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Biochemical Adaptability of the Relationship between Tropical Hard Corals and Photosynthetic Symbiotic Algae under Climate Change

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Abstract Tropical coral reefs, a vital component of the global marine ecosystem, are currently under threat from climate change factors such as rising temperatures, ocean acidification, and extreme weather events. High temperatures induce coral bleaching, resulting in the loss of their energy supply and an acceleration of metabolic rates, rendering them more vulnerable. Ocean acidification affects the formation of calcium carbonate skeletons in symbiotic algae and decreases photosynthetic efficiency, further exacerbating the risk of damage to the symbiotic algae in high-temperature conditions. Extreme weather events directly cause physical damage to corals and alter marine environments, reducing their chances of survival. This review focuses on the impact of climate change on the biochemical adaptability between tropical hard corals and photosynthetic symbiotic algae, exploring their ecological relationship, the influence of climate change on this relationship, and the adaptive mechanisms. Understanding the adaptive mechanisms between hard corals and symbiotic algae is crucial for developing conservation strategies and management plans to maintain the functionality and biodiversity of coral reef ecosystems. It also aids in ensuring the survival and prosperity of this delicate relationship under the challenges posed by climate change, allowing future generations to continue enjoying the magnificence of tropical coral reefs.

Keywords Tropical hard corals; Photosynthetic symbiotic algae; Climate change; Biochemical adaptability; Marine conservation

Tropical hard corals are the core components of coral reef ecosystems, providing shelter and ecosystem services to numerous organisms. They are also crucial factors for the biodiversity and productivity of global marine ecosystems. However, hard corals do not exist in isolation, their relationship with symbiotic algae is the ecological foundation of coral reefs. This symbiotic relationship is unique and delicate: corals offer habitat and protection to algae, while algae, through photosynthesis, provide energy and organic matter to corals (He et al., 2022). This mutualistic association supports the prosperity of hard coral reefs but also renders them highly sensitive to environmental changes.

Before understanding the impacts of climate change on tropical hard corals and their symbiotic algae, it is essential to recognize the widespread threats posed by climate change to tropical marine ecosystems. Global temperature rise leads to elevated sea temperatures, acidified seawater conditions, and more frequent and intense storm events. This series of climate changes affects coral reef ecosystems, disrupting the stable relationship between hard corals and symbiotic algae, jeopardizing the survival of tropical hard coral reefs. Therefore, the biochemical adaptive mechanisms between hard corals and symbiotic algae are crucial for addressing the challenges of climate change (Petrou et al., 2021). This relationship is not only vital for the survival of hard coral reefs but also has profound effects on the biodiversity and productivity of global marine ecosystems.

Current research progress indicates a severe threat to the relationship between hard corals and symbiotic algae due to climate change. High temperatures cause coral bleaching, this phenomenon directly harming their health and depriving them of necessary energy supplies, accelerating metabolism, and increasing vulnerability. Ocean acidification has a direct negative impact on the formation of the calcium carbonate skeleton of symbiotic algae and the efficiency of photosynthesis, further exacerbating the damaged risk of symbiotic algae under high-temperature conditions. Additionally, extreme weather events such as storms cause direct physical damage to hard corals, disrupting the marine environment and reducing their chances of survival.

This study explores the biochemical adaptability between tropical hard corals and symbiotic algae, particularly under the ecological conditions of climate change pressure. The research investigates how hard corals and symbiotic algae adapt to the rising temperatures and acidification of seawater, as well as how they adjust photosynthesis and antioxidant defense mechanisms to cope with the constantly changing environment. Furthermore, the study discusses changes in the species of symbiotic algae and metabolic adaptability in hard corals, providing a scientific basis for the healthy development of marine ecological balance. Understanding the biochemical adaptive mechanisms between tropical hard corals and symbiotic algae helps them survive the challenges of climate change. This relationship is crucial for the stability of hard coral reefs and the health of global marine ecosystems. Through in-depth research and global cooperation, can assist this fragile relationship in surviving and thriving under the threats of climate change, allowing marine environments to become more diverse and multidimensional.

1 Basic Ecological Relationship between Hard Corals and Symbiotic Algae

Tropical hard coral reefs are renowned as one of the most rich and diverse ecosystems on Earth. The foundation of this ecological marvel lies in the delicate ecological relationship between hard corals and symbiotic algae. These small organisms play a crucial role in maintaining the biodiversity and productivity of tropical marine ecosystems.

1.1 Classification of pearl morphology

Hard corals (*Scleractinia*) are the builders of coral reefs, known for their hard calcareous bones, which are, composed of calcified collagen. This rigid external skeleton provides protection for hard corals, allowing them to survive in the turbulent waters and predation by predators. Despite appearing rigid and immobile, hard corals are vibrant organisms, with generally slow growth rates; most corals only grow a few millimeters to centimeters each year.

Hard corals (Figure 1) are widely distributed in shallow marine environments in tropical and subtropical regions globally, particularly in the Pacific, Indian, and Atlantic Oceans. The warm waters of these regions provide favorable conditions for the survival and growth of hard corals. Hard corals usually live in shallow sea water, most species of hard corals live in areas not exceeding 50 meters in depth, although some specialized species can be found in deeper waters.

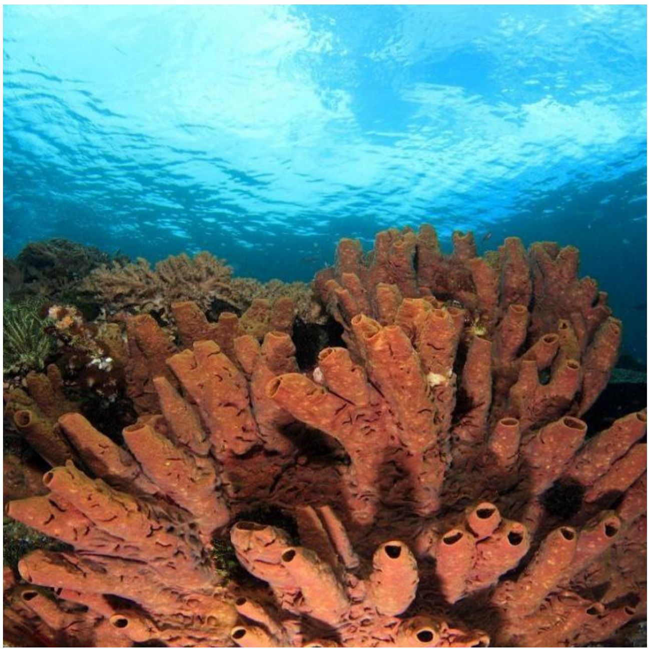

Figure 1 Hard coral

1.2 Role of symbiotic algae in hard coral tissues

Symbiotic algae, typically belonging to the genus Zooxanthellae, are single-celled algae that closely associate with hard corals. These algae reside within the tissues of hard corals, imparting brown or golden pigments to the coral's transparent tissues, hence often referred to as "brown algae." Photosynthetic symbiotic algae convert sunlight into energy through photosynthesis, and then transport organic carbon and nutrients to the hard coral, providing the necessary resources for growth and survival (Hazraty-Kari et al., 2022).

This symbiotic relationship plays a crucial role for hard corals. Symbiotic algae contribute approximately 90% of the energy through photosynthesis, enabling hard corals to grow rapidly and construct their robust skeletons. Additionally, the symbiotic algae provide the necessary organic substances for hard corals, including glucose, amino acids, and fatty acids. Hard corals also offer a suitable habitat for symbiotic algae in this relationship, as well as protection from suspended sediments and predators.

1.3 Mutual dependency between symbiotic algae and corals

The relationship between hard corals and symbiotic algae is one of mutual dependency, where they cooperate to maintain the stability of the entire coral reef ecosystem. However, this relationship is delicate and highly sensitive to environmental changes. Hard corals obtain most of their energy from symbiotic algae, but adverse environmental conditions such as elevated sea temperatures, deteriorating water quality, or storms may harm the symbiotic algae. In such cases, hard corals may expel the symbiotic algae, leading to a phenomenon known as coral bleaching.

Coral bleaching poses a severe threat to the hard coral ecosystem as it causes the loss of a substantial energy supply for hard corals (Wu et al., 2022). If this phenomenon persists for an extended period, hard corals may eventually die, negatively impacting the entire coral reef ecosystem. This makes the interdependence between hard corals and symbiotic algae more significant and underscores its significance as a core issue in the face of climate change threats to tropical hard coral reefs.

The close mutual dependency between hard corals and symbiotic algae is a key factor in the success of tropical coral reef ecosystems. Symbiotic algae provide energy and organic matter to hard corals, enabling their growth and reproduction, while hard corals offer a suitable habitat and protection for symbiotic algae. However, this relationship faces numerous threats, particularly environmental changes resulting from climate change.

2 Impact of Climate Change on the Relationship between Tropical Hard Corals and Symbiotic Algae

Tropical hard coral reefs are among the world's most vulnerable ecosystems, playing a crucial role in the Earth's ecosystems. However, the threats of climate change have had severe impacts on these valuable ecosystems. Among them, the relationship between hard corals and symbiotic algae is particularly fragile, drawing significant attention to the interaction between tropical hard corals and climate change.

2.1 Effects of elevated sea temperatures on corals

One of the most significant impacts of climate change is the rise in sea temperatures. Tropical hard corals are highly sensitive to temperature changes and exist within a relatively narrow temperature range. When sea temperatures increase, hard corals face a series of challenges. Firstly, high temperatures can cause damage to the symbiotic algae within the coral, leading to coral bleaching (Pang et al., 2021). Coral bleaching (Figure 2) is a severe phenomenon as it disrupts the stable relationship between corals and symbiotic algae, causing hard corals to lose the majority of their energy supply.

Furthermore, elevated temperatures accelerate the metabolic rate of hard corals, increasing their demand for more energy. If hard corals cannot acquire sufficient energy, they may cease growth or even start to dissolve, ultimately leading to the decline of coral reefs. Therefore, the rise in sea temperatures poses a severe threat, not only is it harmful to hard corals themselves, but also has adverse effects on the entire coral reef ecosystem.

Figure 2 Bleached coral

2.2 Impact of ocean acidification on symbiotic algae

Another issue caused by climate change is the acidification of seawater (Figure 3). The increase in atmospheric carbon dioxide (CO_2) concentration leads to a decrease in the concentration of carbonate ions (CO_3^{2-}) in seawater, affecting the ocean's acid-base balance. Ocean acidification has a direct impact on the symbiotic algae of hard corals.

Figure 3 Acidified seawater

Symbiotic algae rely on CO_3^{2-} in seawater to form their calcium carbonate skeletons, but ocean acidification makes this process more challenging. Additionally, acidified seawater affects the efficiency of photosynthesis in symbiotic algae, reducing their energy supply. This makes symbiotic algae more vulnerable to the high-temperature stress caused by climate change (Zhang et al., 2012). When seawater becomes both warmer and more acidic simultaneously, symbiotic algae are more susceptible to damage, consequently affecting hard corals.

2.3 Impact of storms, sea level rise, and other climate change factors

In addition to the rise in sea temperatures and ocean acidification, climate change brings other threats, such as storms, sea level rise, and more frequent extreme weather events caused by climate change. Storms can cause physical damage to hard corals, disrupting their robust external skeletons. Furthermore, sea level rise results in larger waves and impacts on coral reef ecosystems, exacerbating the vulnerability of hard corals.

Climate change also triggers more frequent coral bleaching events, leading to the disruption of the relationship between hard corals and symbiotic algae. Additionally, climate change affects water quality, leading to excessive nutrient input and coral reef degradation. This series of climate change factors collectively threatens the ecological relationship between hard corals and symbiotic algae, intensifying the crisis faced by tropical hard coral reefs.

Climate change has severe impacts on the ecological relationship between tropical hard corals and symbiotic algae. Factors such as elevated sea temperatures, ocean acidification, storms, and sea level rise pose threats to the survival and reproduction of hard corals, rendering these coral reef ecosystems more fragile.

3 Adaptive Biochemical Mechanisms to Climate Change

In the face of environmental changes induced by climate change, the delicate relationship between tropical hard corals and their symbiotic algae becomes even more fragile. However, these organisms are not helpless; they exhibit impressive biochemical adaptive mechanisms to cope with new environmental challenges.

3.1 Photosynthetic adaptation

Symbiotic algae are crucial for the survival of hard corals as they provide the necessary energy through photosynthesis. However, the increased temperature and light intensity resulting from climate change can stress symbiotic algae, leading to coral bleaching. To address this challenge, some species of hard corals have demonstrated photosynthetic adaptability.

An important adaptive strategy involves certain hard coral species adjusting the type of symbiotic algae to cope with different environmental conditions. Under high-temperature conditions, some hard corals can establish symbiotic relationships with heat-tolerant algae varieties, thus alleviating the pressure on symbiotic algae caused by elevated temperatures (Kawamura et al., 2021). This phenomenon provides additional survival opportunities for hard corals, enabling them to thrive in a broader range of environmental conditions.

Hard corals and symbiotic algae (Figure 4) can also regulate the rate of photosynthesis to minimize the damage of photosynthetic products to hard corals. Hard corals can adjust the density and pigment content of symbiotic algae to adapt to different light conditions (López-Londoño et al., 2022). This photosynthetic adaptation mechanism helps hard corals mitigate the risk of symbiotic algae being exposed to excessive sunlight while maintaining a sufficient energy supply.

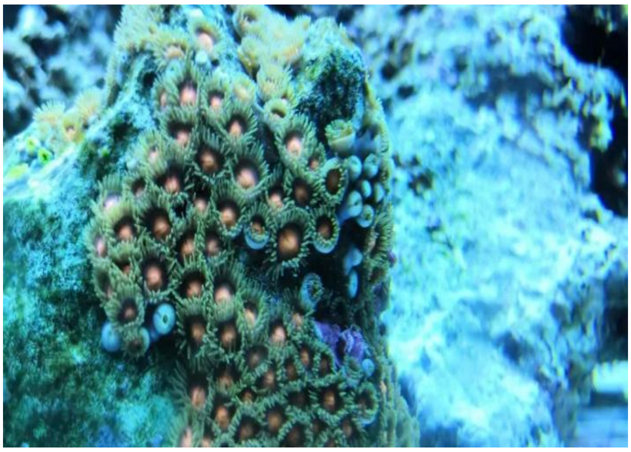

Figure 4 Coral and symbiotic algae

3.2 Changes in symbiotic algae species

With the rise in sea temperatures, some hard corals have begun to establish new symbiotic relationships with different types of photosynthetic algae to adapt to higher temperatures. This change in symbiotic algae species is an adaptive mechanism known as "symbiotic algae switching." This process typically involves hard corals forming new symbiotic relationships with heat-tolerant varieties of symbiotic algae, thereby increasing the chances of survival in high-temperature conditions.

A research team from California State University developed a global ecological and evolutionary model simulating the response of 1,925 coral reefs to warming and ocean acidification under four climate scenarios (Li and Yi, 2021). The model incorporates two competing coral species that respond to future ocean warming and acidification through either the symbiotic algae switching mechanism (replacing existing algae types with more stress-tolerant types) or the symbiotic algae evolution mechanism. The model indicates that the switching mechanism is more effective, and the greatest impact on coral reef degradation is ocean warming rather than acidification. However, the ultimate outcome on a global scale will depend on the impact of warming and specific adaptive mechanisms.

While the model provides a simplified representation of coral ecology and evolution, the research results enhance our understanding of coral adaptability. This understanding can help guide coral reef conservation efforts and suggest future research directions.

3.3 Antioxidative defense mechanisms

Under conditions of high temperature and high light intensity, photosynthetic algae produce excessive oxidative substances, such as oxygen free radicals. These oxidative substances can damage the cells and tissues of hard corals, leading to coral bleaching. To counteract this stress, hard corals have developed a series of antioxidative defense mechanisms.

Oxygen molecules possess strong oxidizing properties and are the main source of free radicals generated within an organism. If free radicals cannot be effectively cleared, they can cause damage to cells and tissues, leading to aging and even death of the organism. Therefore, antioxidants are crucial for organisms, as they can eliminate free radicals within the body, thereby protecting the cells and tissues of corals.

Corals can obtain antioxidants through various pathways. On one hand, corals can self-synthesize antioxidants such as vitamins C and E to enhance their own antioxidative capacity. Additionally, corals can utilize exogenous antioxidants from marine microorganisms and seaweed in the ocean to enhance their antioxidant capacity. These microorganisms and seaweed contain carotenoids, polyphenols, flavonoids, and other antioxidative components, effectively clear free radicals within corals, providing protective effects. Hard corals can produce antioxidative substances, such as superoxide dismutase and catalase, to neutralize oxygen free radicals (Kramer et al., 2022). Hard corals can also adjust the rate of photosynthesis in symbiotic algae to reduce the risk of excessive production of oxygen free radicals. These antioxidative defense mechanisms help hard corals alleviate oxidative stress caused by climate change, thereby increasing their chances of survival.

3.4 Metabolic adaptations of hard corals

Hard corals also exhibit metabolic adaptations to cope with different environmental conditions. When water temperature rises, the metabolic rate of corals increases, leading to faster growth. However, prolonged exposure to high temperatures can exert significant stress on corals, potentially leading to their death. To adapt to high-temperature environments, corals produce heat shock proteins, which protect the cellular structure and functions of corals from damage caused by elevated temperatures. Under high-temperature conditions, some hard corals can adjust their metabolic rates to reduce oxygen and symbiotic algae's demands (Zhang et al., 2021). This helps hard corals survive in high-temperature and low-oxygen environments, enhancing their resilience to the impacts of climate change.

The biochemical adaptability mechanisms between hard corals and symbiotic algae enable them to seek new strategies to maintain their survival and reproduction in the face of climate change challenges. However, although these adaptive mechanisms can help hard corals cope with challenges in the short term, in the long term, they still face significant threats. Therefore, conservation and management measures remain crucial to ensure the ongoing existence of the relationship between hard corals and symbiotic algae, maintaining the ecological balance of coral reef ecosystems.

4 Summary and Outlook

In nature, tropical hard coral reefs play an indispensable role in sustaining biodiversity and productivity in the global marine ecosystem. However, environmental changes triggered by climate change, especially elevated temperatures, ocean acidification, and extreme weather events, pose a severe threat to the ecological relationship between tropical hard corals and symbiotic algae. High temperatures pose a serious threat to the relationship between hard corals and symbiotic algae. Elevated sea temperatures lead to coral bleaching, indicating the loss of the primary energy source provided by symbiotic algae. High temperatures also accelerate the metabolic rate of hard corals, increasing their energy demands and making them more vulnerable to the pressures of climate change. Additionally, ocean acidification directly impacts symbiotic algae, reducing their ability to form calcium carbonate skeletons and affecting the efficiency of photosynthesis (Scucchia et al., 2021). This exacerbates the risk of symbiotic algae being overexposed to high temperatures, further highlighting the mutual dependence between hard corals and symbiotic algae. Furthermore, extreme weather events such as storms and sea-level rise directly threaten hard corals, causing physical damage and reducing their chances of survival.

This study, through exploring the biochemical adaptive mechanisms of this relationship, reveals the survival strategies of hard corals and symbiotic algae in responding to the challenges of climate change. This is not only the importance of understanding these adaptive mechanisms, but also the need to explore future research directions to maintain the stability of this critical ecosystem. However, despite these adaptive mechanisms helping hard corals and symbiotic algae cope with challenges in the short term, they still face significant threats. Therefore, conservation and management measures remain crucial.

Reducing greenhouse gas emissions, improving marine quality, and establishing protected areas are essential measures to maintain the relationship between hard corals and symbiotic algae. This requires coordinated efforts from the international community to address the threats of climate change to tropical hard coral reefs. In-depth research on symbiotic algae transitions, understanding how different species of hard corals implement this strategy to adapt to climate change, and the impact of these new relationships on coral reef ecosystems will provide valuable insights for future conservation strategies. Additionally, further research into the antioxidant defense mechanisms of hard corals, understanding how to better mitigate oxidative stress caused by climate change, is a key direction for future studies. Genetic research can also provide more insights into the climate adaptability of hard corals and symbiotic algae, offering potential pathways for possible genetic engineering methods to enhance their chances of survival. Simultaneously, more effective establishment and management of protected areas to reduce anthropogenic pressures and provide secure habitats will be crucial for the future health of hard coral reefs, ensuring that future generations can continue to marvel at the magnificent beauty of hard coral reefs.

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