Journal of Environmental Studies and Health Research
An open-access International Journal

Review Article

Ocean Acidification: Impacts on Marine Ecosystems and Deep-sea Carbon Sequestration

Md S. Zaman[1,2,*], Robert C. Sizemore[1], San Juanita Sanchez[2]

[1]Department of Biological Sciences, Alcorn State University, Lorman, MS 39096, USA [2]Department of Biology, South Texas College, McAllen, TX 78501, USA

*Correspondence: zaman@alcorn.edu; mzaman@southtexascollege.edu

Cite: Zaman, M.S., Sizemore, R.C., Sanchez, S.J. (2025). Ocean Acidification: Impacts on Marine Ecosystems and Deep-sea Carbon Sequestration. Journal of Environmental Studies & Health Research, 1 (1). https://www.doi.org/10.5281/zenodo.16934900
August 23, 2025.

Abstract

Carbon dioxide (CO_2) is a major greenhouse gas that plays an essential role in Earth's climate system. Oceans help climate stability by absorbing about 30% of the anthropogenic CO_2 emissions. However, this process leads to ocean acidification (OA) and reduces the availability of carbonate ions, which are necessary for organisms that build shells and skeletons, such as corals, mollusks, and certain plankton. Since the Industrial Revolution, ocean pH has dropped by approximately 0.1 units, a significant shift that threatens marine ecosystems. OA affects marine organisms in multiple ways. Calcifying species struggle to form shells, leading to reduced survival and disrupted food webs. Coral reefs, often called the "rainforests of the sea" due to their exceptional biodiversity, are particularly vulnerable, and their decline results in biodiversity and habitat loss. Phytoplankton, the foundation of the marine food web and the ocean's biological carbon pump, also respond in mixed ways; some benefit from higher CO_2, while others are negatively affected, reducing ocean productivity and carbon cycling. OA weakens the ocean's biological carbon pump, reducing long-term carbon storage in the deep sea. It also contributes to harmful algal blooms, which can contaminate seafood and pose human health risks. Economically, OA threatens global seafood production, especially shellfish and crustaceans, jeopardizing food security and coastal livelihoods. This paper explores the biological, ecological, and economic impacts of OA and discusses mitigation strategies such as reducing CO_2 emissions, protecting blue carbon ecosystems, controlling coastal pollution, and supporting adaptive aquaculture. Addressing OA is essential to protect marine biodiversity, sustain seafood resources, and maintain climate stability.

Keywords: Ocean acidification, marine ecology, global carbon cycle, carbon sequestration

Introduction

Carbon dioxide (CO_2) is a greenhouse gas that plays a critical role in Earth's climate system. In the ocean, marine phytoplankton convert CO_2 into organic matter through photosynthesis, thereby forming the foundation of the marine food web and the ocean's biological carbon pump, and helping to regulate atmospheric carbon levels. However, anthropogenic activities such as fossil fuel combustion and deforestation have significantly increased CO_2 levels in the atmosphere. Other natural phenomena, such as volcanoes (USGS, 2025) and wildfires (IFAW, 2024), also significantly contribute to the rise in atmospheric CO_2 levels. Over the past 200 years, the oceans have absorbed an estimated 150 billion metric tons of CO_2. Since the 1700s, the oceans have absorbed roughly one-third of all anthropogenic CO_2 emissions through a combination of physical and chemical processes (NOAA Fisheries, 2025).

While oceanic CO_2 absorption helps slow the rise in atmospheric carbon levels, it also triggers a process known as ocean acidification (OA). When CO_2 dissolves in seawater, it forms carbonic acid (H_2CO_3), which dissociates into hydrogen ions and bicarbonate (HCO_3^-). The increase in hydrogen ions lowers the ocean's pH and reduces the availability of carbonate (CO_3^{2-}) ions, key ingredient for shell formation in calcifying organisms such as oysters, clams, reef-building corals, and pteropods (miniature snails about the size of a pea that are a food source for many fish and oceanic animals) (EPA, 2025a; NOAA, 2024) (Figure 1).

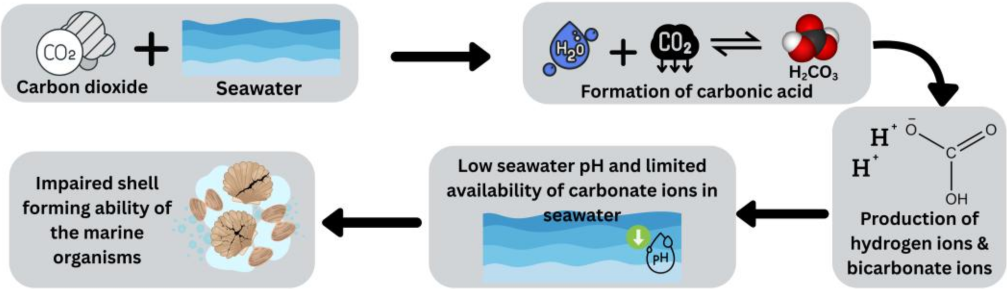

Figure 1: The figure represents the formation of H^+ in seawater, which makes the water acidic and reduces the availability of carbonate ions, inhibiting the shell-forming capacity of the marine organisms.

Over the past 250 years, the pH of ocean surface water has decreased by 0.11 units, corresponding to a 30%–40% increase in hydrogen ion concentration, a significant shift in chemical balance (Feely et al., 2023). As atmospheric CO_2 continues to rise, ocean pH is expected to decline further, posing increasing threats to marine biodiversity and ecosystem stability. OA not only affects the ability of marine organisms to build shells and skeletons but also disrupts broader ecological processes, including primary production and food web dynamics (NOAA, 2025a).

Another critical impact of OA is its interference with the ocean's biological carbon pump (BCP), a natural mechanism for long-term carbon sequestration. The BCP operates as follows: phytoplankton performs photosynthesis, producing organic matter; this organic matter moves through the food chain and eventually sinks to the deep ocean in the form of marine snow (which includes dead organisms, organic particles, fecal matters, and other debris from marine organisms) where it is stored, sequestering carbon for centuries or longer (WHOI, 2025) (Figure 2). Acidification can impair this process, making the carbon pump less efficient and reducing the amount of CO_2 that is removed from the atmosphere, thus impacting Earth's climate (WHOI, 2025).

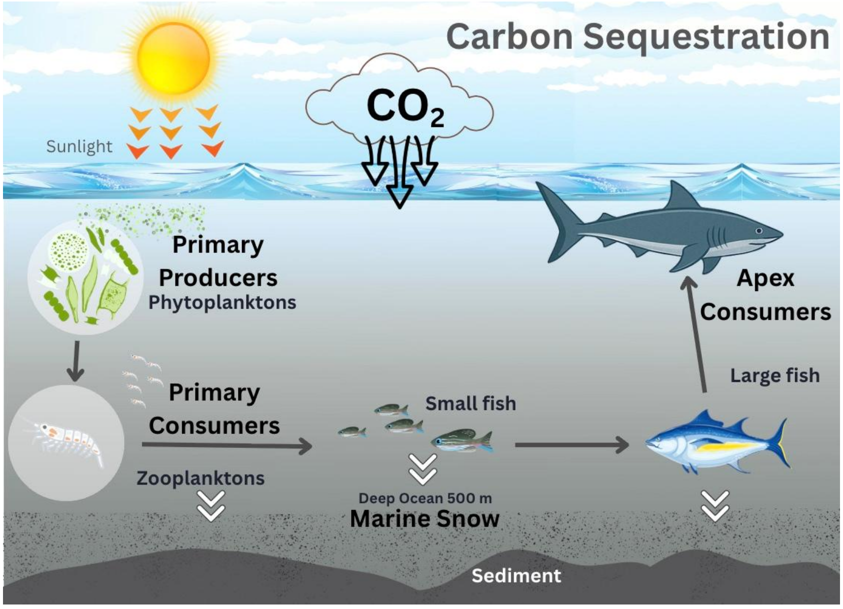

Figure 2: The figure illustrates the Ocean's Food Cycle, depicting the production of organic matter. This organic material progresses through the marine food chain and ultimately descends to the deep ocean as marine snow. Marine snow consists mainly of deceased organisms, organic particles, fecal matter, and other debris from marine life. This material accumulates on the ocean floor, where sediments sequester carbon for centuries.

OA also has implications for human health. Certain harmful algal species, such as dinoflagellates and diatoms, tend to proliferate more rapidly in acidified conditions, called harmful algal blooms (HABs). HABs produce toxins, such as brevotoxins, saxitoxins, and domoic acids, that can accumulate in seafood such as shellfish and fish, posing health risks to humans through consuming contaminated products (NOAA Fisheries, 2025).

The Effects of Ocean Acidification on Marine Ecology

The gradual yet persistent change in ocean water chemistry due to OA is having profound effects on marine ecology, altering species distribution, reproduction, behavior, and ecosystem structure.

Impact on Plankton and the Food Web

Phytoplankton are the ocean's main producers. They use dissolved inorganic carbon for photosynthesis. In theory, higher CO_2 levels should boost photosynthesis by lowering the energy needed to absorb carbon, a phenomenon known as *CO_2 fertilization*. However, the phytoplankton species respond to OA in distinctive ways. Non-calcifying phytoplankton, such as certain diatoms and cyanobacteria, may grow faster with higher CO_2, while others show no change or even decline (Schulz, 2017). Nutrients, light, and temperature also play a role in shaping these effects (EPA, 2025b).

Disruption of Calcifying Organisms and Damage to Coral Reef Ecosystems

Shell-bearing marine organisms, such as corals, mollusks (clams, oysters, mussels), echinoderms (sea urchins, starfish), and certain plankton, build their shells or skeletons from calcium carbonate. These organisms are most directly affected by OA (IOOS, 2025). OA reduces the availability of carbonate ions in seawater, which are essential for forming shells or skeletons in these marine organisms. As a result, these organisms struggle to build and maintain their shells and skeletons, making them more vulnerable to predation and environmental stress (NOAA, 2025b). This vulnerability can lead to population decline and disrupt the food chains that depend on them.

Studies show that phytoplankton, such as *Emiliania huxleyi* (coccolithophores), depend on carbonate ions to build their calcium carbonate plates, and they are especially vulnerable to OA. As ocean pH drops, their calcification slows, leading to thinner or distorted plates, which harms their growth and reproduction. This also weakens their role in transporting carbon to the deep ocean (OCB, 2025). Given their ecological importance, a decline in phytoplankton abundance could significantly impact ocean productivity, biogeochemical cycling, and energy flow processes in the oceans.

Coral reefs are the backbone of vibrant marine ecosystems and are often called the "rainforests of the sea" due to their extraordinary biodiversity (NOAA, 2025a). They offer shelter and nourishment to countless marine species, act as natural barriers protecting coastlines from storm surges, and sustain vital fisheries and tourism industries. Corals form their intricate skeletons using calcium carbonate; however, rising ocean acidity slows their growth, leaving reefs vulnerable to erosion and bleaching (NOAA, 2025a). As these reefs deteriorate, the complex habitats they support begin to collapse, resulting in a loss of biodiversity and significant shifts in marine community structures.

Shifts in Biodiversity and Ecosystem Services

Some marine organisms struggle to survive at lower pH levels. For example, some fish species, such as crabs, lobsters, and tropical reef fish, exhibit impaired abilities to detect predators, find suitable habitats, or navigate when exposed to more acidic waters (Kroeker et al., 2013). However, tolerant invasive species, such as *Caulerpa taxifolia* (killer algae), *Pelagia noctiluca* (jellyfish), and *Crepidula fornicate* (mollusks) may find opportunities to thrive in a low pH environment (R&D World, 2015). This can lead to shifts in species distribution, altered species interactions and competitions, which potentially lead to further ecological imbalance.

The collective impact of OA causes a reduction in marine biodiversity and the degradation of ocean ecosystems. Marine ecosystems provide essential services, such as oxygen production, carbon sequestration, nutrient cycling, and food supply. The decline in the health and functioning of these ecosystems endangers their ability to support oceanic life.

The Interrelationship of Ocean Acidification and the Global Carbon Cycle, and Its Impact on Ocean Carbon Sequestration

The global carbon cycle involves the continuous exchange of carbon among the atmosphere, oceans (hydrosphere), living organisms (biosphere), and Earth's crust (geosphere) (Figure 3). As stated earlier, oceans absorb atmospheric CO_2, which reacts with seawater to form carbonic acid, leading to OA. This disrupts the ocean's chemical balance and reduces the availability of carbonate ions, which are essential for marine organisms that build calcium carbonate shells and skeletons (NOAA, 2025b).

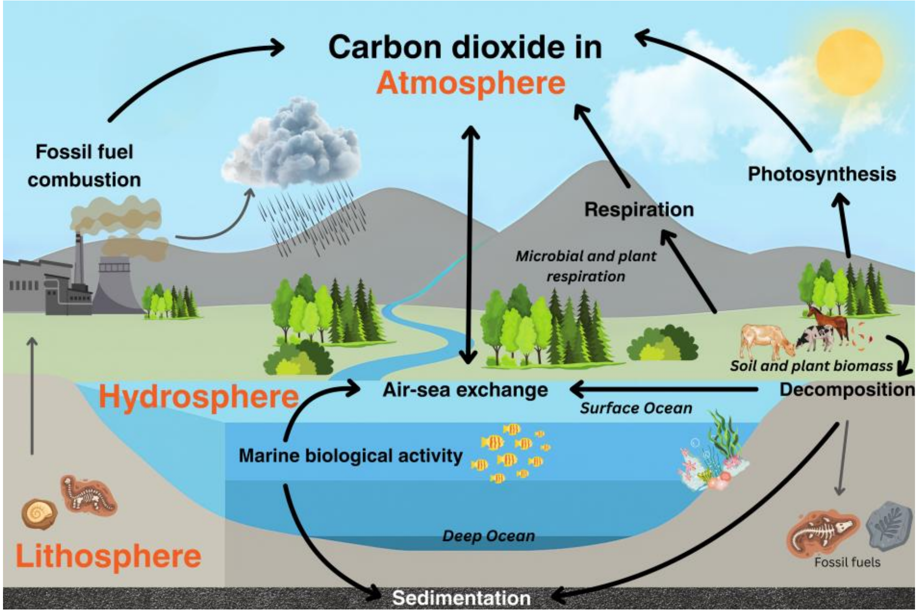

Figure 3: The figure represents the Global Carbon Cycle, which involves the continuous exchange of carbon among the atmosphere, hydrosphere, biosphere, and geosphere.

This chemical shift impacts oceanic biological productivity and disrupts the ocean's biological pump, a crucial process in which plankton absorb CO_2 through photosynthesis and transfer organic carbon to deeper ocean layers via the food web, thereby facilitating long-term carbon storage (WHOI, 2025).

Ocean acidification and the carbon cycle are closely linked. When oceans absorb less CO_2, more remains in the atmosphere, which could contribute to a rise in atmospheric temperature. Conversely, when oceans absorb more CO_2, increased acidity harms marine life.

To address these challenges, a balanced approach is needed, including:

1. Reducing global CO_2 emissions,
2. Restoring and protecting carbon-storing ecosystems, such as the cultivation of mangrove forests and seaweed beds, and
3. Enhancing CO_2 monitoring systems to track changes in both the ocean and atmosphere.

The Impacts of OA on Seafood Production

Seafood production holds significant economic value for coastal communities, where a significant number of people depend on fisheries both for their food and as a primary source of income. Globally, fisheries play a crucial role in supporting food security and livelihoods.

As stated earlier, ocean acidification (OA) has significant adverse effects on seafood production. One of the most direct impacts is on shell-forming organisms such as oysters, clams, and mussels, which are among the most widely consumed seafood. Studies have shown that OA poses a serious threat to these species, as well as to lobsters and other shellfish This chemical shift affects oceanic biological productivity and interferes with the ocean's biological pump, a key process where plankton absorb CO_2 through photosynthesis and transfer organic carbon to deeper ocean layers through the food web, aiding long-term carbon storage (WHOI. 2025).

A 2023 study reported that the continued absorption of carbon dioxide by the oceans is increasing water acidity, which in turn impedes the growth of young Atlantic Sea Scallops. This problem could be further aggravated by rising ocean temperatures. This is particularly concerning considering the economic significance of Atlantic Sea scallops, which contributed $670 million to the U.S. fishery in 2021 (Pousse et al., 2023). The U.S. fishery had an estimated total commercial value of $6.5 billion that year (NOAA, 2024).

The broader economic impact of OA is alarming. The International Atomic Energy Agency (IAEA) has projected that by 2100, global shellfish fisheries could suffer an annual production loss of $100 billion (IAEA, 2017). Similarly, another study estimated that the U.S. shell fishing industry could lose over $400 million per year by the end of the century (Remedios, 2021). A 2014 United Nations report further warned that changes in ocean chemistry could cost the global economy more than $1 trillion annually by 2100 (Bradbury, 2014).

Beyond shellfish, OA affects a variety of other marine species. For example, studies indicate that it can impair the development, growth, and survival of crab species such as tanner crabs, potentially threatening valuable crab fisheries (NOAA Fisheries, 2023). This chemical shift affects oceanic biological productivity and interferes with the ocean's biological pump, previously described (WHOI, 2025).

OA has also been shown to alter the behavior and prey-finding abilities of crabs and lobsters, further endangering these populations (Gravinese et al., 2020). Additionally, crabs and Pacific cods are particularly vulnerable to OA during their early developmental stages (Gravinese et al., 2020). In tropical reef fish, OA disrupts sensory systems, making it more difficult for them to locate food, avoid predators, and navigate their environment (Branch et al., 2013). While research is ongoing, scientists are increasingly concerned that other commercially important fish species may experience similar detrimental effects.

The societal consequences of OA are far-reaching. It jeopardizes not only global food supplies but also cultural traditions and the resilience of coastal populations. This is especially critical in developing countries, where seafood serves as a primary source of protein. A decline in seafood resources due to OA could intensify food insecurity.

Mitigation Strategies

1. Since ocean acidification is driven by atmospheric CO_2 dissolving into seawater, cutting greenhouse gas emissions is the most direct and effective approach in lowering the atmospheric CO_2 levels. This goal can be achieved by reducing fossil fuel use, transitioning to renewable energy, and improving energy efficiency.

2. Ecosystems, such as mangroves, seagrasses, and salt marshes, naturally absorb and store carbon (blue carbon ecosystem). Mangroves can store up to 174 grams of carbon per square meter each year (Alongi, 2014). Protecting and restoring these habitats not only enhances carbon sequestration but also buffers coastal waters against acidification.

3. Excess nutrients from agriculture and wastewater can worsen coastal acidification. Agencies like the EPA and NOAA should be working closely to reduce coastal eutrophication and monitor estuarine acidification using advanced sensors.

4. Fish larvae are more vulnerable to water chemistry than adults. Shellfish hatcheries, especially in the Pacific Northwest, are experimenting with breeding more resilient species and adjusting water chemistry in hatchery tanks to protect vulnerable larvae.

5. Alkalinity enhancement is an experimental project that involves adding alkaline substances, such as crushed limestone to seawater to neutralize acidity. If successfully implemented, it could help restore ocean pH balance in targeted areas.

6. The engagement and close cooperation of the public, governments, and international agencies can help formulate sensible policies critical to addressing this complex issue.

Discussion

Ocean acidification (OA) is a growing environmental issue with far-reaching effects on marine life, ecosystems, and human societies. While the ocean plays a vital role in slowing climate change by absorbing atmospheric CO_2, this benefit comes at a cost. The chemical reactions that follow CO_2 absorption lower ocean pH, which is detrimental to the shell-building capacity of various ocean organisms. As a result, shell-forming species such as oysters, clams, corals, and certain plankton face increasing challenges in growth, reproduction, and survival.

OA also affects non-calcifying species, but its impact varies. Some phytoplankton may benefit from higher CO_2 levels, while others may suffer reduced growth or calcification, disrupting their role in the marine food web and the ocean's carbon pump (WHOI, 2025). Coral reefs, which support extraordinary biodiversity and provide economic value through fisheries and tourism, are especially vulnerable. Their decline leads to habitat loss for many species and weakens coastal protection.

Moreover, OA has implications beyond ecological damage. It threatens global seafood supplies, affects the fishing economy, and poses human health risks due to the potential rise of harmful algal blooms (NOAA Fisheries, 2025). The effects are especially concerning in developing countries, where seafood is a major source of nutrition and income. Addressing OA requires urgent global action to reduce CO_2 emissions and adopt sustainable marine practices.

Another important function of the oceans is that they act as a major carbon sink, moving carbon to the deep sea through the biological pump. When the remains of aquatic organisms and other organic matter are deposited on the deep-sea floor as ocean snow, they remain sequestered there for hundreds of years. This directly helps the oceans to maintain pH levels and thus fight ocean acidification. This process supports the survival of aquatic organisms, particularly shell-building species, and the absorption of atmospheric CO_2 helps reduce atmospheric CO_2 levels.

Limitations of This Study

While this study gives a general overview of the causes, effects, and possible solutions to ocean acidification (OA), it has several limitations that should be acknowledged.

1. This study uses existing research information from a global perspective. Therefore, it does not represent the local or regional perspectives.
2. The biological responses to OA vary greatly across species, environments, and developmental stages. This paper does not reflect these variations in detail. For example, while some phytoplankton and shell-forming organisms are known to be vulnerable to lower pH levels, others may be more tolerant. These differences are complex and require more focused studies.
3. The study briefly discussed how OA might affect human health and economies, especially in poorer regions. More detailed studies are needed to understand the real impact on specific communities.
4. Among the proposed remediation strategies discussed in this paper is the enhancement of ocean alkalinity. This approach remains in the experimental stage, having been tested only on small scales, and its effectiveness at larger scales has yet to be established.

Future Research Directions

To better understand and respond to OA, future research should focus on the following areas:

1. More studies are needed on how different marine species, especially those with commercial or ecological importance, respond to acidification under varying conditions (e.g., temperature, light, nutrients).

2. Further experiments are to be designed to study the synergistic effects of seawater temperature, eutrophication, and acidification to gain insights into ecosystem-level effects of OA.
3. Further research on how OA affects the ocean's ability to store carbon over time will help predict future climate scenarios and carbon cycle feedback.
4. Mitigation and adaptive strategies are to be further investigated involving AI, satellite data, and other modern technologies
5. Socioeconomic impacts are to be studied by evaluating how OA affects fisheries, aquaculture, food security, and coastal economies. That will support informed policymaking and community adaptation strategies.
6. Developing better sensors and monitoring networks to track changes in ocean chemistry will support early detection and rapid response to OA hotspots.

Conclusions

Addressing OA requires global cooperation to cut carbon emissions and strengthen ocean health. Research, strong policies, and public involvement play key roles in understanding and reducing its impact. Effective strategies, such as sustainable fishing, restoring coastal areas, and cutting pollution, can help decrease OA's effects.

OA is a serious issue that affects seafood, marine life, and the well-being of people, especially in coastal communities. Quick action is needed to protect biodiversity and secure ocean-based livelihoods. By targeting the root causes and applying smart solutions, we can help keep the oceans thriving for future generations.

Acknowledgments: *Not applicable.*

Patents: *Not applicable.*

Institutional Review Board Statement: *Not applicable.*

Informed Consent Statement: *Not applicable.*

Conflicts of Interest: *None.*

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