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Ocean Acidification and Its Impact on Marine Biodiversity: Ecological Consequences and Future Perspectives

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Abstract

Ocean acidification has emerged as one of the most serious environmental issues affecting marine ecosystems in the twenty-first century. Human activities such as fossil fuel combustion, deforestation, and industrialization results into rapid increase in the level of atmospheric carbon dioxide (CO_2) has altered the chemistry of oceans to a significant level. Carbon dioxide released from source reaches to one of the sink i.e. oceans which absorb nearly one third of the anthropogenic CO_2 released into the atmosphere. When carbon dioxide mixes with seawater, forms carbonic acid which subsequently dissociated into bicarbonate and hydrogen ions. The hydrogen ions released in sea water increase the pH level of sea water and alters the carbonate balance essential for marine life. Since the beginning of the Industrial Revolution, the average pH of surface ocean waters has decreased from approximately 8.2 to about 8.1. Although this change appears small, it represents nearly a 30% increase in ocean acidity and indicates a significant shift in ocean chemistry. This chemical alteration reduces the availability of carbonate ions which is required by marine organism for the formation of calcium carbonate shells and skeletons. Acidification of oceans mainly affects the calcifying organism like corals, mollusks and other certain plankton species. Under acidic conditions, low calcification rates, reduced growth, weakened shells and physiological stress has been observed. In addition to ecological impacts, ocean acidification also threatens fisheries, aquaculture industries, and coastal economies that depend on marine biodiversity. Therefore, understanding the causes, mechanisms, and ecological consequences of ocean acidification is essential for developing effective conservation strategies and sustainable marine management policies in the context of global climate change.

Keywords: *Ocean acidification, Marine biodiversity, Climate change, Coral reefs, Calcification, Marine ecosystems*

1. Introduction

Oceans being the largest ecosystem on the planet, covers nearly 71 percent of the earth surface, supports diversity of organisms ranging from microscopic plankton to large marine animals. Marine ecosystem offers services like food production, nutrient cycling, coastal protection and climate regulation. Biodiversity under water also plays a vital role in maintaining ecological stability and resilience in underwater environment. Biodiversity of oceans, starting from microbes to whales and ranging from surface water to lower benthic zone, forms a dynamic framework enabling the flow of energy that shapes and sustains the marine ecosystem. Human being relies on the biodiversity and function of marine system for many services ranges from basic as producing seafood or as much of the oxygen we breathe. Less apparent ecosystem services linked closely to biodiversity and ecosystem function are waste processing and improved water quality, elemental cycling, shoreline protection, and aesthetic or educational experiences (Cooley et al. 2022). In the recent scenario, earth atmosphere and climate changes poses a great variation due to human activities. One of the most notable changes is the increase in the level of carbon dioxide which results from burning of fossil fuel, deforestation, and industrial processes (Doney, S. C., et al.,2009). From the beginning of industrial revolution, atmospheric CO_2 level increased from approximately 285 ppm to 420 ppm. The oceans acts as natural sink and absorb a substantial portion of the excess carbon dioxide from the atmosphere. (Orr, J. C., et al. (2005). By doing so, although the atmosphere become less of CO_2, instead this absorption leads to changes in the chemistry of oceans. It leads to chemical changes in the seawater. When carbon-dioxide dissolves in water, it reduces the pH of the water and alters the carbonate chemistry of the marine environment. The process is known as Ocean acidification. Its a growing concern that ocean acidification caused by fossil fuel emissions, in concert with effect of human activities which will cause significant changes in biodiversity and function of the marine ecosystem. It's a matter of discussion that effect due to ocean acidification on ecosystem is like other environmental disturbances effects. The reduction in the pH of seawater and the associated decline in carbonate ion concentration can negatively affects the marine organisms, especially those that depend on calcium carbonate to build shell and skeletons. These organisms include mollusks, corals, crustaceans, and certain plankton species.

In addition to the affecting individual species, ocean acidification can disturb marine food web, changes species distribution and led to changes in the structure and functioning of ecosystem. Coral reefs are among the most biodiverse ecosystem in oceans, and highly sensitive to ocean acidification. The degradation of coral reef may result in the significant loss to biodiversity and ecosystem services.

Knowing the importance of marine ecosystem for global biodiversity and for human kind, it is essential to understand the mechanism and impacts of Ocean acidification. To plan for future, the society needs the information to understand how ocean acidification and other environment changes affect fishes, sea life and other service delivering from the effiecient function of marine ecosystem. This paper aims to examine the different causes and chemical process under water, assess its impacts on marine ecosystem and discuss the mitigation and conservation strategies.

a. Chemistry of Ocean Acidification

Ocean acidification occurs because of chemical reactions between carbon dioxide and seawater. When carbon dioxide from the atmosphere dissolves in seawater, it reacts with water molecules to form carbonic acid. This process initiates a series of chemical reactions that alter the carbonate chemistry of ocean water.

The chemical reactions involved in ocean acidification can be summarized as follows:

$CO_2 + H_2O \rightarrow H_2CO_3$

$H_2CO_3 \rightarrow HCO_3^- + H^+$

$H^+ + CO_3^{2-} \rightarrow HCO_3^-$

As we all know the formation of hydrogen ions leads to decrease in pH level, makes the seawater more acidic. Although the ocean is slightly alkaline, a minor change in the pH represent significant change in the chemistry of ocean water. One of the most important effect is the reduction in the availability of carbonate ions. Carbonate ions plays an important role for the benefit of marine organism. Carbonate ions are essential for making the calcium carbonate which will form hard structure such as shell and skeletons. When the carbonate ion concentration decreases, the organism must expand more energy to maintain this calcification process. This decrease also reduces the saturation state of calcium carbonate minerals such as aragonite and calcite. Without this, it's become very difficult for marine organism to make their form and maintain their skeletal structures.

From the beginning of industrial revolution, the average decrease in pH is approximately 0.1 units. Although this change appears small, but this can pose serious threat and the rate be increased to 0.3 to 0.4 units if carbon dioxide emission continues to increase at current rates.

b. The effects of ocean acidification on organisms

Various physiological processes like photosynthesis, calcification, acid base homeostasis, gas exchange, and respiration can be influenced by changes in the chemistry of oceans. (Melzner et al. 2009). High level of carbon in oceans are expected to affect primary producers in different ways, leading to shift in the structure of phytoplankton population (Donet et al. 2009). Effect on different life stages can sum to significant impact on population success. For example, during periods of low sea surface temperature effects on marine organisms that rely on calcium carbonate to build shells and skeletons are particularly vulnerable to ocean acidification (Caldeira, K., & Wickett, M. E. 2003). These organisms include corals, mollusks, echinoderms, and certain plankton species.

1) Coral Reefs

Coral reefs are among the most biologically diverse ecosystem, plays a major role as source of food.(Hoegh-Guldberg, O., et al. 2007). It is estimated that 500 million people mainly in the coral triangle area, depends directly on the reefs for their survival (Wilkinson, 2008). The reef also protect the coast from erosion by waves and also reduce the wave energy upto 96% (Ferrario et al 2014). Although they occupy less than 1 percent of the ocean floor, yet they support twenty five percent of all marine species Reef-building corals produce calcium carbonate skeletons that form complex reef structures, providing habitat and shelter for numerous marine organisms. Apart from these key ecosystem services, reefs are also important reserves for tomorrow's medicines (Bruckner, 2002). They thus contribute significantly to the well-being of man both now and in the future.

Unfortunately, the health of reef systems across the globe is highly threatened. Ocean acidification reduces the calcification of corals to large extent, making it difficult for them to build and maintain their skeleton. Due to slower rate of calcification, coral growth also slows down, and the reef structure become weaker and become susceptible to erosion and damage by Stroms.

Furthermore, acidification can exacerbate the effects of other environmental stressors such as rising sea temperatures, pollution, and overfishing. The combined effects of these stressors may lead to widespread coral reef degradation and biodiversity loss.

2) Impact on Mollusks and Shellfish

Mollusks including oysters and clams depend on the calcium carbonate to construct their protective shells. Ocean acidification lowers the amount of carbonate ion thus decreasing the rate of calcification. As a result of this shells become weaker and more sensitive to dissolution.. Experimental studies have shown that mollusks exposed to acidified seawater often display reduced shell growth, shell deformities, and structural weakening. The early life stages of mollusks are more sensitive to seawater chemistry. Larval shellfish require rapid calcification to form protective covering son after fertilization (Dutkiewicz, S.,2021). Acidified environment delays shell formation, can cause malformation and increase mortality rate. As an example, oyster hatcheries in several regions have reported larval mortality with low carbonate saturation states. These impact threatens both aquaculture and natural populations. Physiological processs in mollusks are also affected by ocean acidification. Organisms have to expend more energy to regulate internal balance under acidic conditions. And in return, this leads to decreased energy for growth, reproduction and immune responses.

3) Impacts on Marine Food Webs

Marine food webs are complex networks of predator–prey relationships that sustain ocean ecosystems. Mollusks and other calcifying organisms occupy important ecological roles in these food webs. Ocean acidification can therefore produce cascading effects across multiple trophic levels Hofmann, G. E., et al. (2020).. Many planktonic organisms, such as pteropods and coccolithophores, are sensitive to acidification because they also rely on calcium carbonate structures. These organisms form the base of many marine food chains and serve as an important food source for fish, marine mammals, and seabirds Declines in plankton populations can reduce the availability of food for higher trophic levels, ultimately affecting fish populations and marine biodiversity. Changes in the abundance of shellfish and plankton can alter predator–prey relationships. Predators that rely heavily on mollusks as a food source, including crabs, fish, birds, and marine mammals, may experience reduced food availability. Such disruptions may cause shifts in species composition and ecosystem structure. Ocean acidification may also affect the biochemical composition of primary producers, altering their nutritional value. Reduced nutritional quality can impair growth and survival of herbivores and higher-level consumers.

a. **Ecological Impacts on Marine Ecosystems:** Decreasing the number of calcifying organism can lead to reduction in marine biodiversity. The species unable to adapt in acidic environment may decline or disappear from the marine ecosystem. Shellfish reef and coral reef provide habitat to marine organism . the weakning of these structure may reduce habitat complexity leading to ocean acidification can influence theiry nutrient cycling, and ecosystem resileinece. These all changes may interact with other environment stressors such as ocean warming, pollution and overfishing, further threating marine ecosystems.

b. **Socio-Economic Impacts:** Aquaculture and shellfisheries are highly vulnerable to ocean acidification. Reduced growth and survivals of mollusks can results in decreased production and economic losses. Many coastal economies heavily depends on harvesting of shellfish and aquaculture.

c. Mitigation and Conservation Strategies

Addressing ocean acidification requires coordinated global efforts to reduce carbon dioxide emissions and protect marine ecosystems. Reducing greenhouse gas emissions is the most effective strategy for slowing the rate of ocean acidification. Transitioning to renewable energy sources, improving energy efficiency, and reducing deforestation can help decrease atmospheric carbon dioxide concentrations. Marine protected areas can also enhance ecosystem resilience by reducing other stressors such as overfishing and habitat destruction. Protecting biodiversity can help ecosystems adapt to changing environmental conditions. Restoration of coastal ecosystems such as mangroves, seagrasses, and salt marshes can also help mitigate ocean acidification. These ecosystems absorb carbon dioxide and act as natural carbon sinks. Research and monitoring programs are essential for understanding the long-term impacts of ocean acidification and developing adaptive management strategies.

d. Future Research Directions

Despite the massive achievement in the knowledge of ocean acidification, there is still a lot of uncertainty on the long-term ecological implications of the phenomenon. The long term monitoring of ocean chemistry and marine biodiversity should be integrated in future research. The relationship between ocean acidification and warming and pollution on marine ecosystems requires experimental studies. Ecosystem modeling developments can assist in forecasting the future of marine biodiversity in the various climate conditions. This will require interdisciplinary studies that involve oceanography, ecology, and social sciences with the aim of coming up with effective management strategies.

e. Conclusion

Ocean acidification is one of the gravest hazards to the marine life and biodiversity. Uptake of carbon dioxide emitted by humans into the oceans has led to severe transformations in the water chemistry of the seas such as lower PH and lower carbonate ions. The changes have great impacts on the calcifying organisms including corals, mollusks and plankton. The disappearance of these organisms may upset the marine food webs, change the structure of the ecosystems and decrease biodiversity. To preserve marine biodiversity and guarantee the sustainability of ocean ecosystems in the long term, it is crucial to implement effective conservation policies to go along with further scientific research.

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