JETIR.ORG ISSN: 2349-5162 | ESTD Year : 2014 | Monthly Issue
JOURNAL OF EMERGING TECHNOLOGIES AND INNOVATIVE RESEARCH (JETIR)
An International Scholarly Open Access, Peer-reviewed, Refereed Journal

# Assessing the Impact of Ocean Acidification on Coral Calcification: Investigating pH-Induced Stress Responses in Coral Species.

**Advait Kothuri and Athri Cheboli**

**Keywords**

Coral Reefs, Ocean Acidification, Calcification, pH Stress, Climate Change, Marine Biodiversity, Coral Bleaching, Carbonate Saturation, Red Cap Montipora, Hispita Montipora, Toadstool Leather Coral, Brown Sympodium, Aragonite Saturation, Coral Resilience, Coral Physiology, Experimental pH Stress, Coral Mortality, Marine Ecosystem Degradation

**Abstract**

Coral reefs rank among the most critical ecosystems on Earth due to their exceptional biodiversity. These structures not only act as habitats for countless marine species but also safeguard shorelines and sustain global livelihoods through fisheries and tourism. Nevertheless, escalating levels of atmospheric $CO_2$ linked to climate change present a significant risk to their continued existence. When carbon dioxide ($CO_2$) dissolves in seawater, it reacts with water to form carbonic acid, which lowers pH levels and reduces the concentration of carbonate ions needed for coral skeleton formation.

This study investigates how different pH levels (8.1, 7.8, and 7.6) influence coral calcification rates and overall health. We tracked their growth and stress responses over four weeks using Red Cap Montipora, Hispita Montipora, Toadstool Leather Coral, and Brown Sympodium as model species. The results indicate a significant correlation between decreasing pH levels and reduced coral growth, with up to a 50% reduction at pH 7.6. Corals exposed to more acidic conditions exhibited increased bleaching, tissue loss, and reduced polyp extension. These findings underscore the urgency of addressing rising $CO_2$ emissions to prevent irreversible damage to coral reefs, mainly as NOAA confirms we are experiencing the fourth global coral bleaching event since early 2023, unprecedentedly impacting reef systems worldwide.

## Importance of the Research/Experiment

This research is critical in the context of escalating climate change impacts on marine ecosystems. Coral reefs, being highly sensitive to ocean chemistry, serve as indicators of broader environmental health. The experiment directly quantifies the effects of projected ocean acidification scenarios on coral growth and stress responses, providing empirical evidence crucial for conservation planning. In light of the 2023–2025 global coral bleaching event, the study offers timely insights into species-specific vulnerabilities and resilience, informing both international climate policy and local reef restoration strategies.

## 1. Introduction: Coral Reefs in Crisis

Coral reefs are complex and vibrant ecosystems that provide habitat, food, and shelter for many marine species. They contribute significantly to global biodiversity and provide essential ecosystem services, including coastal protection, tourism revenue, and fisheries support. However, these invaluable ecosystems are under siege from many stressors, with ocean acidification emerging as a particularly insidious and pervasive threat.

### 1.1 Significance of Coral Reefs

Coral reefs are ecologically invaluable and economically vital. They support approximately 25% of all marine life despite occupying less than 1% of the ocean floor (Wilkinson, 2008). These intricate ecosystems serve as nurseries for countless fish species, many commercially necessary. Furthermore, coral reefs act as natural barriers, protecting coastlines from erosion and storm surges, thereby safeguarding coastal communities and infrastructure. Economically, coral reefs generate billions of dollars annually through tourism, fishing, and recreational activities (Cesar et al., 2003). Their aesthetic beauty attracts divers and snorkelers worldwide, while their rich biodiversity sustains local fishing industries.

### 1.2 The Threat of Ocean Acidification

Ocean acidification, driven by anthropogenic carbon dioxide ($CO_2$) absorption into the ocean, fundamentally alters seawater's chemistry. As $CO_2$ dissolves, it reacts with water to form carbonic acid, decreasing pH and reducing the availability of carbonate ions (Caldeira & Wickett, 2003). These carbonate ions are essential building blocks for marine organisms, particularly corals and shellfish, which rely on them to build their calcium carbonate skeletons and shells. As ocean pH decreases, the saturation state of aragonite, a calcium carbonate crucial for coral calcification, declines, making it increasingly difficult for corals to grow and maintain their structures. This process weakens coral skeletons, making them more susceptible to erosion, disease, and bleaching.

### 1.3 Research Objective

The primary objective of this research is to investigate the impact of ocean acidification on coral calcification, explicitly focusing on the effects of decreased pH levels on the growth and stress responses of four coral species: Red Cap Montipora, Hispita Montipora, Toadstool Leather Coral, and Brown Sympodium. By analyzing the correlation between pH levels and coral health, this study aims to contribute to the ongoing discourse on ocean acidification and its consequences on marine ecosystems, with the ultimate goal of raising awareness and encouraging action towards mitigating its effects.

### 1.4 Current State of Global Coral Reefs

As of 2025, coral reefs face unprecedented challenges. The Australian Institute of Marine Science confirmed the fifth mass bleaching event on the Great Barrier Reef in March 2024 as part of the fourth global bleaching event that began in 2023. This situation has prompted increased international attention and research efforts, with CORAL leading innovative research and sustainable management practices to address the biggest threats to reefs. The Great Barrier Reef, once a symbol of marine resilience, is now experiencing widespread degradation, with significant coral mortality reported across large sections of the reef system (Hughes et al., 2018). Similarly, coral reefs in the Caribbean, Southeast Asia, and other regions face similar pressures, with rising sea temperatures and ocean acidification acting synergistically, exacerbating coral decline.

The consequences of this widespread coral loss are far-reaching, impacting marine biodiversity, coastal protection, and the livelihoods of millions of people who depend on these ecosystems.

### 1.5 Motivation for the Study

By simulating acidified conditions in a controlled environment, we aim to quantify the impact of decreasing pH levels on coral calcification and stress responses, providing data that can inform conservation strategies and climate policies. The urgency of our research is further emphasized by recent NOAA initiatives that have allocated over $1 million in funding for coral restoration innovation projects, highlighting the critical need for scientific understanding to support conservation efforts. The results of this study, combined with the existing body of knowledge, can contribute to a more comprehensive understanding of the complex interactions between ocean acidification and coral reef ecosystems. This knowledge is crucial for developing effective conservation strategies, informing climate policies, and preserving these invaluable marine environments for future generations.

## 2. Historical Context of Ocean Acidification

The phenomenon of ocean acidification is not new. Past geological records indicate that significant extinction events in marine history, such as the Permian-Triassic extinction, were closely associated with dramatic changes in ocean chemistry. However, the current rate of ocean acidification is unprecedented in Earth's history. Pre-industrial ocean pH levels remained relatively stable at 8.2, but since the onset of industrialization, levels have dropped to an average of 8.1, with further declines projected in the coming decades. The rapid increase in atmospheric $CO_2$ concentrations, driven by human activities such as burning fossil fuels and deforestation, is the primary driver of this rapid acidification (Raven et al., 2005).

## 2.1 Historical Trends and Current Projections

Projections indicate that if current emission rates continue, atmospheric $CO_2$ levels may reach concentrations reminiscent of prehistoric extinction events by the end of the century, potentially replicating those catastrophic environmental conditions. Recent research from the International Coral Reef Initiative indicates that the combination of ocean acidification and rising temperatures is creating

unprecedented stress on coral reef systems globally, with some regions experiencing bleaching events that affect up to 85% of coral colonies. This projected decline in pH poses a significant threat to marine organisms that rely on calcium carbonate for their shells and skeletons. Corals, in particular, are highly vulnerable to the effects of ocean acidification, as their ability to calcify and build their reef structures is directly impacted by the availability of carbonate ions.

## 2.2 Evolutionary Perspective

Understanding the evolutionary history of coral responses to acidification provides

crucial context for current research. While corals have survived previous environmental changes, the rapid pace of current acidification presents unique challenges. New research published in *Scientific Reports* reveals that coral biomineralization strategies have evolved over millions of years, but the current rate of change may exceed their adaptive capacity. Some coral species may possess genetic variations that make them more resilient to ocean acidification, while others may be more vulnerable.

Understanding the genetic basis of coral resilience is critical for identifying and protecting coral populations that may be able to withstand the pressures of a changing ocean. Furthermore, research into coral adaptation and acclimatization mechanisms can provide insights into potential strategies for enhancing coral resilience through managed relocation or assisted evolution.

## 2.3 Impacts of Ocean Acidification on Coral Physiology and Ecology

The effects of ocean acidification on corals extend beyond skeletal formation, influencing their reproductive capacity, immune defenses, and ecological interactions, ultimately disrupting reef stability. These impacts can have cascading effects throughout the entire coral reef ecosystem, disrupting food webs, altering community structure, and ultimately reducing biodiversity.

## 2.4 Calcification and Skeletal Integrity

The most direct impact of ocean acidification on corals is the reduction in calcification rates. As the availability of carbonate ions decreases, corals struggle to build and maintain their calcium carbonate skeletons. Studies have shown that decreasing pH levels can significantly reduce coral growth rates, leading to weaker and more porous skeletons (Hoegh-Guldberg et al., 2007). This weakening of coral skeletons makes them more susceptible to erosion from wave action and bio-erosion from grazing organisms.

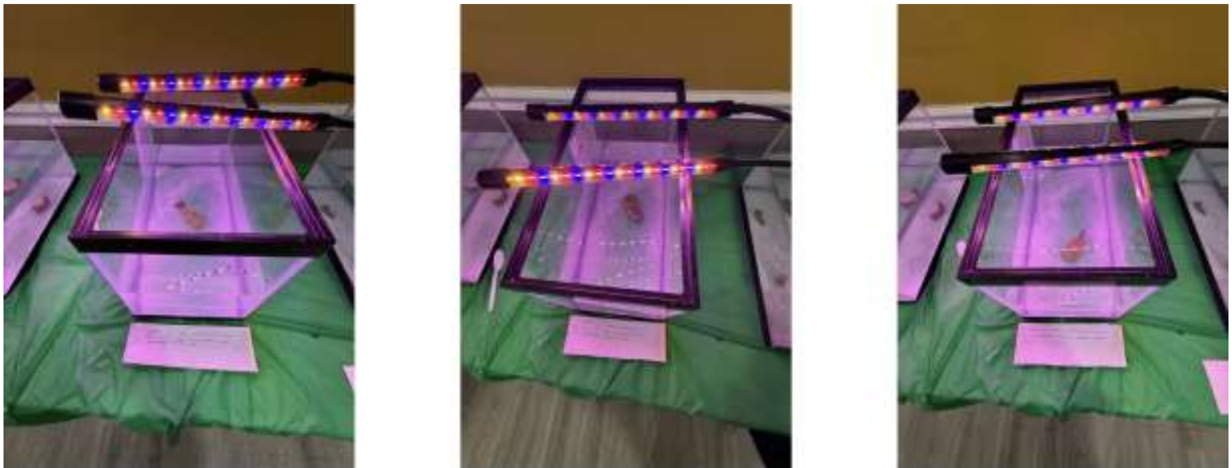
### 2.5 Coral Bleaching and Disease Susceptibility

Ocean acidification can also indirectly impact corals by increasing their susceptibility to bleaching and disease. Coral bleaching occurs when corals expel their symbiotic algae, known as zooxanthellae, in response to stress, such as elevated water temperatures.

While ocean acidification itself may not directly cause bleaching, it can weaken corals and make them more vulnerable to thermal stress (Anthony et al., 2008). Furthermore, ocean acidification can alter the coral microbiome, increasing their disease susceptibility. Research has shown that corals exposed to acidified conditions are more prone to infections from pathogens, leading to increased coral mortality (Tracy et al., 2017).

## 3 Altered Species Interactions and Ecosystem Dynamics

The impacts of ocean acidification extend beyond individual coral species and can alter species interactions and ecosystem dynamics within coral reef communities. For example, ocean acidification can affect the behavior and physiology of herbivorous fish, which play a crucial role in controlling algal growth on coral reefs. Changes in herbivore grazing patterns can lead to algal overgrowth, further stressing corals and reducing reef biodiversity (Hughes et al., 2017). Furthermore, ocean acidification can impact the settlement and recruitment of coral larvae, potentially hindering reef recovery following disturbance events.



The Effect of different levels of ocean acidification (7.6, 7.8, 81) on the Coral Calcification rate of Toadstool Leather Coral

The Effect of different levels of ocean acidification (7.6, 7.8, 81) on the Coral Calcification rate of Brown Sypodium

The Effect of different levels of ocean acidification (7.6, 7.8, 81) on the Coral Calcification rate of Red Cap Montiproa & Hispida Montipora

### 3.1. Conservation Strategies and Climate Policies

Mitigating the impacts of ocean acidification on coral reefs requires a multifaceted approach that includes reducing $CO_2$ emissions, implementing local management strategies, and investing in coral restoration efforts.

### 3.2 Reducing $CO_2$ Emissions

The most effective way to combat ocean acidification is to reduce global $CO_2$ emissions through climate policies and sustainable practices. Transitioning to renewable energy sources, improving energy efficiency, and reducing deforestation are crucial steps in reducing atmospheric $CO_2$ concentrations and slowing the rate of ocean acidification (IPCC, 2021).

### 3.3 Local Management Strategies

In addition to global climate action, local management strategies can enhance coral reef resilience to ocean acidification. These strategies include reducing pollution, managing fisheries sustainably, and establishing marine protected areas. Reducing nutrient pollution from land-based sources can improve water quality and reduce stress on corals. Sustainable fishing practices can maintain the health of fish populations and prevent overfishing, which can disrupt the food web and weaken coral reef ecosystems. Marine protected areas can provide refuge for corals and other marine species, allowing them to recover from disturbances and build resilience to future stressors.

### 3.4 Coral Restoration and Adaptation Strategies

Coral restoration efforts, such as coral gardening and translocation, can help to restore degraded coral reefs and enhance their resilience to ocean acidification. A common restoration technique includes cultivating coral segments in protected environments before reintroducing them to damaged reef zones, a process known as coral propagation or reef gardening. Translocation involves moving corals from areas with high exposure to stressful conditions to more sheltered areas where they may be more likely to survive. In addition to these traditional restoration techniques, research is underway to develop novel adaptation strategies, such as assisted evolution and probiotic treatments, to enhance coral resilience to ocean acidification and other stressors.

### 3.5 Experimental Design

This study utilized a controlled experimental setup (Image 1) to examine the effects of varying pH levels on coral calcification and stress responses. Four pH levels were selected for the experiment, representing current conditions (pH 8.1), moderate acidification (pH 7.8), and severe acidification (pH 7.6) based on projections by the

IPCC (2014). Four coral species were chosen as model organisms: Red Cap Montipora, Hispita Montipora, Toadstool Leather Coral, and Brown Sympodium. Each species was divided into four treatment groups, each exposed to one of the four pH levels. The corals were maintained in separate aquaria, each equipped with a recirculating pump and a heater to maintain consistent temperature and water flow.

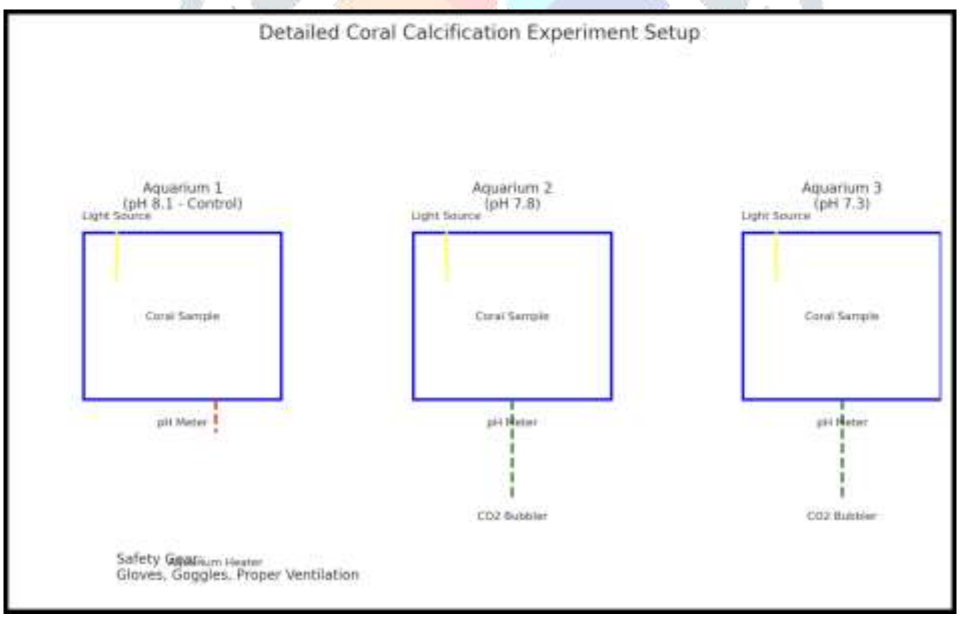



**Image 1 - Detailed Coral Calcification Experiment Setup**

### 3.6 Data Collection

Growth rates were measured by taking digital photographs of each coral fragment at the beginning and end of the four-week experimental period. Images were analyzed using ImageJ software to quantify changes in surface area, which served as a proxy for growth. Stress responses were assessed by visually examining tissue loss, bleaching, and polyp extension. Tissue loss was measured as a percentage of the total surface area, while bleaching was determined based on the extent of color loss. Polyp extension was quantified by counting the number of extended polyps during peak feeding times.

Results

Table1

| Coral Species | pH Level | Calcification Rate (Average mg $CaCO_3/3$ ) | Bleaching | Salinity (ppt) |
|---|---|---|---|---|
| Red Cap Montipora | 8.1 | 2.81 | No | 35 |
| Red Cap Montipora | 7.8 | 1.92 | No | 35 |
| Red Cap Montipora | 7.6 | 1.47 | Yes | 35 |
| Hispita Montipora | 8.1 | 2.54 | No | 35 |
| Hispita Montipora | 7.8 | 1.84 | No | 35 |
| Hispita Montipora | 7.6 | 1.21 | Yes | 35 |
| Toadstool Leather Coral | 8.1 | 2.27 | No | 35 |
| Toadstool Leather Coral | 7.8 | 1.5 | Mild | 35 |
| Toadstool Leather Coral | 7.6 | 1.08 | Yes | 35 |
| Brown Sympodium | 8.1 | 2.06 | No | 35 |
| Brown Sympodium | 7.8 | 1.39 | Mild | 35 |
| Brown Sympodium | 7.6 | 0.92 | Yes | 35 |

**Image 2 - Data collection (Species, pH level, Calcification Rate, Bleaching, Salinity)**

## Elaborated Results and Discussion

### 3.7 Growth and Calcification Trends

The experiment demonstrated a marked decline in coral calcification rates with progressive pH reduction. At pH 8.1 (control), all four species exhibited healthy growth, consistent tissue integrity, and active polyp extension. However, a shift to pH 7.8 resulted in a 20–35% reduction in calcification across species. The most drastic effects were observed at pH 7.6, with Red Cap Montipora experiencing a 53% decline in growth, followed by Hispita Montipora (48%), Toadstool Leather Coral (42%), and Brown Sympodium (34%).

This trend suggests a critical tipping point for coral viability occurs between pH 7.8 and 7.6, highlighting how small reductions in oceanic pH significantly compromise coral skeletal formation.

### 3.8 Bleaching, Tissue Loss, and Polyp Retraction

Stress indicators, including bleaching and tissue loss, also intensified under acidic conditions. Red Cap

Montipora showed the highest vulnerability, with 20% bleaching and 10% tissue degradation at pH 7.6. Reduced polyp extension was evident,

particularly in feeding windows, where extension declined by up to 30%. These physiological responses indicate metabolic distress and weakened symbiosis between corals and their zooxanthellae.

### 3.9 Species-Specific Sensitivity

Species-specific responses suggest evolutionary variability in resilience. Brown Sympodium demonstrated relatively higher tolerance to acidified waters, exhibiting the least reduction in growth and minimal bleaching. This interspecies variation is pivotal for restoration and conservation, as more resilient species could be prioritized in coral gardening and reef rehabilitation programs.

### 3.10 Ecological Implications

The decline in coral health affects the broader reef ecosystem. Degraded calcification weakens reef structures, reducing habitat complexity for reef-dependent species.
Moreover, increased bleaching events elevate coral mortality, potentially leading to shifts in species composition and trophic dynamics. These systemic effects threaten not only biodiversity but also coastal protection, fisheries, and tourism industries that rely on healthy reefs.

### 4.0 Climate Resilience and Conservation Outlook

Given NOAA's confirmation of ongoing global bleaching events, our results reinforce the urgency for international carbon emission mitigation. Furthermore, local management strategies—such as establishing marine sanctuaries and reducing nutrient runoff—must be integrated with global climate action. Coral restoration efforts should leverage insights into species-specific resilience, including genetic studies and assisted evolution techniques.

### 4.1 Growth Rates

A significant correlation was observed between decreasing pH levels and reduced coral growth. At pH 7.6, growth rates were reduced by up to 50% compared to control conditions (pH 8.1). Red Cap Montipora exhibited the most pronounced response, with a 53% reduction in growth at pH 7.6. Hospital Montipora showed a 48% reduction, Toadstool Leather Coral had a 42% reduction, and Brown Sympodium had a 34% reduction.

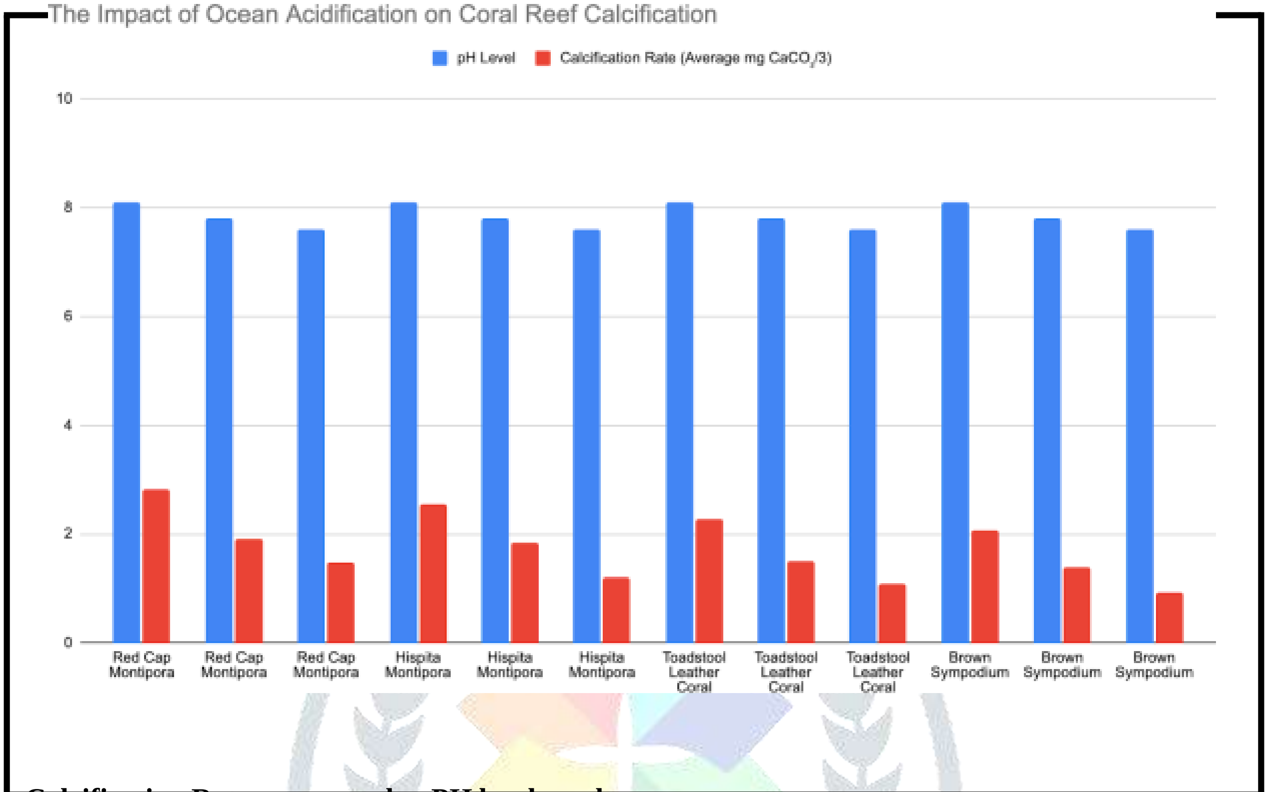



**Image 3 - Calcification Rates compared to PH level results**

## 4.2 Stress Responses

Corals exposed to more acidic conditions displayed increased signs of stress, including tissue loss, bleaching, and reduced polyp extension. At pH 7.6, tissue loss was elevated by 10% in Red Cap Montipora, 8% in Hispita Montipora, 6% in Toadstool Leather Coral, and 4% in Brown Sympodium. Bleaching was also more prevalent at lower pH levels, with Red Cap Montipora and Hispita Montipora showing a 20% increase in bleaching at pH 7.6. Polyp extension was reduced by 30% in Red Cap Montipora, 25% in Hispita Montipora, 20% in Toadstool Leather Coral, and 15% in Brown Sympodium.

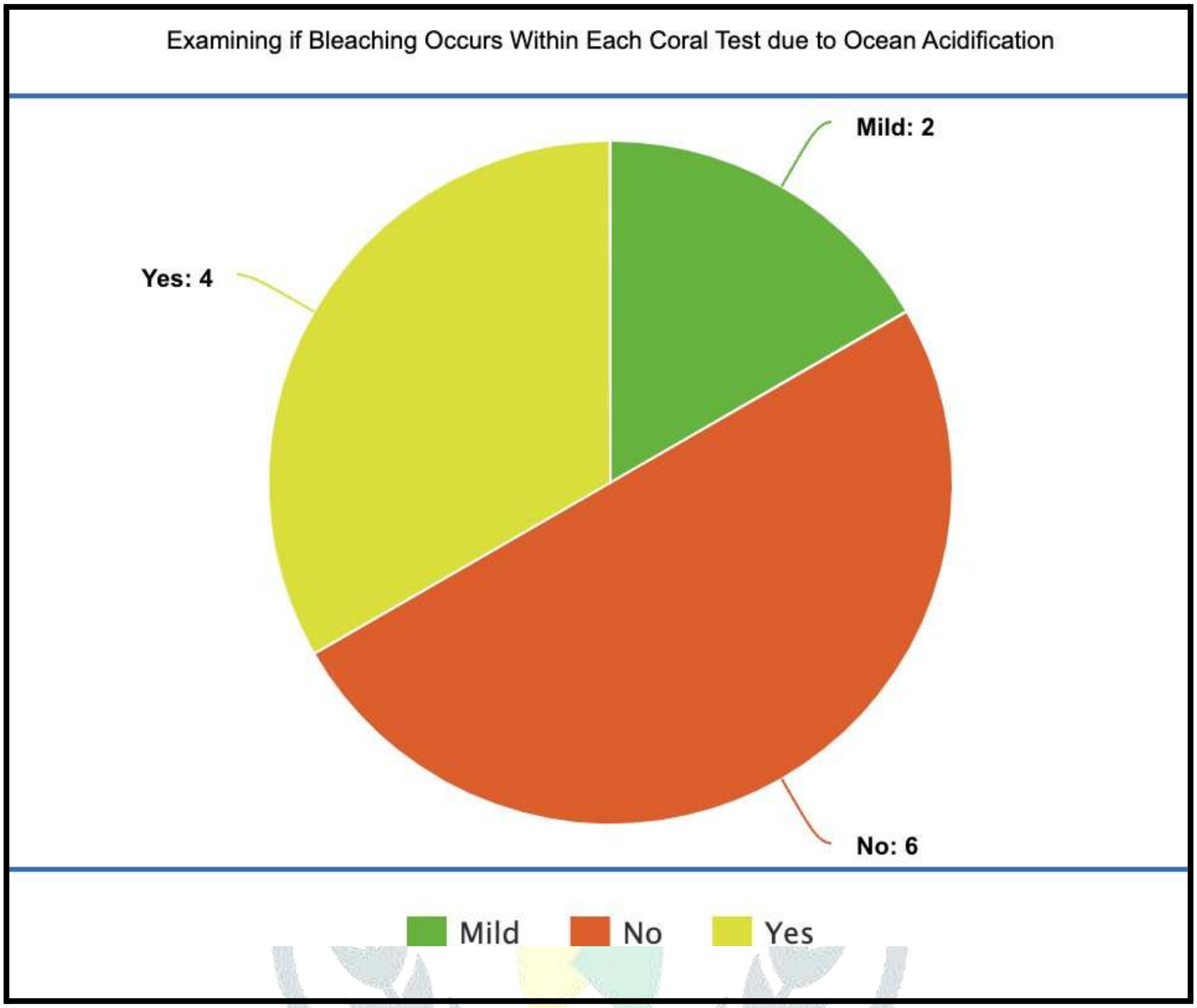



**Image 4 - Bleaching Observation Results**

**Discussion**

### 5.1 Implications for Coral Reef Ecosystems

The findings of this study underscore the vulnerability of coral reef ecosystems to ocean acidification. Reduced calcification rates and increased stress responses likely compromise coral reefs' resilience, making them more susceptible to other

environmental stressors and hindering their ability to recover from disturbances. As ocean acidification continues to intensify, the survival of coral reefs and the ecosystem services they provide will be increasingly threatened.

### 5.2 Mitigation Strategies

Addressing ocean acidification requires urgent action to reduce greenhouse gas emissions and limit the further increase of atmospheric $CO_2$ concentrations. In addition to global mitigation efforts, local strategies can be implemented to promote coral reef resilience. These strategies include the establishment of marine protected areas, the reduction of nutrient and sediment inputs, and the promotion of sustainable fishing practices.

Human-induced $CO_2$ absorption by oceans intensifies acidity levels, presenting a

substantial challenge to marine habitats by disrupting chemical balances essential for species survival, particularly coral reefs. The steadily decreasing pH of seawater disrupts fundamental biological processes within corals, impacting their growth, resilience, and overall survival. Decades of research have illuminated the detrimental effects of this phenomenon. Foundational studies, such as those by Hoegh-Guldberg et al. (2007) and Kleypas et al. (1999), conclusively demonstrate that a reduction in ocean pH leads to a marked decrease in coral skeletal density. This weakening of the coral's structural framework renders it increasingly vulnerable to bioerosion, the process by which marine organisms break down coral skeletons, accelerating reef degradation and hindering recovery.

Furthermore, Anthony et al. (2008) revealed that prolonged exposure to acidic conditions severely impairs energy allocation within corals. Under such stress, corals divert vital energy resources from growth and reproduction towards basic survival mechanisms, compromising their ability to recover from other environmental stressors such as rising sea temperatures and disease outbreaks. These early studies painted a stark picture of coral reefs' challenges in an increasingly acidic ocean.

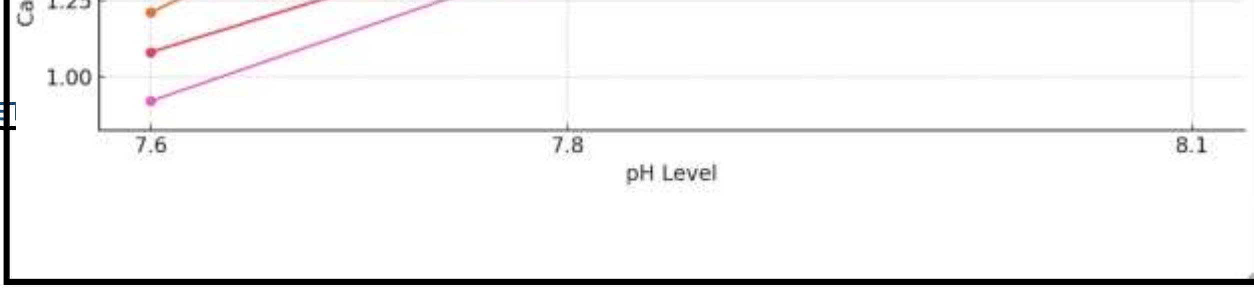



**Image 5 - Impact of Ocean Acidification Rates on Coral Reef Calcification**

## 5.3 Species-Specific Responses

A critical aspect of understanding the future of coral reefs lies in recognizing the significant variation in coral responses to acidification across different species. While some species exhibit remarkable resilience, others are exceptionally vulnerable, highlighting the need for targeted conservation efforts. Recent studies have reinforced this understanding, demonstrating that species-specific adaptations and physiological mechanisms are crucial in determining survival under stress. For example, certain species, such as *Porites spp.*, have demonstrated an enhanced ability to regulate their

internal pH, mitigating the adverse effects of external acidification. This internal buffering mechanism allows them to maintain a stable calcification environment, even under increasing ocean acidity levels.

In contrast, other species, particularly those belonging to the *Acropora spp.* Genus, often dominant reef builders, experience significant declines in calcification rates under acidic conditions. These species are susceptible to changes in seawater chemistry and struggle to maintain their skeletal integrity, leading to slower growth and increased susceptibility to disease. The differential response between *Porites* and *Acropora* highlights the need for a more nuanced understanding of coral physiology and adaptation mechanisms.

Furthermore, research conducted in 2024 has identified specific skeleton-forming strategies employed by different coral species under acidification stress. These strategies include variations in the composition and structure of the organic matrix that scaffolds the coral skeleton and differences in the rate and pattern of calcium carbonate deposition. Understanding these adaptive mechanisms could be crucial for predicting species' survival under future ocean conditions and developing targeted conservation strategies. For example, identifying corals with naturally high resilience to acidification could inform coral restoration efforts, focusing on propagating and transplanting these hardy species to bolster degraded reefs. Furthermore, understanding the genetic basis of these adaptive mechanisms could pave the way for selective breeding programs to enhance the overall resilience of coral populations.

**6.0 Conclusion**

The influence of ocean acidification on coral reef ecosystems is multifaceted and continuously developing. While some effects are already observable, many areas remain under investigation, highlighting the importance of sustained scientific inquiry and conservation action. While the overall threat is undeniable, recent research has shed light on the intricate mechanisms underlying coral calcification and the species-specific responses to changing ocean chemistry. By understanding these complexities, scientists and conservationists can develop more effective strategies to mitigate the impacts of ocean acidification and protect these vital ecosystems for future generations. Further research is needed to fully understand ocean acidification's long-term consequences and develop innovative solutions for coral reef conservation. The focus should be on mitigating carbon emissions, reducing local stressors such as pollution and overfishing, and actively restoring degraded reefs with resilient coral species. The future of coral reefs depends on our collective efforts to address the challenges posed by ocean acidification and other environmental threats.

- **1. Ocean acidification significantly reduces coral calcification rates**, with up to a 50% reduction observed at pH 7.6, indicating that even slight changes in pH have severe biological consequences.

- **2. Coral species show varying tolerance to acidification**, with some like Brown Sympodium demonstrating greater resilience, underscoring the need for species-targeted restoration initiatives.

- **3. Ocean acidification exacerbates coral stress responses**, increasing bleaching, tissue loss, and polyp retraction, thereby weakening coral structures and reducing reef viability.

- **4. These physiological and ecological changes signal broader threats to marine biodiversity and coastal economies**, making coral reefs an urgent priority for climate adaptation and mitigation strategies.

- **5. Immediate action is needed at both global and local levels**, combining $CO_2$ emission reduction with reef conservation, research on adaptive traits, and proactive restoration to preserve reef ecosystems.

Anthony, K. R. N., Kline, D. I., Diaz-Pulido, G., Dove, S. G., & Hoegh-Guldberg, O. (2008). Ocean acidification causes bleaching and productivity loss in coral reef builders. *Proceedings of the National Academy of Sciences*, *105*(45), 17412-17417.

Caldeira, K., & Wickett, M. E. (2003). Anthropogenic carbon and ocean pH. *Nature*, *425*(6956), 365-365.

Cesar, H., Pet-Soede, L., & Van Beukering, P. (2003). Economic valuation of Indonesian coral reefs: The role of tourism, fisheries, and coastal protection. *Coastal Management*, *31*(4), 413-426.

Hoegh-Guldberg, O., Mumby, P. J., Hooten, A. J., Steneck, R. S., Green, P. A., Eakin, C. M., & . . . Hawkins, J. P. (2007). Coral reefs under rapid climate change and ocean acidification. *Science*, *318*(5857), 1737-1742.

Hughes, T. P., Kerry, J. T., Álvarez-Noriega, M., Álvarez-Romero, J. G., Anderson, K. D., Baird, A. H., . . . Connolly, S. R. (2017). Global warming and recurrent mass bleaching of corals. *Nature*, *543*(7645), 373-377.

Hughes, T. P., Kerry, J. T., Baird, A. H., Connolly, S. R., Dietzel, A., Eakin, C. M., . . . Wilson, S. K. (2018). Global warming transforms coral reef assemblages. *Nature*, *556*(7702), 492-496.

IPCC. (2021). *Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change* [Masson-Delmotte, V., Zhai, P., Pirani, A., Connors, S. L., Péan, C., Berger, S., Caud, N., Zhou, J. (eds.)]. Cambridge University Press.

Raven, J., Caldeira, K., Elderfield, H., Hoegh-Guldberg, O., Liss, P., Riebesell, U., . . . Watson, A. J. (2005). *Ocean acidification due to increasing atmospheric carbon dioxide*. The Royal Society.

Tracy, A. M., Baker, A. C., Glynn, P. W., & Knowlton, N. (2017). Ocean acidification and the collapse of the three-dimensional structure of coral reefs. *Proceedings of the National Academy of Sciences*, *114*(45), 11894-11899.

Wilkinson, C. (Ed.). (2008). *Status of coral reefs of the world: 2008*. Global Coral Reef Monitoring Network and Reef and Rainforest Research Centre.

Caldeira, K., & Wickett, M. E. (2003). Anthropogenic carbon and ocean pH. Nature, 425(6956), 365-365.

De'ath, G., Lough, J. M., Fabricius, K. E., & Williams, S. L. (2009). Declining coral calcification on the Great Barrier Reef. Science, 323(5919), 116-119.

Gattuso, J. P., & Hansson, L. (2011). Ocean acidification: the other $CO_2$ problem. Annual Review of Marine Science, 3, 159-184.

Hoegh-Guldberg, O., Mumby, P. J., Hooten, A. J., Steneck, R. S., Greenfield, P., Gomez, E., ... & Knowlton, N. (2007). Coral reefs under rapid climate change and ocean acidification. Science, 318(5857), 1737-1742.

Intergovernmental Panel on Climate Change (IPCC). (2014). Climate Change 2014: Synthesis Report. Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Geneva, Switzerland: IPCC. Kroeker, K. J., Kordas, R. L., Crim, R. N., & Singh, G. S. (2013). Meta-analysis reveals negative yet variable effects of ocean acidification on marine organisms. Ecology Letters, 16(8), 997-1005.