The Impact of Ocean Acidification on Coral Reef Ecosystems: A Synthesis of Biological and Chemical Perspectives

Sritaja Sirivolu

Legacy School Bangalore, Karnataka, India
Email: *srita.sirivolu[at]gmail.com*

Abstract: ***Ocean acidification, driven by increased absorption of atmospheric carbon dioxide (CO_2), alters marine chemistry and threatens coral reef ecosystems. This literature review synthesizes recent research (2012–2025) on four key impacts: coral bleaching events, disruption of coral-algae symbiosis, degradation of calcium carbonate saturation, and reef restoration and mitigation strategies. The current rate of ocean acidification is approximately ten times faster than anything experienced during the last 300 million years (IUCN). Studies show that the ability of ocean systems to adapt to changes in ocean chemistry due to CO_2 and warming waters lead to declining ocean pH and aragonite saturation, compromising coral skeletal formations via impaired calcification, which threatens metabolic function (EPA, 2025) and exacerbating bleaching due to thermal stress from global warming. Emerging interventions—such as selective breeding, localized alkalinity enhancement, coral gardening and marine protected areas—show potential. For instance, the transplantation of heat-tolerant coral species in the Great Barrier Reef has demonstrated increased resilience to bleaching. However, their effectiveness is limited by the efficiency of reduction in global CO_2 emissions. This synthesis highlights the urgency of interdisciplinary strategies to protect coral reefs in a changing ocean.***

Keywords: Ocean acidification, Coral bleaching, Coral-Algae symbiosis, Coral calcification, Aragonite saturation, Restoration strategies

1. Introduction

Ocean acidification refers to the gradual reduction in the ocean's pH due to increased absorption of CO_2 from the atmosphere. The oceans act as carbon sinks, which naturally absorb CO_2 from the atmosphere. Ocean water and carbon dioxide combine to form carbonic acid (H_2CO_3), a weak acid that dissociates into hydrogen ions (H^+) and bicarbonate ions (HCO_3^-). With increasing human activity, such as burning fossil fuels for energy, transport and industrial purposes, the amount of CO_2 absorbed by the ocean is increasing, causing the water to become more acidic.

According to NOAA (2025), the oceans absorb approximately 30% of anthropogenic CO_2 emissions. Since the Industrial Revolution, carbon emissions have lowered global ocean pH by 0.1 units, causing a 30% increase in ocean acidity, altering carbonate chemistry.

Coral reefs, often called the "rainforests of the sea," support biodiversity by providing habitats, spawning grounds, foundation for food chains and nutrients (the Coriolis effect), and nutrient cycling (carbon & nitrogen cycles). For these reasons of high primary productivity, they are vital for the fishing economy as they sustain fisheries worldwide and support the livelihoods of local and global fishermen (fisheries for crustaceans, molluscs, sea urchins etc). They provide other economic value in tourism & recreation. Additionally, they act as natural barriers, reducing wave energy and protecting coastlines from erosion and storm surges.

Yet, they are highly vulnerable to environmental changes, particularly ocean acidification, which disrupts carbonate chemistry essential to reef formation (Albright & Cooley, 2019). This shift in ocean chemistry can disrupt the delicate balance required for coral calcification and overall reef health.

Coral bleaching, a consequence of ocean acidification, is a critical environmental phenomenon where corals lose their vibrant colours, appearing white or dull due to the expulsion of zooxanthellae, the symbiotic algae that live in coral tissues. (Lee, 2024). The loss of these symbiotic algae can have cascading negative effects in the overall health of reef ecosystems due to loss of the corals' ability to build their structures and grow further. This can have devastating effects on the marine biodiversity that depends on the corals for habitats and food, as well as negatively affecting livelihoods that depend on the fishing economy.

This literature review explores the effects of ocean acidification on coral reef systems, with a focus on the underlying biological and chemical mechanisms and resulting conservation challenges. I will be structuring it around four critical aspects: loss of coral-algae symbiosis, bleaching and its effect on marine carbonate chemistry, impaired calcification, and reef restoration and mitigation strategies as well as their limitations.

2. Methodology

This literature review was conducted by systematically synthesizing peer-reviewed studies published between 2012 to 2025 to assess the impacts of ocean acidification on coral reef ecosystems. Relevant articles were sourced from databases such as PubMed, Google Scholar and other environmental websites like The Coral Reef Research Hub, NOAA, EPA, using keywords including "ocean acidification," "coral bleaching," "coral calcification," "aragonite saturation," and "reef restoration." Studies were selected based on their focus on biological and chemical mechanisms, relevance to coral reef resilience against rising CO_2 levels and global warming, and inclusion of statistics on real-world restoration strategies. A total of 39 studies were analysed, prioritizing those with quantitative data on pH effects, aragonite saturation, and mitigation outcomes. The review was structured around four key themes: disruption of coral-algae symbiosis, carbonate chemistry degradation, restoration strategies, and their limitations, using a comparative approach to integrate findings across disciplines and highlight gaps in current conservation efforts.

3. Literature Review

3.1 Disruption of Coral–Algae Symbiosis & Bleaching

The relationship between corals and zooxanthellae (a type of photosynthetic algae: single-celled dinoflagellates that live within the coral's tissues), is an essential mutualistic symbiosis for reef ecosystems. The zooxanthellae provide up to 90% of essential energy in the form of sugars and lipids, as well as oxygen, to the coral via photosynthesis, as well as removal of waste products, while the corals provide the algae with a protected environment, carbon dioxide and other nutrients required for photosynthesis. (Lee, 2024)

Coral calcification is the process where corals deposit calcium carbonate ($CaCO_3$) to build their skeletons, a process that combines calcium and carbonate ions from the seawater. The nutrients (e.g.: glucose) supplied by the zooxanthellae provide the coral with the energy required to build and grow its calcium carbonate skeleton. By using the energy provided by the zooxanthellae, the coral extracts calcium (Ca^{2+}) and carbonate ions (CO_3^{2-}) from the surrounding seawater. Coral calcification is also enhanced by the zooxanthellae as they remove carbon dioxide from the corals' internal environment via photosynthesis, providing a higher pH that allows the combination of calcium and carbonate ions to form calcium carbonate (Allison et al., 2018), which is secreted to build the corals' hard, protective skeleton (Kault et al., 2022).

Coral bleaching is a stress response that occurs when the coral-zooxanthellae relationship breaks down and the zooxanthellae are expelled from their coral hosts or when pigments within the zooxanthellae are degraded (Reef Resilience Network). Bleaching is a response to environmental stressors, notably rising ocean temperatures caused by global warming. This causes the corals to become stark white or a dull, muted colour due to the expulsion of zooxanthellae, leaving corals weakened, more susceptible to disease, and often leading to death if conditions do not improve (Lee, 2024). Although thermal stress is the primary driver, ocean acidification also exacerbates bleaching's effects by compromising symbiosis and energy balance. Ocean acidification hinders the ability of corals to recover from these bleaching events because it reduces the amount of calcium carbonate available that corals need to grow back to health (Union of Concerned Scientists, 2019). Additionally, this also poses a threat to shell-building organisms (mussels, clams, crustaceans etc) as they do not have the basic compounds required to build protective shells and skeletons, reducing their chances of survival.

3.2 Degradation of Carbonate Chemistry & Impaired Calcification

Ocean acidification fundamentally alters carbonate chemistry due to the excess dissolved CO_2 in seawater turning into carbonic acid, which releases extra H^+ ions, lowering seawater pH. These H^+ ions combine with carbonate ions (CO_3^{2-}) to form bicarbonate ions (HCO_3^-). This means fewer carbonate ions are available to form calcium carbonate, reducing aragonite saturation (a measure of calcium carbonate available in seawater), and inhibiting coral skeletal growth. Aragonite is one of the more soluble types of calcium carbonate and is frequently used by calcifying marine organisms (organisms that build calcium carbonate structures). Aragonite saturation state is commonly used to track ocean acidification because it is a measure of carbonate ion concentration. Corals and other calcifiers are more likely to survive and reproduce when the aragonite saturation state is greater than 3. When aragonite saturation state falls below 3, these organisms become stressed, and when saturation state is less than 1, shells and other aragonite structures begin to degrade and dissolve (NOAA, 2015).

In a study done by Martinez et al. (2019), three Caribbean coral species were transplanted into a low aragonite saturation (Ω_a) environment. One species (Porites astreoides) had 20% lower survival in low Ω_a conditions compared to normal conditions. Another species (Porites porites) had only 33% survival under low Ω_a. For all the species, the skeletal density that they had built in low Ω_a was 15–30% less than under normal conditions. This indicated that their skeletons were more fragile or more susceptible to degradation.

Another study on the Great Barrier Reef (GBR) by Mongin et al. (2016) showed that the range of low Ω_a across the reefs is much larger than previously thought: in their model, the range is 1.43 for the GBR reefs, whereas earlier global coarse maps showed a variation of 0.4-1.0 in observations. The variability of 1.43 modelled by Mongin et al. was much larger than what coarse maps or earlier observations suggested (0.4–1.0), indicating that reef-scale heterogeneity of low Ω_a is higher than assumed. This variability matters for predicting how reefs will be when projecting future declines, because ignoring this local-to-regional variability can lead to under-estimation of the risks for specific reefs. The authors suggested that future decline in Ω_a on the GBR may be more severe than broad-scale models (like IPCC reports) indicate because they do not capture this fine-scale variability.

Direct effects under these low aragonite saturation conditions include corals, along with species like oysters, mussels, pteropods etc, struggling to build and maintain stable structures, leading to weakened shells and skeleton, and slower growth. Additionally, crustose coralline algae (CCA: a hard, pink algal species substrate for reefs to build on top of), also precipitates calcium carbonate in their cell walls which helps bind reef structures and provide surfaces for coral larvae settlement. However, at lower pH levels CCA becomes weaker and degrades as carbonate content reduces. As a result, coral polyps will not have the essential foundation required to grow and build the coral reefs, hampering reproduction and regeneration of reef ecosystems.

4. Restoration Strategies: Selective Breeding, Alkalinity Enhancement, Coral Replantation and MPAs

To counter ocean acidification's impacts, several restoration and mitigation strategies have emerged:

- **Selective Breeding**: This involves using nature's natural selection mechanism by growing heat-resistant corals in the lab and placing them in degraded coral areas. These new heat-tolerant corals will naturally reproduce offspring which are much more resilient to withstand global warming and the resulting bleaching of the corals.
- **Localized Alkalinity Enhancement:** In this process, researchers discovered that if alkalinity of the seawater is increased (using limestone, for example), it will reduce the acidity which in turn increases the aragonite concentration there by making the corals stronger due to higher calcium content. Although the effectiveness of this approach was proven in smaller scale ponds and lab tanks, replicating this successfully on a large scale is still under research.
- **Coral Re-plantation/Coral Gardens:** This process involves structurally removing healthy corals and planting them in the degraded areas. Alternatively, the degraded structures can be cosmetically repaired by attaching fragments of broken coral to the reef to restore habitats for marine life. This method is a more effective and immediate solution; however, implementation is time consuming due to the delicate nature of the corals and the precision required to attach fragments.
- **Marine Protected Areas (MPAs)**: MPAs reduce non-chemical stressors like overfishing and pollution, allowing ecosystems to better cope with ocean acidification. Placing MPAs in naturally thriving areas may create buffer zones that serve as stepping stones for resilient species (Coral Vita, 2025). NOAA's Coral Reef Conservation Program integrates resilience-based management, pollution reduction, sustainable fisheries, and genetic restoration under a comprehensive strategy.

5. Limitations of Mitigation Strategies

The strategies given above won't have that much of an impact if the larger issue of warming oceans and increased emissions persists. Strategies like MPAs and coral re-plantation are only possible when there are safe seawater areas available. Due to rapid global warming and ongoing acidification of the oceans, the likelihood of finding such safe zones will reduce causing these approaches to be ineffective.

Selective breeding can be an effective method in the long run but will be a costly effort given the regular re-breeding and dependence on the natural adaptation of corals to take effect. In a study conducted by researchers at New Castle University, they demonstrated that heat-resistance of corals can be increased by 1°C by subjecting the parents to a range of short-term exposure (+2.5-3.5°C over a duration of 1 week to 1 month). This, however, didn't make the future generation resistant to higher temperatures. Which means regular re-breeding and longer exposure to heat will be needed to ensure future generations become heat-tolerant, but this evolution may not keep in pace with the rapid warming of oceans (Humanes et al., 2024).

Localized alkalinity enhancement requires significant investments and is also difficult to scale given the vastness of the ocean. A simulation study conducted on the Great Barrier Reef suggested that even if 9000 tonnes of alkaline solution released each 3 days for about a year will only reduce the acidification by only 0.05, which basically offsets about 4.2 years' worth of acidification. Such slow impact will not be able to keep up with the rapid pollution of seawater, thereby requiring other control methods to maximize the benefits of this method (Mongin et al., 2021).

Coral re-plantation suffers from being able to withstand unsteady ocean conditions (typhoons, waves etc.). Furthermore, re-planted corals may not be able to get 100% larval settlements or growth resulting in lower populations because even in natural conditions 100% growth is not possible, thereby requiring additional control mechanisms for re-plantation to be effective (Okubo, 2023).

MPAs are difficult to implement at large scale, considering the vastness of the ocean. As of 2020 only about 10% of total coral environments are protected via MPAs. Lack of funding, inefficient management and rapid changing of water temperatures makes sustaining MPAs challenging and not a viable long-term solution. (Climate Sustainability Directory, 2025)

6. Conclusion

Ocean acidification driven by a 0.1-unit pH decline since pre-industrial times, threatens coral reefs by undermining coral reef resilience through chemical and biological disruptions, disrupting coral-algae symbiosis, impairing calcification and skeletal formation, and coral recruitment while increasing vulnerability to other stressors like global warming. Restoration strategies: selective breeding, alkalinity enhancement, coral gardening, and MPAs, offer localized solutions but are limited by scalability and cost. Such strategies adapt to the rapid changes of the ecosystem are known to be effective, but their long-term impact depends on localized implementation and reduction in global greenhouse gas emissions. Long-term reef survival hinges on global CO2 emission reductions, supported by interdisciplinary approaches integrating marine biology, chemistry, and policy. Innovations like automated alkalinity enhancing and genetic engineering hold promise but require further research and investment. Urgent, coordinated action is essential to preserve coral reefs as critical ecosystems.

References

[1] Albright, R., & Cooley, S. (2019). A review of interventions proposed to abate impacts of ocean acidification on coral reefs. Regional Studies in Marine Science, 29, 100612. https://doi.org/10.1016/j.rsma.2019.100612

[2] Movilla, J., Calvo, E., Pelejero, C., Coma, R., Serrano, E., Fernández-Vallejo, P., & Ribes, M. (2012). Calcification reduction and recovery in native and non-native Mediterranean corals in response to ocean acidification. Journal of Experimental Marine Biology and Ecology, 438, 144–153. https://doi.org/10.1016/j.jembe.2012.09.014

[3] Effects of ocean and coastal acidification on marine life. (2025). U.S. Environmental Protection Agency. https://www.epa.gov/ocean-acidification/effects-ocean-and-coastal-acidification-marine-life

[4] Ocean acidification. (2025). National Oceanic and Atmospheric Administration. https://www.noaa.gov/education/resource-collections/ocean-coasts/ocean-acidification

[5] Allison, N., Cole, C., Hintz, C., Hintz, K., Rae, J., & Finch, A. (2018). The effect of ocean acidification on tropical coral calcification: Insights from calcification fluid DIC chemistry. Chemical Geology, 497, 162–169. https://doi.org/10.1016/j.chemgeo.2018.09.004

[6] Hoegh-Guldberg, O., Mumby, P. J., Hooten, A. J., Steneck, R. S., Greenfield, P., Gomez, E., Harvell, C. D., Sale, P. F., Edwards, A. J., Caldeira, K., Knowlton, N., Eakin, C. M., Iglesias-Prieto, R., Muthiga, N., Bradbury, R. H., Dubi, A., & Hatziolos, M. E. (2007). Coral reefs under rapid climate change and ocean acidification. Science, 318(5857), 1737–1742. https://doi.org/10.1126/science.1152509

[7] Ocean acidification: Issues brief. (2017). International Union for Conservation of Nature. https://iucn.org/resources/issues-brief/ocean-acidification

[8] Martinez, A., Crook, E. D., Barshis, D. J., Potts, D. C., Rebolledo-Vieyra, M., Hernandez, L., & Paytan, A. (2019). Species-specific calcification response of Caribbean corals after 2-year transplantation to a low aragonite saturation submarine spring. Proceedings of the Royal Society B: Biological Sciences, 286(1905), 20190572. https://doi.org/10.1098/rspb.2019.0572

[9] Australian Institute of Marine Science. (2024). Identifying crustose coralline algae that induce coral settlement. https://www.aims.gov.au/research-topics/featured-projects/reef-spawning-research-aims/identifying-crustose-coralline-algae-induce-coral-settlement

[10] Jiménez-López, D., Ortega, T., Sierra, A., Ponce, R., Gómez-Parra, A., & Forja, J. (2021). Aragonite saturation state in a continental shelf (Gulf of Cádiz, SW Iberian Peninsula): Evidence of acidification in the coastal area. Science of The Total Environment, 787, 147858. https://doi.org/10.1016/j.scitotenv.2021.147858

[11] Mongin, M., Baird, M. E., Tilbrook, B., Matear, R. J., Lenton, A., Herzfeld, M., Wild-Allen, K., Skerratt, J., Margvelashvili, N., Robson, B. J., Duarte, C. M., Gustafsson, M. S. M., Ralph, P. J., & Steven, A. D. L. (2016). The exposure of the Great Barrier Reef to ocean acidification. Nature Communications, 7, 10732. https://doi.org/10.1038/ncomms10732

[12] NOAA Sea-level Rise and Coastal Flooding Impacts Viewer / Sea of Solutions. (2015). Ocean acidification: Saturation state: Aragonite saturation state. https://sos.noaa.gov/catalog/datasets/ocean-acidification-saturation-state/

[13] Humanes, A., Lachs, L., Beauchamp, E., Bukurou, L., Buzzoni, D., Bythell, J., Craggs, J. R. K., de la Torre Cerro, R., Edwards, A. J., Golbuu, Y., Martinez, H. M., Palmowski, P., van der Steeg, E., Sweet, M., Ward, A., Wilson, A. J., & Guest, J. R. (2024). Selective breeding enhances coral heat tolerance to marine heatwaves. Nature Communications, 15, 8703. https://doi.org/10.1038/s41467-024-52895-1

[14] Hawaiʻi Department of Land and Natural Resources. Crustose coralline algae (CCA). Accessed on July 7, 2025, from https://dlnr.hawaii.gov/holomua/crustose-coralline-algae/

[15] Cossarini, G., Lazzari, P., & Solidoro, C. (2015). Spatiotemporal variability of alkalinity in the Mediterranean Sea. European Geosciences Union, Biogeosciences, 12(6), 1647–1658. https://doi.org/10.5194/bg-12-1647-2015

[16] European Environment Agency. (2025). Ocean acidification. https://www.eea.europa.eu/en/analysis/indicators/ocean-acidification

[17] Reef Resilience Network. Coral bleaching. Accessed on July 1, 2025, from https://reefresilience.org/bleaching/

[18] Copernicus Marine. Ocean acidification: Monitoring ocean acidification (pH) through carbon uptake. Accessed on August 17, 2025, from https://marine.copernicus.eu/ocean-climate-portal/ocean-acidification

[19] Grimsditch, G. D., & Salm, R. V. (2006). Coral reef resilience and resistance to bleaching (By IUCN Resilience Science Group Working Paper Series - No 1, IUCN Global Marine Programme, & The Nature Conservancy; p. 52). IUCN. http://www.iucn.org/themes/marine/pubs/pubs.htm

[20] World Ocean Review. (2024). Alkalinity enhancement: An approach in its infancy. https://worldoceanreview.com/en/wor-8/targeted-interventions-in-marine-chemistry/

[21] Wang, X., Zoccola, D., Liew, Y. J., Tambutte, E., Cui, G., Allemand, D., Tambutte, S., & Aranda, M. (2021). The evolution of calcification in reef-building corals. Molecular Biology and Evolution, 38(9), 3543–3555. https://doi.org/10.1093/molbev/msab103

[22] Basic information about coral reefs. (2025). U.S. Environmental Protection Agency. https://www.epa.gov/coral-reefs/basic-information-about-coral-reefs

[23] What is Zooxanthellae?. (2024). NOAA Ocean Service. https://oceanservice.noaa.gov/education/tutorial_corals/coral02_zooxanthellae.html

[24] McCulloch, M., D'Olivo, J., Falter, J., Trotter, J., & Montagna, P. (2017). Coral calcification in a changing world and the interactive dynamics of pH and DIC upregulation. Nature Communications, 8, 15686. https://doi.org/10.1038/ncomms15686

[25] EBSCO. (2024). (publisher Lee, M). Bleaching coral reefs. https://www.ebsco.com/research-starters/environmental-sciences/bleaching-coral-reefs

[26] Kault, J. (2021). Do corals store carbon? Coral Guardian. https://www.coralguardian.org/en/do-corals-store-carbon/

[27] The Ocean Portal Team. (2014). Ocean acidification – invertebrates. Smithsonian National Museum of Natural History. https://ocean.si.edu/ocean-life/invertebrates/ocean-acidification

[28] Kurniawan, D. (2020). 7 scientific facts you may not know about corals. Anambas Foundation.

https://www.anambasfoundation.org/7-scientific-facts-you-may-not-know-about-corals/
[29] Union of Concerned Scientists. (2019). CO_2 and ocean acidification. https://www.ucs.org/resources/co2-and-ocean-acidification
[30] National Science Foundation. (2018). Scientists pinpoint how ocean acidification weakens coral skeletons. https://www.nsf.gov/news/scientists-pinpoint-how-ocean-acidification
[31] Kault, J., Jacob, F., & Detournay, O. (2022). Carbon balance in corals. Coral Guardian. https://www.coralguardian.org/en/carbon-balance-in-corals
[32] Grabowski, M. (2023). $4M for marine carbon removal projects could revolutionize climate mitigation, conservation. University of Hawaiʻi, School of Ocean & Earth Science & Technology. https://www.soest.hawaii.edu/soestwp/announce/news/4m-for-marine-carbon-removal-nopp/
[33] Reef Resilience Network. (2025). Emergent increase in coral thermal tolerance reduces mass bleaching under climate change. https://reefresilience.org/article-summaries/emergent-increase-in-coral-thermal-tolerance-reduces-mass-bleaching-under-climate-change/
[34] What is ocean acidification?. (2024). NOAA Ocean Service. https://oceanservice.noaa.gov/facts/acidification.html
[35] Mongin, M., Baird, M. E., Lenton, A., Neill, C., & Akl, J. (2021). Reversing ocean acidification along the Great Barrier Reef using alkalinity injection. Environmental Research Letters, 16(6), 064068. https://doi.org/10.1088/1748-9326/ac002d
[36] Feely, R. A., Sabine, C. L., Byrne, R. H., Millero, F. J., Dickson, A. G., Wanninkhof, R., Murata, A., Miller, L. A., & Greeley, D. (2012). Decadal changes in the aragonite and calcite saturation state of the Pacific Ocean. Global Biogeochemical Cycles, 26(3), GB3001. https://doi.org/10.1029/2011GB004157
[37] Okubo, N. (2023). Insights into coral restoration projects in Japan. Ocean & Coastal Management, 232, 106371. https://doi.org/10.1016/j.ocecoaman.2022.106371
[38] What are the limitations of marine protected areas?. (2025). Climate Sustainability Directory. https://climate.sustainability-directory.com/question/what-are-the-limitations-of-marine-protected-areas/
[39] Humanes, A., Lachs, L., Beauchamp, E., Bukurou, L., Buzzoni, D., Bythell, J., Craggs, J. R. K., de la Torre Cerro, R., Edwards, A. J., Golbuu, Y., Martinez, H. M., Palmowski, P., van der Steeg, E., Sweet, M., Ward, A., Wilson, A. J., & Guest, J. R. (2024). Selective breeding enhances coral heat tolerance to marine heatwaves. Nature Communications, 15, 8703. https://doi.org/10.1038/s41467-024-52895-1