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Review Article

Rising tide of ocean acidification

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ABSTRACT

This comprehensive review explores the escalating environmental crisis of ocean acidification, primarily driven by anthropogenic carbon dioxide molecule (CO_2) emissions. In this study, we employed a systematic methodology to collect and analyze literature relevant to ocean acidification. Our research involved an exhaustive search of databases such as PubMed, Web of Science, Google Scholar, and Mendeley to gather pertinent studies published up until 2024. In addition, we consulted secondary sources, including expert panel reports, to enhance the depth of our analysis. Socio-economic ramifications are profound, particularly for fisheries, tourism, and coastal communities that rely heavily on marine resources. This research underscores the potential for substantial exacerbates in these sectors, emphasizing the need for targeted policies and management strategies to mitigate the adverse effects of ocean acidification. By addressing these critical areas, the study informs stakeholders and supports the development of adaptive measures that can sustain local economies and preserve biodiversity in affected regions. The economic consequences could be substantial, exacerbating global social and economic disparities. Speculative considerations highlight the potential for significant global impacts and the urgent need for proactive, coordinated action. This review emphasizes the importance of continued research and monitoring to develop effective mitigation and adaptation strategies, underscoring the critical role of global cooperation and innovation in environmental management. This review aims to serve as a call to action, highlighting the urgency to preserve marine ecosystems and their services to humanity in the face of this growing environmental challenge.

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INTRODUCTION

Ocean acidification, one of the world's most important environmental problems, refers to the ongoing decrease in the pH of the Earth's oceans, primarily caused by the uptake of carbon dioxide molecules (CO_2) from the atmosphere [1]. When carbon dioxide molecules (CO_2) dissolves in seawater, it reacts to form carbonic acid (H_2CO_3), which lowers the ocean's pH, altering its essential chemical balance (Fig. 1) [2]. The absorption of human-generated CO_2 by the oceans leads to an increase in hydrogen ion (H^+) and bicarbonate ion (HCO_3^-) concentrations while simultaneously reducing carbonate ion (CO_3^{2-}) levels. This decline in carbonate ions results in the shallowing of carbonate saturation horizons, which can adversely affect the formation and maintenance of shells and skeletons in various marine calcifies such as foraminifera, corals, echinoderms, mollusks, and bryozoans. These changes in ocean chemistry directly result from increased atmospheric carbon dioxide molecules (CO_2) and represent a significant shift in the marine environment with potential impacts on marine biodiversity and ecosystem health [2, 3].

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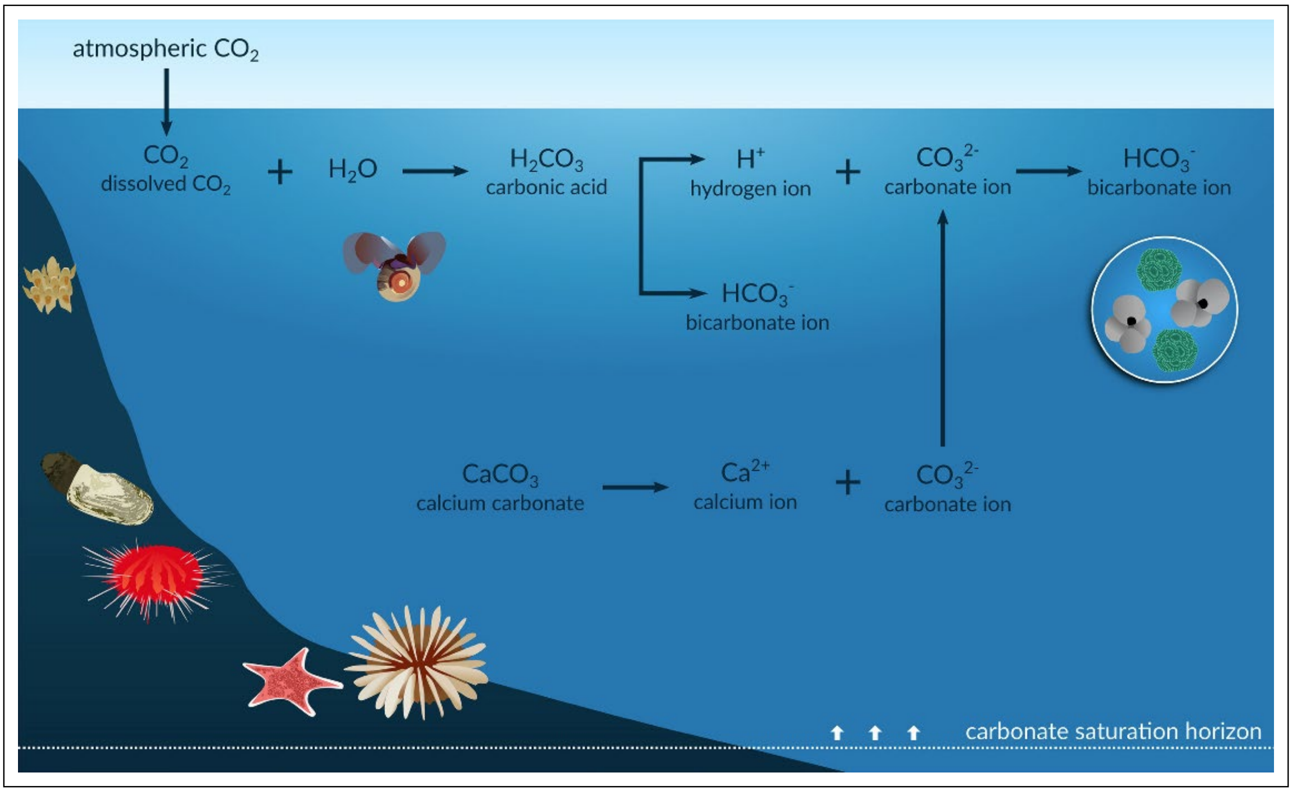

Figure 1. The process of ocean acidification [2].

In this study, we employed a systematic methodology to collect and analyze the literature relevant to the topic of ocean acidification. The research involved an exhaustive search of databases such as PubMed, Web of Science, Google Scholar, and Mendeley databases, which was conducted to gather pertinent studies published up to 2024. Additional secondary sources, including panel reports, were also consulted to enhance the depth of the analysis. The search utilized a combination of keywords related to "ocean acidification," "climate change," "algae," "ecology," and "Marine ecosystems." We established specific inclusion and exclusion criteria for literature selection: articles needed to be published in English between 1990 and 2024 and specifically address ocean acidification and environmental impact. The analysis aimed to identify patterns, trends, and gaps in the current research landscape. This helped me understand the effectiveness of different methodologies and the overall scope of research on the specified topic. Secondary sources, including panels on climate change, were primarily used to provide contextual background and support findings from the primary literature. This approach not only enriches the understanding of the subject matter but also underpins future research directions in this area.

This process has accelerated since the Industrial Revolution, with the Intergovernmental Panel on Climate Change (IPCC) reporting a 26% increase in ocean acidity since pre-industrial times [4]. The significance of ocean acidification cannot be overstated, given its profound impact on marine ecosystems. It mainly affects calcifying organisms such as corals, mollusks, and some plankton species, compromising their ability to build shells and skeletons, which are crucial for their survival and, by extension, the health of the entire marine food web [5]. The current rate of acidification presents an unprecedented challenge; studies suggest that the current rate is over ten times faster than any acidification in the last 55 million years; Figure 2 shows the pH level of the oceans between 1985–2020 [6]. This literature review aims to consolidate current knowledge on ocean acidification, identify research gaps, and inform effective policy and management strategies. By synthesizing a wide array of interdisciplinary studies, the review highlights areas needing further investigation and guides future research priorities. Additionally, it seeks to educate stakeholders and the public, enhancing awareness and fostering collaborative efforts toward mitigating the impacts of ocean acidification.

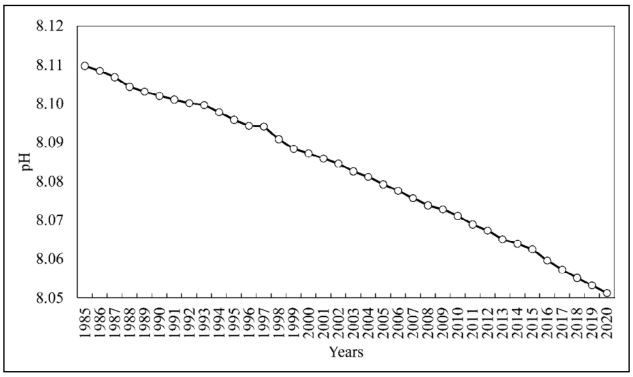

Figure 2. pH level of the oceans between 1985–2020.

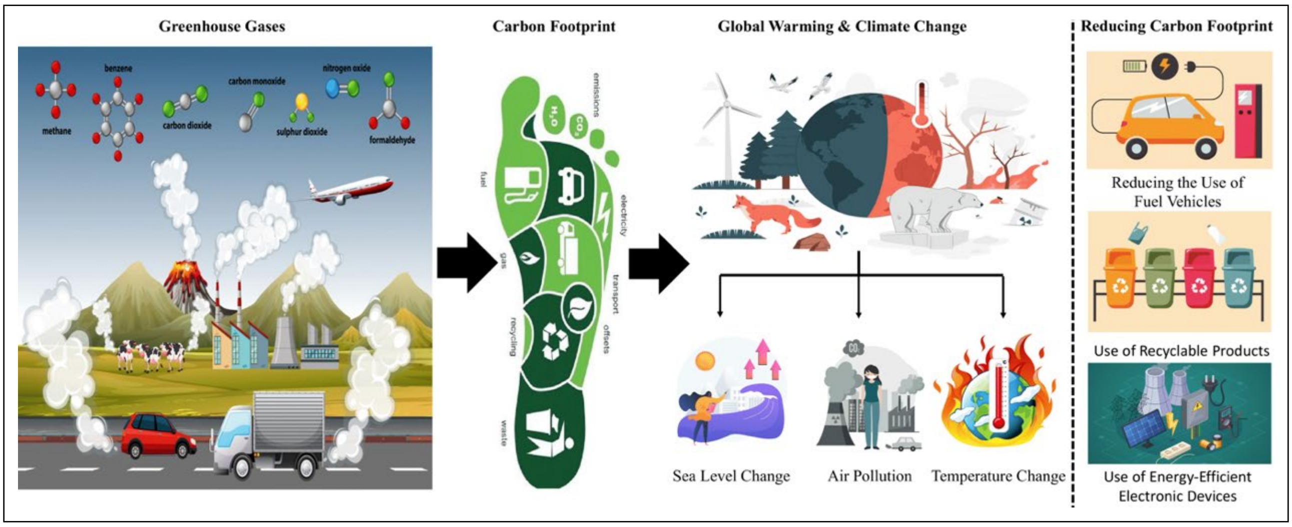

Figure 3. Carbon footprint context path [11].

FUNDAMENTAL CAUSES OF OCEAN ACIDIFICATION

Carbon Dioxide Emissions and Atmospheric Changes

The primary driver of ocean acidification is the increased concentration of CO_2 in the Earth's atmosphere [7]. According to the National Oceanic and Atmospheric Administration, atmospheric CO_2 levels have risen from approximately 280 parts per million (ppm) in the pre-industrial era to over 410 ppm today, primarily due to human activities such as fossil fuel combustion and deforestation [8–10]. The increase in CO_2 emissions, along with the rising carbon footprint values (Fig. 3) [11], leads to various issues, including climate change-induced human migrations [12–14]. Oceans absorb CO_2 produced by these activities, leading to significant changes in their chemical composition [15]. The dissolved CO_2 reacts with seawater to form carbonic acid, which dissociates into bicarbonate and hydrogen ions, causing a decrease in pH [16, 17].

Industrial and Agricultural Impacts

Beyond fossil fuel combustion, other industrial and agricultural practices and urbanization stress contribute significantly to ocean acidification [18–20]. Industries such as cement manufacturing release substantial CO_2, further exacerbating this issue [21]. Additionally, nutrient run-off from agricultural fields, particularly those rich in nitrogen and phosphorus, leads to eutrophication [22]. This process reduces oxygen levels in water bodies and contributes to acidification by producing nitrous oxide, another potent greenhouse gas [23]. Practices like deforestation and land use changes also play a role, as they decrease the Earth's capacity to absorb CO_2, leading to higher concentrations of this gas in the atmosphere [24]. Transitioning to functional foods with lower environmental impacts can reduce carbon emissions and serve as a measure against ocean acidification [25]. The intersection of these factors - increased CO_2 emissions, industrial practices, and agricultural activities - culminates in the progressive acidification of our oceans [26].

BIOLOGICAL AND ECOLOGICAL EFFECTS

Impact on Marine Life

Ocean acidification, primarily driven by increased atmospheric CO_2, critically impacts marine organisms, especially those that form calcium carbonate structures [27]. Research shows a direct correlation between acidification and the reduced ability of species like mollusks and certain plankton to maintain their calcium carbonate shells [5]. This weakening leads to higher mortality rates and reproductive challenges [28]. Additionally, studies have demonstrated that acidification can disrupt neural processing in fish, altering their behavior and diminishing their ability to detect predators [29]. Some of them are indicated in Table 1, affecting crucial ecological relationships.

Effects on Reef Ecosystems

Coral reefs, the biodiversity hotspots of the oceans, are particularly susceptible to acidification [32]. The process inhibits the availability of carbonate ions, essential for coral calcification [33]. According to a study by [33], a decrease in ocean pH by 0.1 units, which has occurred since the Industrial Revolution, can lead to a 20-30% reduction in coral calcification rates. This weakening of coral structures and other stressors like thermal stress significantly decline reef health and the biodiversity they support [34].

Long-Term Effects on Biodiversity and Ecosystem Health

The long-term implications of ocean acidification on marine biodiversity and ecosystem health are profound [35]. As individual species face survival challenges, the ripple effects can shift community composition and ecosystem function [36]. It was highlighted that acidification not only affected overfishing and habitat destruction but also posed a significant threat to the stability and productivity of marine ecosystems [37]. The loss of biodiversity and ecosystem services, such as fisheries and carbon sequestration, may have far-reaching consequences for global environmental stability and human well-being.

Table 1. Concise summary of critical studies on the impact of ocean acidification on marine species

Species affected	Type of impact	Key findings	References
Corals, oysters	Reduced calcification, shell thinning	Increased ocean acidity leads to the bonding of hydrogen ions with carbonate ions, making it difficult for these organisms to build and maintain calcium carbonate shells.	[1]
General marine species	Altered production of calcium carbonate	Around 30% of all CO_2 emissions are absorbed by the ocean, altering calcium carbonate production and affecting various marine species.	[27, 30]
Marine biodiversity (general)	Various impacts, including reduced calcification and skeletal structure	A comprehensive review of over 300 scientific literature showing alarming potential ecological scenarios and effects on marine biodiversity.	[31]
Marine calcifiers in the Southern Ocean	Variable impacts due to regional differences	Highlights how regional variations in ocean acidification affect different species, explicitly referring to the Southern Ocean and its marine calcifiers.	[2]

SOCIOECONOMIC IMPACTS

Effects on Fisheries and Marine Resources

Ocean acidification poses significant risks to global fisheries, a primary source of protein for billions worldwide [38]. A study by [39] indicates that mollusks, a key component of global fishing, are particularly vulnerable to acidification. The decline in mollusk populations due to their reduced calcification ability can lead to substantial economic losses [39]. For instance, the shellfish industry in the United States alone, valued at one billion dollars annually, faces significant risks [40]. Additionally, changes in plankton communities, the base of the marine food web, could alter fish populations, impacting fisheries and the dependent economies [41].

Impact on Coastal Communities and the Global Economy

Coastal communities are especially vulnerable to the effects of ocean acidification [42]. These communities rely heavily on marine resources for economic and food security [43]. A decline in marine biodiversity and fisheries can lead to loss of income, increased food insecurity, and reduced economic growth in these areas [44]. Furthermore, as coral reefs degrade, their protection against storm surges and erosion diminishes, threatening coastal infrastructure and homes [45]. Regarding tourism, fisheries, and coastal defense, the economic value of coral reefs is estimated to be tens of billions of dollars annually [46]. Globally, the financial loss due to reduced biodiversity and ecosystem services because of ocean acidification could be substantial, affecting industries from tourism to seafood and impacting global economic systems.

CURRENT RESEARCH AND FINDINGS

Scientific Studies and Experimental Results

Recent advancements in oceanography and climate science have shed new light on the multifaceted impacts of ocean acidification. Experimental studies are central to this research, providing critical insights into marine organisms' physiological and ecological responses to acidification. For example, [47] investigated volcanic CO_2 vents as natural laboratories to understand long-term ecosystem responses to acidification. They observed substantial shifts in marine communities where the water was more acidic, indicating potential future changes under continuing acidification.

In addition to organism-level studies, researchers are increasingly focusing on the ecosystem-level effects of acidification. The European Project on Ocean Acidification has conducted extensive research, revealing how acidification can alter nutrient cycles, food webs, and overall marine productivity [1]. These findings are crucial for predicting the broader ecological consequences of ongoing ocean pH changes [1].

Global and Regional Case Studies

Case studies from various parts of the world highlight the regional differences in the impacts of ocean acidification. Researchers have observed substantial acidification impacts on pteropods–tiny, shelled organisms vital to the marine food web in regions like the California Current System [48, 49]. A study [50] showed that these organisms are experiencing severe shell dissolution, which could have far-reaching effects on the marine ecosystem and fisheries.

Ocean acidification poses a unique threat in the Mediterranean Sea, a hotspot of biodiversity and endemism [51]. These changes have significant implications for the overall health of the Mediterranean marine ecosystem and the economies that depend on it [52]. Furthermore, acidification is affecting the Antarctic food web in the Southern Ocean [53]. Studies like those by [54] demonstrate that acidification can disrupt the availability of carbonate ions necessary for the growth of phytoplankton, the base of the Antarctic food chain. This disruption has potential cascading effects on the ecosystem, from krill to higher trophic levels like fish, seabirds, and marine mammals [54, 55].

MITIGATION AND MANAGEMENT STRATEGIES

Reduction and Adaptation Strategies

As the IPCC emphasizes, effective ocean acidification mitigation primarily hinges on reducing atmospheric CO_2 levels [56]. Strategies for CO_2 reduction include transitioning

Table 2. Ocean acidification mitigation strategies

Strategy	Description	Effectiveness	Challenges	References
Coastal blue carbon	Conservation and restoration of coastal wetlands like mangroves and seagrasses to sequester and store carbon.	Effective locally for buffering ocean acidification effects.	Limited global impact and reliance on habitat availability.	[76, 77]
Alkalinity enhancement	Increases the ocean's CO_2 storage capacity by changing seawater chemistry to absorb more CO_2 from the atmosphere.	Potentially valuable for mitigating acidification, albeit slowly.	There are many unknowns around the technique and its long-term impacts.	[76, 78]
Kelp farming & afforestation	It uses fast-growing kelp or other algae to capture CO_2, potentially mitigating acidification.	It may have local or seasonal mitigating effects.	Risk of displacing existing phytoplankton productivity, other negative impacts.	[76, 79]
Forecasting and management	Utilizes models and predictions to inform management strategies to protect marine resources and communities.	It helps in preparing communities and industries for future changes.	Dependent on the accuracy and reliability of models and predictions.	[76]
Technology development	Developing tools to monitor and mitigate changing ocean chemistry.	Supports localized mitigation efforts.	Requires technological advancement and widespread deployment.	[76]

to renewable energy sources, enhancing energy efficiency, and implementing carbon capture and storage technologies [11]. For example, wind and solar energy development has demonstrated significant potential in reducing fossil fuel reliance, as evidenced by the global growth of renewable energy sectors [57].

Adaptation strategies are also critical, especially for vulnerable marine ecosystems and communities dependent on them [45]. Aquaculture practices, for instance, can be adapted to be more resilient to changing ocean conditions [58]. Various biological and limnological monitoring applications can be applied to conservation strategies [59, 60]. Human impact also changes lake ecosystems [61, 62]. Research on the Pacific oyster industry in the United States [63] has highlighted the success of monitoring and buffering seawater pH as an adaptation measure. Just as some algae species have biotechnological properties for the treatment of harmful dyes, terraforming mars, functional foods, green building, biofuel, [64–69], and certain types of algae can also help in reducing ocean acidification [70].

Policy Recommendations and International Collaborations

Policy frameworks play a crucial role in addressing ocean acidification [71]. National policies, such as implementing rigorous emission reduction targets and promoting sustainable marine practices, are essential [72]. Internationally, the Paris Agreement under the United Nations Framework Convention on Climate Change sets a global framework for reducing emissions, but further action is needed to target ocean acidification specifically [73]. Some Ocean Acidification Mitigation Strategies are given in Table 2. International collaborations are vital for research, monitoring, and sharing best practices. Initiatives like the Global Ocean Acidification Observing Network provide platforms for international scientific cooperation, enhancing our understanding and capacity to respond to acidification [74]. Furthermore, integrating ocean acidification into global conservation and management strategies, such as those under the Convention on Biological Diversity, is imperative for a coordinated global response [75].

CONCLUSION

This comprehensive review of ocean acidification has revealed a critical environmental challenge characterized by the rapid increase in ocean acidification driven by CO_2 emissions from human activities. This phenomenon significantly impacts marine life, ecosystems, and socio-economic structures, with variations in effects observed regionally, suggesting that certain areas like the Arctic are experiencing changes faster than others. The impact on marine biodiversity and ecosystems extends beyond immediate effects on calcifying organisms such as mollusks and corals. The potential for cascading effects through the marine food web raises concerns about the collapse of specific ecosystems, leading to significant biodiversity loss. These ecological changes pose profound economic impacts, particularly on industries like fisheries and tourism and on coastal communities dependent on marine resources. The economic consequences could be severe, with global costs potentially reaching billions and exacerbating existing social and economic disparities. Emerging research and forecasting tools enhance our understanding of ocean acidification and aid in planning and response strategies. Innovative research is required to understand and forecast the long-term effects of acidification, with the development of new models and monitoring tools playing a crucial role.

Speculatively, biotechnological advancements may offer solutions to enhance the resilience of vulnerable species and ecosystems. To address these challenges, a multi-faceted approach is necessary. Reducing CO_2 emissions through renewable energy and carbon capture technologies is crucial. Equally important are adaptation strategies for marine ecosystems and human communities, strengthened policy frameworks, and international collaboration. Future international agreements might include specific targets and techniques for combating ocean acidification. The speculative possibility of innovative solutions highlights the potential for significant global impacts, emphasizing the critical need for proactive and coordinated action. In conclusion, the insights gathered from this study underscore the urgency of international cooperation and innovation in environmental management. Immediate and concerted efforts are needed to mitigate the impacts of ocean acidification and preserve marine ecosystems and their services to humanity. Though uncertain, speculative future scenarios reinforce the potential for innovative solutions and significant global impacts, emphasizing the critical need for proactive and coordinated action.

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DATA AVAILABILITY STATEMENT

The author confirm that the data that supports the findings of this study are available within the article. Raw data that support the finding of this study are available from the corresponding author, upon reasonable request.

CONFLICT OF INTEREST

The author declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

USE OF AI FOR WRITING ASSISTANCE

Not declared.

ETHICS

No need to ethical approval for this study.

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