specific protocols for the deployment, anchoring, and transplantation of corals. Biorock is a patented technique that utilizes electrolytic deposits of calcium carbonate to form artificial structures **(Goreau and Hilbertz, 2005)**. To enhance reef restoration, either in situ or ex situ coral cultivation may be necessary; however, regardless of the method employed, the costs associated with transplantation can be exorbitant, potentially reaching up to US$ 15,000 per square meter restored **(Ferrario *et al*., 2014)**. The French NGO Coral Guardian implements reef restoration initiatives that actively engage local communities, thereby reducing costs and fostering greater community involvement in sustainable development efforts to enhance their livelihoods.

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اثار تحمض المحيطات على الشعاب المرجانية فى البحر الاحمر وطرق معالجتها – دراسة مرجعية

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يعتبر تحمض المحيطات مشكلة بيئية متنامية تُشكل تهديدات جسيمة للنظم البيئية البحرية، وخاصةً الشعاب المرجانية. ويتعرض البحر الأحمر، بتنوعه البيولوجي البحري الفريد وظروفه المناخية الفريدة، لتأثيرات تحمض المحيطات بشكل متزايد. تركز هذه الدراسة على دراسة آثار تحمض المحيطات على الشعاب المرجانية في البحر الأحمر، مع التركيز على عواقبها الفسيولوجية والبيئية والاجتماعية والاقتصادية. وقد بينت الدراسات المختلفة أن التغيرات في كيمياء مياه البحر، وخاصةً انخفاض الرقم الهيدروجيني (pH) وتوافر أيونات الكربونات، تكلس المرجان، تُعيق وتُعطل العلاقات التكافلية، وتؤدي إلى ابيضاض الشعاب المرجانية. تُسلط الدراسة الضوء ايضا على هشاشة أنواع المرجان في البحر الأحمر، والتي تتفاقم بفعل عوامل ضغط بيئية مثل تقلبات درجات الحرارة والتلوث والصيد الجائر. علاوةً على ذلك، تستكشف الدراسة استراتيجيات مُختلفة للتخفيف من هذه الآثار، بما في ذلك استعادة الشعاب المرجانية من خلال التدخل الفعال، ودراسات التكيف الجيني، وإنشاء مناطق بحرية محمية، والحد من عوامل الضغط البيئية المحلية. وتوصي الدراسة بضرورة التصدي لمشكلة تحمض المحيطات في البحر الأحمر من خلال تضافر الجهود العالمية والإقليمية للحد من انبعاثات ثاني أكسيد الكربون، إلى جانب استراتيجيات محلية للحفاظ على البيئة لتعزيز مرونة النظم البيئية للشعاب المرجانية. ويؤكد هذا الاستعراض على الحاجة الملحة للبحث متعدد التخصصات والعمل التعاوني لحماية مستقبل الشعب المرجانية في المنطقة.

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