



OCEAN ACIDIFICATION: CONSEQUENCES FOR MARINE LIFE AND GLOBAL ECOSYSTEM HEALTH

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Abstract:

Ocean acidification (OA) is one of the most pressing challenges facing marine ecosystems and global biodiversity due to its impact on ocean chemistry. As carbon dioxide (CO₂) levels in the atmosphere rise, a significant portion of this CO₂ is absorbed by the oceans, leading to a decrease in pH and subsequent chemical changes that negatively affect marine organisms. This article explores the consequences of ocean acidification on marine life, including impacts on coral reefs, shellfish, fish populations, and overall ecosystem health. Furthermore, it examines how OA disrupts biogeochemical cycles, marine food webs, and global climate regulation. The article also discusses the specific implications of ocean acidification for Pakistan's marine ecosystems and provides recommendations for mitigating its effects. Understanding the mechanisms and consequences of ocean acidification is crucial for the preservation of marine biodiversity and the sustainability of ocean services that support human societies

Keywords: *Ocean Acidification, Marine Ecosystems, Carbon Dioxide, Biodiversity Loss*

INTRODUCTION

Ocean acidification refers to the process by which increasing levels of carbon dioxide (CO₂) in the atmosphere are absorbed by the oceans, leading to a reduction in the pH of seawater. This process results in changes to the ocean's chemical composition, with significant impacts on marine life and ecosystems. As atmospheric CO₂ concentrations continue to rise due to human activities such as fossil fuel burning, deforestation, and industrial processes, ocean acidification is expected to accelerate, with profound consequences for marine biodiversity and ecosystem services.

Marine ecosystems, particularly coral reefs, shellfish populations, and the organisms at the base of the marine food web, are particularly vulnerable to the effects of ocean acidification. These ecosystems play a critical role in regulating the global climate, supporting fisheries, and providing habitat for a wide range of marine species. In regions like Pakistan, where coastal and marine ecosystems provide livelihoods for millions of people, ocean acidification poses a direct threat to both ecological and economic stability. Understanding the science of ocean acidification and its effects on marine life is crucial for developing effective conservation strategies and mitigating its impacts on global ecosystems.

1. Ocean Acidification: Mechanisms and Causes

Overview of Ocean Acidification and Its Causes:

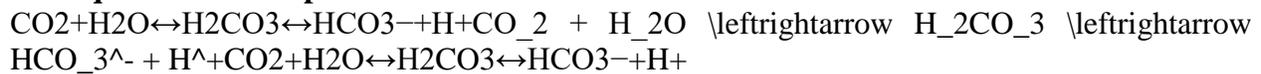
Ocean acidification refers to the ongoing decrease in the pH of the Earth's oceans caused by the absorption of excess carbon dioxide (CO₂) from the atmosphere. This process has become more prominent in recent decades due to the rapid increase in atmospheric CO₂ concentrations resulting from human activities such as the burning of fossil fuels, deforestation, and industrial emissions. The oceans act as a natural buffer, absorbing approximately one-third of the anthropogenic CO₂ released into the atmosphere. However, this excess CO₂ is leading to a chemical transformation in seawater, making it more acidic and reducing its capacity to support marine life that relies on stable pH levels for survival.

Ocean acidification is a significant environmental issue, as it alters the chemical composition of seawater, impacting marine ecosystems and species that depend on carbonate ions to build their shells and skeletons. Over time, these changes can have cascading effects on marine biodiversity, food webs, and global climate regulation.

The Role of Atmospheric CO₂ in Driving Ocean Acidification:

The primary cause of ocean acidification is the increased concentration of carbon dioxide in the atmosphere. As CO₂ levels rise, a significant portion of this gas dissolves into the surface waters of the oceans. When CO₂ dissolves in water, it reacts with water molecules to form carbonic acid (H₂CO₃). This acid then dissociates into bicarbonate (HCO₃⁻) and hydrogen ions (H⁺), leading to a decrease in pH.

The equation for this process is:

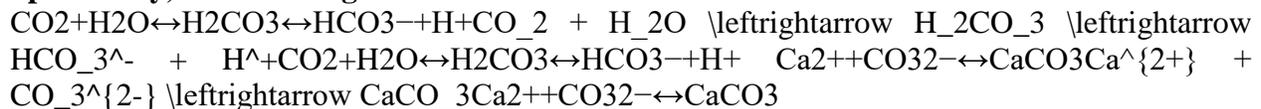


The increase in hydrogen ions (H⁺) lowers the pH of seawater, making it more acidic. This rise in acidity disrupts the availability of carbonate ions (CO₃²⁻), which are essential for organisms like corals, shellfish, and plankton to build their calcium carbonate (CaCO₃) shells and skeletons. The ongoing increase in atmospheric CO₂ will continue to exacerbate ocean acidification, threatening marine life and ecosystems.

Chemical Reactions in Seawater Leading to Decreased pH and Carbonate Ion Availability:

The decrease in pH and carbonate ions is a direct consequence of the chemical reactions that occur when CO₂ dissolves in seawater. As the concentration of hydrogen ions increases, the concentration of carbonate ions (CO₃²⁻) decreases. This reduction in carbonate ions has significant implications for marine organisms that rely on calcium carbonate for their shells, skeletons, and exoskeletons.

Specifically, the following reactions occur in seawater:



As the availability of carbonate ions decreases, organisms like corals, mollusks, and some plankton species find it more difficult to produce calcium carbonate, leading to weaker shells, reduced calcification, and impaired growth. This disruption in calcification is one of the most profound effects of ocean acidification on marine life.

2. Impact of Ocean Acidification on Marine Life

Effects on Coral Reefs: Decline in Coral Calcification Rates and Reef-Building Capacity:

Coral reefs are among the most affected ecosystems by ocean acidification. Corals rely on calcium carbonate (CaCO₃) to build their skeletons and create the reef structures that provide habitat for countless marine species. As ocean acidification reduces the availability of carbonate

ions, corals face difficulties in maintaining the rate of calcification necessary to build and sustain their skeletons.

The decline in calcification rates results in weaker coral structures, making them more susceptible to physical damage, disease, and bleaching events. In the long term, this reduces the capacity of coral reefs to grow and regenerate, threatening the biodiversity they support and the ecosystem services they provide, such as coastal protection, tourism, and fisheries.

Research has shown that ocean acidification can lead to coral bleaching, where corals expel the symbiotic algae (zooxanthellae) that provide them with food and color. The stress induced by acidification weakens the symbiotic relationship, causing corals to bleach and, in many cases, die. The degradation of coral reefs due to acidification has significant implications for marine biodiversity, as they are among the most biodiverse ecosystems on Earth.

Impacts on Marine Shellfish: Decreased Shell Formation in Mollusks and Crustaceans:

Mollusks, such as oysters, clams, and mussels, and crustaceans, such as crabs and lobsters, are highly vulnerable to ocean acidification. These organisms rely on calcium carbonate to form their shells and exoskeletons. As the availability of carbonate ions decreases due to acidification, shell formation becomes more difficult, leading to thinner, weaker shells.

Studies have shown that acidified waters result in slower growth rates, reduced survival, and greater susceptibility to predation and disease in shellfish populations. In particular, oysters and mussels have been found to suffer from increased mortality rates, reduced reproductive success, and weakened shells that are unable to provide adequate protection. The negative impact on shellfish populations threatens the entire marine food web, as these organisms serve as both primary producers (filter feeders) and as a food source for other marine species, including fish, seabirds, and humans.

Disruptions in Marine Food Webs: Effects on Plankton, Fish Populations, and the Broader Marine Ecosystem:

Ocean acidification has a cascading effect on marine food webs. Phytoplankton, which form the base of the marine food web, are particularly sensitive to changes in ocean chemistry. Some species of plankton, such as coccolithophores, rely on calcium carbonate for the production of their protective shells. The reduction in carbonate availability due to acidification hampers their ability to produce shells, potentially leading to population declines.

Zooplankton, which feed on phytoplankton, may also be impacted by changes in plankton populations. These disruptions ripple up the food chain, affecting fish populations, marine mammals, and other predators. For example, many fish species rely on plankton as a primary food source, and reduced availability of plankton can lead to declines in fish stocks, affecting fisheries and marine biodiversity. Furthermore, ocean acidification can alter fish behavior, including their ability to detect predators and find food, which may reduce survival rates.

As ocean acidification impacts the entire food web, it also threatens the livelihoods of human populations that depend on fish and shellfish for food and income. In regions like Pakistan, where coastal communities rely on marine resources, the consequences of ocean acidification could be economically devastating.

3. Ecological Consequences of Ocean Acidification for Global Ecosystem Health

Impacts on Biogeochemical Cycles: Alterations in Nutrient Cycling, Carbon Sequestration, and Oxygen Production:

Ocean acidification has significant implications for the biogeochemical cycles that regulate the flow of essential elements like carbon, nitrogen, and phosphorus in marine ecosystems. The alteration of these cycles can have far-reaching consequences for global climate regulation and ecosystem health.

One of the most significant impacts is on the carbon cycle. Marine organisms, including phytoplankton and corals, play a vital role in carbon sequestration by absorbing CO₂ from the atmosphere and converting it into organic carbon. As ocean acidification affects the ability of these organisms to perform photosynthesis and calcification, the efficiency of carbon sequestration in oceans may decline, contributing to higher atmospheric CO₂ levels and exacerbating climate change.

The alteration of nutrient cycling due to acidification can also impact food web dynamics, as shifts in nutrient availability affect the growth and productivity of marine organisms. Disruptions in the oxygen cycle, due to reduced productivity and increased hypoxia (low oxygen levels) in acidified waters, could further harm marine life.

Influence on Marine Biodiversity and Ecosystem Resilience:

Ocean acidification undermines the resilience of marine ecosystems, particularly coral reefs and shellfish populations. As species that are critical to the structure and function of ecosystems face decline, the overall biodiversity of marine environments decreases. This loss of biodiversity reduces ecosystem resilience, making it more difficult for ecosystems to recover from disturbances such as storms, disease outbreaks, and climate change.

The loss of biodiversity weakens ecosystem services that benefit human populations, such as coastal protection, fisheries, and carbon sequestration. As marine biodiversity declines, ecosystem stability and function become increasingly compromised, threatening the health of global ecosystems.

The Role of Marine Ecosystems in Regulating Global Climate and Sustaining Human Populations:

Marine ecosystems are vital in regulating the global climate and supporting human populations. Oceans act as a carbon sink, absorbing approximately one-quarter of the world's CO₂ emissions and mitigating the effects of climate change. Healthy marine ecosystems, such as coral reefs, mangroves, and seagrass beds, also provide critical services, including shoreline protection, food security, and economic opportunities for coastal communities.

As ocean acidification threatens the health of these ecosystems, the ability of oceans to regulate climate and support human populations is diminished. This could lead to increased vulnerability to climate-related impacts such as coastal erosion, flooding, and loss of marine resources. For countries like Pakistan, where coastal ecosystems provide significant resources, the consequences of ocean acidification could be devastating for both environmental and socio-economic stability.

Ocean acidification is a global environmental issue with profound implications for marine ecosystems, biodiversity, and human well-being. The ongoing increase in atmospheric CO₂ is driving changes in ocean chemistry that threaten the ability of marine organisms to survive and thrive. From the decline in coral reefs and shellfish populations to the disruption of marine food webs and biogeochemical cycles, the consequences of ocean acidification are far-reaching. To mitigate these effects, global efforts to reduce CO₂ emissions, protect marine ecosystems, and enhance conservation strategies are essential. For regions like Pakistan, where marine ecosystems play a vital role in supporting coastal communities, addressing ocean acidification is crucial for the sustainability of both marine and human life.

4. Ocean Acidification in Pakistan: Local Implications for Marine Ecosystems

Status of Pakistan's Coastal and Marine Ecosystems: Coral Reefs, Mangroves, and Fisheries:

Pakistan's coastal and marine ecosystems are of significant ecological, economic, and cultural importance. These ecosystems include coral reefs, mangrove forests, and fisheries, all of which are highly vulnerable to the effects of ocean acidification. Pakistan's coastal areas, particularly

the Makran Coast, Ormara, and Gwadar, support a rich diversity of marine life, including vital coral reefs, mangroves, and fish stocks.

- **Coral Reefs:** The coral reefs off Pakistan's coast, such as those in the Churna Island region and the Baluchistan coast, are important for supporting biodiversity. They provide habitat for a wide range of marine organisms, including fish, mollusks, and crustaceans. However, these reefs are highly susceptible to stress from ocean acidification, which can reduce coral calcification rates and affect reef-building organisms. The declining health of coral reefs will likely result in a loss of biodiversity, diminishing their role in coastal protection, tourism, and fisheries.
- **Mangrove Ecosystems:** Mangroves, which are essential for coastal stabilization, breeding grounds for fish, and carbon sequestration, are also threatened by the changes in water chemistry associated with ocean acidification. Mangroves help in the mitigation of coastal erosion, provide food for marine species, and act as carbon sinks. The decline in mangrove health due to acidification could have cascading effects on marine biodiversity and the livelihoods of local communities who depend on these ecosystems.
- **Fisheries:** Pakistan's fisheries sector, particularly in coastal areas like Karachi and Gwadar, plays a crucial role in food security and the economy. Ocean acidification impacts marine food webs, from plankton to top predators, thereby affecting fish stocks and the overall health of the fishery industry. Acidification-induced declines in shellfish populations will also affect the fisheries dependent on mollusks and crustaceans, reducing the availability of these important seafood resources.
- **Vulnerabilities of Pakistan's Marine Species to Ocean Acidification:**
Pakistan's marine species, including coral reefs, shellfish, crustaceans, and plankton, are highly vulnerable to ocean acidification. Ocean acidification reduces the availability of carbonate ions, which are crucial for the formation of calcium carbonate shells and skeletons in marine organisms.
This affects:
 - **Shellfish:** Species such as oysters, mussels, and clams face challenges in building their calcium carbonate shells, leading to thinner, weaker shells and increased vulnerability to predators and environmental stressors.
 - **Coral Species:** Coral reefs in Pakistan's coastal regions depend on the ability of coral polyps to secrete calcium carbonate for building their skeletons. Ocean acidification directly hampers this process, reducing coral resilience and the ability to recover from environmental stressors like bleaching and physical damage.
 - **Plankton:** Phytoplankton and zooplankton, which form the foundation of marine food webs, are also affected. Changes in the ability of plankton to produce calcium carbonate shells can disrupt the entire marine food web, ultimately impacting fish populations and the ecosystems that depend on them.
- **Socio-Economic Impacts on Coastal Communities and Fisheries in Pakistan:**
Ocean acidification threatens the livelihoods of millions of Pakistanis who depend on marine ecosystems for food, income, and cultural heritage. Fisheries contribute significantly to Pakistan's economy, providing jobs and protein for coastal communities. Declines in fish stocks and the degradation of coral reefs will lead to reduced catch yields, job losses, and food insecurity.
 - **Fisheries and Aquaculture:** Coastal communities rely on fishing for income, and acidification will disrupt fish populations, affecting their income. Additionally, the aquaculture industry, particularly shellfish farming, will be impacted by the reduced availability of mollusks and the weakening of fish stocks.

- **Tourism:** Coral reefs are a major tourist attraction in coastal areas of Pakistan, providing opportunities for eco-tourism and marine-related activities. The degradation of coral reefs due to acidification could lead to a decline in tourism revenue, affecting local businesses and communities dependent on the tourism sector.

5. Mitigation and Adaptation Strategies for Ocean Acidification

- **Global and Regional Efforts to Reduce CO₂ Emissions and Combat Ocean Acidification:**

Reducing atmospheric CO₂ emissions is essential for mitigating ocean acidification and its impacts on marine ecosystems. Global agreements such as the Paris Agreement aim to limit global temperature rise and reduce CO₂ emissions, which is crucial for slowing the progression of ocean acidification. Regional efforts in South Asia and the Indian Ocean also focus on enhancing climate change resilience in coastal and marine ecosystems.

- **Carbon Capture and Storage (CCS):** Technologies like CCS that capture CO₂ from the atmosphere and store it underground can help mitigate the future effects of ocean acidification by preventing additional CO₂ from entering the oceans.
- **Renewable Energy Adoption:** Transitioning to renewable energy sources and promoting energy efficiency are vital strategies for reducing the CO₂ emissions driving ocean acidification.

In Pakistan, efforts should focus on reducing emissions from fossil fuels, promoting clean energy, and supporting global agreements that combat climate change and protect marine biodiversity.

- **Marine Conservation Strategies:** Protecting Coral Reefs, Shellfish Beds, and Marine Biodiversity:

Protecting and restoring marine ecosystems is crucial to maintaining biodiversity and ensuring the continued provision of ecosystem services. Some key conservation strategies include:

- **Marine Protected Areas (MPAs):** Establishing MPAs can help safeguard important habitats such as coral reefs, mangroves, and shellfish beds. These areas allow ecosystems to thrive without the pressures of human activities like overfishing and coastal development.
 - **Coral Restoration Projects:** Coral restoration efforts, such as coral gardening and artificial reefs, can help rebuild damaged reefs and support their resilience to acidification. Additionally, enhancing coral resilience through selective breeding or genetic engineering could help corals adapt to acidifying oceans.
 - **Sustainable Fisheries Management:** Implementing sustainable fishing practices and regulations, including limits on overfishing, the use of selective fishing gear, and seasonal fishing bans, can help maintain fish stocks and protect marine biodiversity.
- **Policy Recommendations for Mitigating the Impacts of Ocean Acidification in Pakistan and Beyond:**

Policy interventions are essential for addressing the challenges of ocean acidification and ensuring the resilience of marine ecosystems.

Key recommendations include:

- **National Policy Integration:** Ocean acidification should be incorporated into national climate change and marine conservation policies. Pakistan should develop a comprehensive strategy for managing the impacts of acidification, including protection of marine ecosystems, promotion of sustainable fisheries, and public education.
- **Regional Cooperation:** Pakistan should work with neighboring countries in the region, particularly those in the Indian Ocean, to share research, technologies, and conservation strategies aimed at addressing ocean acidification and its effects on marine ecosystems.

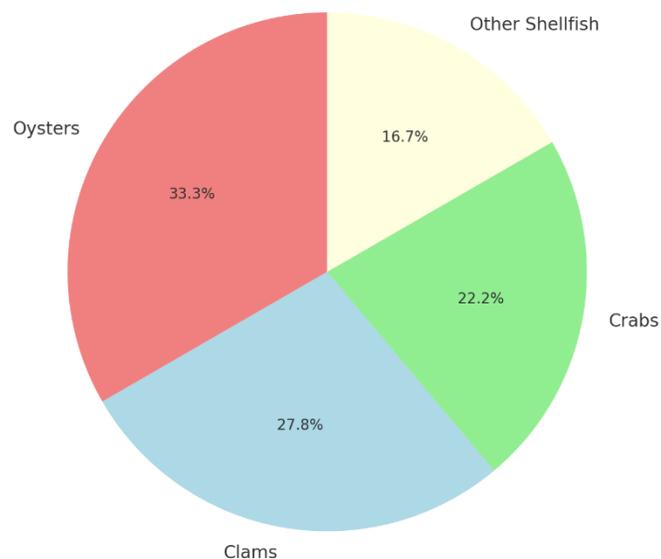
- **Research and Monitoring:** Establishing long-term monitoring programs to track ocean acidification and its impacts on marine life is essential for informed decision-making. Supporting research into the ecological effects of acidification and developing adaptive management strategies for local communities are also critical.
- **Public Awareness and Education:** Raising awareness about the causes and consequences of ocean acidification can help foster community engagement in conservation efforts. Educating the public, especially coastal communities, on sustainable fishing practices, the importance of coral reefs, and the effects of climate change is vital for building resilience.

Ocean acidification presents a significant threat to marine ecosystems and coastal communities in Pakistan and around the world. The effects of acidification on coral reefs, shellfish, and marine food webs are already being observed and will continue to worsen unless urgent action is taken to reduce CO₂ emissions and protect marine biodiversity. Pakistan's coastal ecosystems, including coral reefs and fisheries, are vulnerable to the impacts of ocean acidification, which could lead to economic losses and food insecurity for millions of people.

Mitigating the impacts of ocean acidification requires global and regional cooperation to reduce CO₂ emissions, enhance marine conservation efforts, and implement effective adaptation strategies. In Pakistan, protecting marine biodiversity, promoting sustainable fisheries, and raising public awareness are essential for preserving the health of coastal ecosystems and ensuring the livelihoods of coastal communities. By adopting these strategies, Pakistan can contribute to global efforts to combat ocean acidification and build resilience in marine ecosystems.

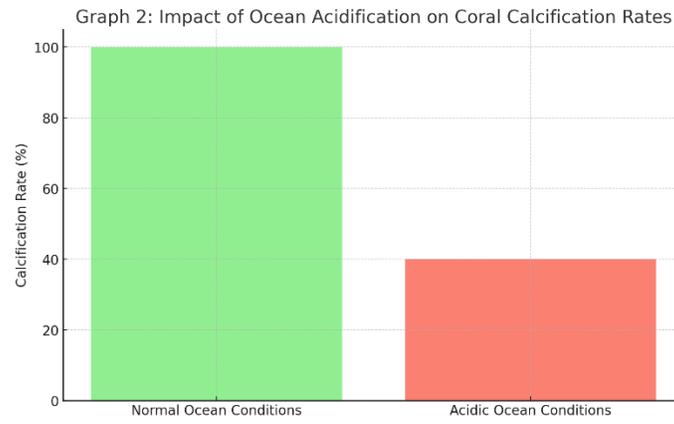
Graphs and Charts:

Chart 1: Effects of Ocean Acidification on Marine Shellfish



Graph 1: pH Decline in Oceans Over the Past Century

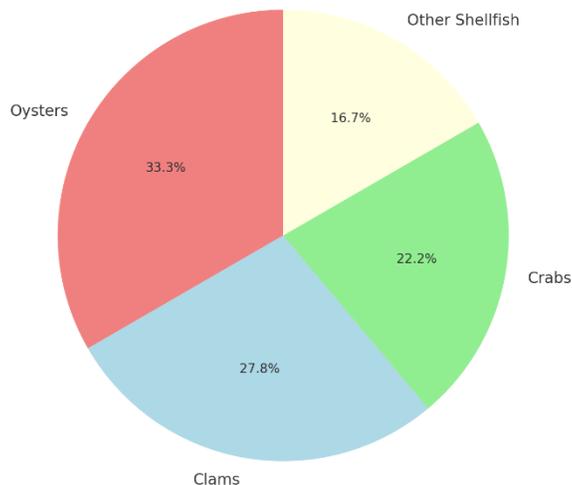
A line graph showing the gradual decrease in ocean pH from pre-industrial levels to the present day, highlighting the correlation between increased atmospheric CO₂ and ocean acidification. This graph will demonstrate the ongoing trend of ocean acidification.



Graph 2: Impact of Ocean Acidification on Coral Calcification Rates

A bar graph comparing coral calcification rates under normal ocean conditions and under acidic conditions. This graph will show how ocean acidification significantly reduces the ability of corals to build their calcium carbonate skeletons.

Chart 1: Effects of Ocean Acidification on Marine Shellfish



Graph 3: Ocean Acidification and Marine Food Web Disruption

A flowchart demonstrating how ocean acidification impacts the marine food web, from plankton (phytoplankton and zooplankton) to top predators (fish, marine mammals). This will highlight the cascading effects of acidification on the entire food chain.

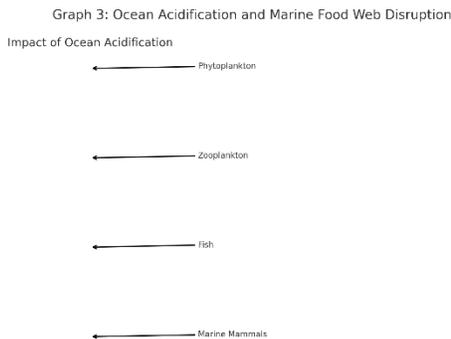


Chart 1: Effects of Ocean Acidification on Marine Shellfish

A pie chart illustrating the percentage of marine shellfish species (e.g., oysters, clams, crabs) affected by ocean acidification. It will show the varying degrees of impact, including reduced shell formation and increased mortality rates.

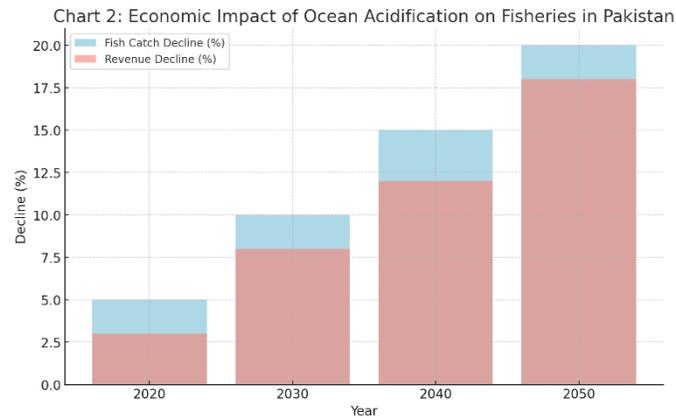


Chart 2: Economic Impact of Ocean Acidification on Fisheries in Pakistan

A bar graph depicting the projected decline in fish catch and revenue from the fisheries sector in Pakistan due to the effects of ocean acidification on marine biodiversity and fish populations. This will emphasize the socio-economic risks to coastal communities.

Summary:

Ocean acidification is a growing threat to marine ecosystems, with significant consequences for biodiversity and global ecosystem health. As atmospheric CO₂ levels rise, the oceans absorb more carbon, leading to lower pH levels and the depletion of carbonate ions, which are essential for marine organisms like corals and shellfish to build their calcium carbonate structures. The impacts of ocean acidification are widespread, affecting not only individual species but also entire marine ecosystems and food webs. Coral reefs, shellfish populations, and other marine organisms that depend on calcium carbonate face particular challenges in acidic waters, leading to declines in biodiversity and ecosystem services.

For countries like Pakistan, where marine ecosystems provide critical services such as coastal protection, fisheries, and carbon sequestration, the effects of ocean acidification present a direct threat to both ecological and economic stability. Understanding the mechanisms and consequences of ocean acidification is crucial for developing strategies to mitigate its impacts. Efforts to reduce CO₂ emissions, protect marine biodiversity, and conserve ecosystems through sustainable practices are essential for safeguarding the health of marine ecosystems and the global environment.

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