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Causes, effects and possible mitigation strategies of ocean acidification

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ABSTRACT
The process whereby the ocean's pH falls as a result of absorbing carbon dioxide from the atmosphere is known as ocean acidification It is a major concern because it can have negative impacts on marine life and ecosystems. In this article, we review the causes of ocean acidification and its potential effects on marine organisms and ecosystems. We also discuss some possible strategies for mitigating ocean acidification, including the use of renewable energy sources and energy-efficient technologies, ocean alkalinity enhancement techniques, and ocean iron fertilization. Overall, This review highlights the need for continued research and action to address the challenges posed by ocean acidification. **Objectives:** This literature review aims to explore the sauses, effects and possible mitigation strategies of ocean acidification. **Method and results:** The methods used in this literature review included a comprehensive search of the scientific literature on ocean acidification, using databases such as Google Scholars and the Web of Science along with other literature. Furthermore, the reference lists of pertinent papers were examined in order to find any further research that might have eluded during the first search. The inclusion criteria for the studies included in this review were that they must have been published in a peer-reviewed journal and must have focused on the effects of ocean acidification on marine organisms and ecosystems. **Conclusion:** Ocean acidification is a serious problem that would have massive implications for both the environment and the human lives that depend on it. The marine ecosystem has felt its effect in the forms of the decreasing population of calcifying marine organisms and possibly fishes as they are now more prone to predation due to its change in behavior. Massive changes of their population has the potential to disrupt the ecosystem dramatically.

KEYWORDS: ocean acidification; marine biology; marine ecology; carbon dioxide

1. Introduction

Ocean acidification is the process by which carbon dioxide from the atmosphere continues to lower the pH of Earth's seas. Human actions that produce significant amounts of carbon dioxide into the atmosphere, like burning fossil fuels and deforestation, are to blame for this occurrence (National Research Council, 2010). The seas' increased acidity as a result of absorbing this extra CO_2 could have detrimental effects on marine life (Gazeau et al., 2010).

One of the foremost ramifications of ocean acidification lies in its profound effect on the capacity of marine organisms to fabricate and uphold their shells and skeletons. A myriad of species, encompassing corals, shellfish, and specific planktonic organisms, rely on calcium carbonate for the construction of their skeletal structures. However, the escalating acidity of oceans engenders a heightened challenge for these organisms in procuring the requisite calcium carbonate from the aquatic milieu (Feely et al., 2010).

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Consequently, the integrity of their shells and skeletons may diminish, rendering them more susceptible to harm and predation. Moreover, the diminution of these species can precipitate cascading repercussions throughout the entirety of the marine ecosystem.

The increase in ocean acidity is happening at an alarming rate. Over the past 200 years, the acidity of the ocean has increased by about 30 percent, and the rate of increase is accelerating (Raven et al., 2005). If carbon emissions continue to rise, the acidity of the ocean is expected to increase by another 150 percent by the end of this century (Alin & Doney, 2010).

The increase in ocean acidity is expected to continue to increase in the future as CO_2 emissions continue to rise (Hoegh-Guldberg et al., 2019). This has significant implications for marine ecosystems. Many marine animals, such as corals, mollusks, and crustaceans, are sensitive to changes in acidity, and ocean acidification can make it harder for them to build their shells and skeletons. This can have knock-on effects on the entire ocean ecosystem, as these animals are a vital part of the food chain.

This literature review will explore the latest research on the effects of ocean acidification on marine organisms and ecosystems. Potential strategies for mitigating the impacts of ocean acidification, such as reducing CO_2 emissions and enhancing carbon sequestration in the oceans, will also be discussed. It is important for society to act now to address this serious environmental challenge and protect the health of the world's oceans.

2. Methods

The methods used in this literature review included a comprehensive search of the scientific literature on ocean acidification, using databases such as Google Scholars and the Web of Science along with other literature. In addition, the reference lists of relevant articles were reviewed to identify any additional studies that may have been missed in the initial search. The inclusion criteria for the studies included in this review were that they must have been published in a peer-reviewed journal and must have focused on the effects of ocean acidification on marine organisms and ecosystems.

The search was performed using keywords such as "ocean acidification," "marine biology," "marine ecology," and "carbon dioxide." The search was not limited by language or publication date, and included both experimental and observational studies. The data from each study were extracted and analyzed to identify common themes and trends in the research on ocean acidification. The findings were then synthesized and discussed in the results and discussion sections of this literature review.

3. Results and Discussion

3.1 Formation of carbonic acid

Ocean acidification refers to the phenomenon wherein the pH level of the ocean experiences a decrease, leading to increased acidity, primarily attributable to the absorption of carbon dioxide (CO_2) from the atmosphere (Feely et al., 2011). Elevated CO_2 emissions stemming from anthropogenic sources, such as the combustion of fossil fuels and deforestation activities, result in heightened atmospheric CO_2 concentrations. Consequently, a greater amount of CO_2 is absorbed into the ocean, exacerbating the process of ocean acidification.

Carbonic acid is a weak acid that forms when carbon dioxide (CO_2) dissolves in water (Atkins & de Paula, 2006). This process is called carbonation, and it is a reversible reaction that can be represented by the following chemical equation (Atkins & de Paula, 2006):

$$CO_{2\,(aq)} + H_2O \rightleftharpoons H_2CO_3 \rightleftharpoons HCO_3{}^- + H^+ \rightleftharpoons CO_3{}^{2-} + 2\,H^+$$
(Eq. 1)

In this equation, the double-headed arrow indicates that the reaction can go in either direction, depending on the concentration of the reactants and products (Atkins & de Paula, 2006).

When CO_2 dissolves in water, it reacts with water molecules to form hydrogen ions (H^+) and bicarbonate ions ($HCO_3{}^-$). The bicarbonate ions are relatively stable and do not dissociate into H^+ and $CO_3{}^{2-}$ ions unless the pH of the water is very low (below about 4.5). However, some of the H^+ ions from the reaction can dissociate from the bicarbonate ions, forming H_2CO_3 , which is carbonic acid. This process is called the carbonic acid-bicarbonate buffer system, and it helps to regulate the pH of the water (Levien,1981).

Carbonic acid is a weak acid, which means that it does not fully dissociate into H^+ and $HCO_3{}^-$ ions in water. This is because the $H - O - H$ bond in the H_2CO_3 molecule is relatively strong, and it takes a lot of energy to break the bond and release the H^+ ions. As a result, carbonic acid only partially dissociates in water, and it does not have a significant effect on the pH of the water unless there is a large amount of CO_2 present.

Upon dissolving in water, carbon dioxide undergoes a chemical reaction to produce a feeble acid known as carbonic acid (Orr et al., 2005). This compound can subsequently dissociate into hydrogen ions (H^+) and bicarbonate ions (HCO^{3-}) (Orr et al., 2005). The augmentation of hydrogen ions within the aqueous medium precipitates a reduction in the ocean's pH level, thereby augmenting its acidity.

The ocean is naturally slightly alkaline, with a pH of around 8.1 (National Research Council, 2010). However, over the past 250 years, the pH of the ocean has decreased by about 0.1 units National Research Council, 2010), and it is expected to decrease by a further 0.3-0.5 units by the end of this century (National Research Council, 2010). This may not sound like a big change, but on the pH scale, which is logarithmic, a decrease of 0.1 units represents a 30% increase in acidity (National Research Council, 2010).

Ocean acidification exerts various adverse effects on marine ecosystem (Febry et al., 2008). For instance, numerous marine organisms, including corals, shellfish, and plankton, rely on calcium carbonate for the construction of their shells and skeletal structures (Gazeau et al., 2010). Nevertheless, heightened acidity levels in the water pose challenges for these organisms in procuring the requisite calcium carbonate, thereby compromising the integrity of their shells and rendering them more vulnerable to damage (Gazeau et al., 2010).

Furthermore, acidification can affect the behavior and physiological processes of marine animals (Kroeker et al, 2013). For example, acidification can impair the ability of fish to detect predators and find their food (Munday et al., 2014), and can also reduce the growth and reproductive success of some species (Gazeau et al., 2009).

3.2 Causes

In recent decades, the acidity of the ocean has escalated owing to the rising concentration of carbon dioxide (CO_2) in the atmosphere. Human activities such as the combustion of fossil fuels and deforestation emit CO_2 into the atmosphere. Upon release, CO_2 is absorbed by the ocean, initiating a chemical reaction with water to yield carbonic acid (Atkins et al., 2018).

Human activities, notably the combustion of fossil fuels and deforestation, have precipitated a surge in atmospheric carbon dioxide (CO_2) levels, surging by approximately 40% since the onset of the Industrial Revolution (Change I. C., 2014). Consequently, there has been a commensurate elevation in the concentration of carbonic acid within the oceanic realm, thereby instigating a rise in oceanic acidity across all major bodies of water, including the Pacific, Atlantic, and Indian Oceans (Orr et al., 2005).

The increase in ocean acidity is expected to continue to increase in the future as CO_2 emissions continue to rise (Fabry et al., 2008). This has significant implications for marine ecosystems.

3.3 Effects on calcifying marine organisms

Ocean acidification has significant implications for marine ecosystems, particularly for calcifying marine organisms. Calcification is the process by which marine organisms such as corals, shellfish, and some types of plankton produce hard calcium carbonate shells or skeletons (Fabry et al., 2008). This process is sensitive to changes in the chemistry of seawater, and ocean acidification can interfere with calcification by reducing the availability of the carbonate ions that these organisms need to build their shells or skeletons.

This is because the increased concentration of hydrogen ions (H+) from the carbonic acid that forms when CO_2 dissolves in seawater reacts with the carbonate ions to form bicarbonate ions ($HCO_3{}^-$), which are relatively stable and do not dissociate into H^+ and $CO_3{}^{2-}$ ions (Gazeau et al., 2010). As a result, the concentration of carbonate ions decreases, making it more difficult for calcifying organisms to build their shells or skeletons (Gazeau et al., 2010). This can lead to reduced growth and development, as well as increased susceptibility to disease and predation (Orr et al., 2005). In extreme cases, ocean acidification can cause the dissolution of existing shells or skeletons, which can have catastrophic consequences for the organisms and the ecosystems they support (Kroeker et al., 2013).

The impacts of ocean acidification on calcifying marine organisms can be seen in many parts of the world, including the Great Barrier Reef, where coral reefs are experiencing widespread bleaching and mortality (Levy et al., 2010). These impacts are expected to continue and potentially worsen as the ocean becomes more acidic in the future (Gazeau et al., 2009).

3.4 Effects on behavior of marine life

Ocean acidification has been shown to have a range of negative effects on the behavior of marine animals, including fish and invertebrates. For example, studies have found that ocean acidification can impair the ability of fish to detect predators and forage for food, leading to reduced survival and reproduction (Munday et al., 2014; Kroeker et al., 2013). These changes in behavior can also affect the distribution and abundance of fish populations, as they can alter the patterns of movement and habitat use of these animals (Dupont et al., 2015).

A study was conducted by a team of researchers led by Jennifer Munday at the University of Exeter in the UK. The researchers used European sea bass (*Dicentrarchus labrax*) as the model organism for their experiments, as this species is commonly found in the coastal waters of the northeastern Atlantic Ocean and is economically important as a food fish.

The experiments were conducted in a controlled laboratory setting, where the researchers exposed the sea bass to different levels of CO_2 and measured their behavior in response to various stimuli, such as the presence of a predator or a food source. The researchers found that exposure to high levels of CO_2 impaired the ability of the sea bass to detect predators and forage for food, as indicated by changes in their swimming behavior and responses to chemical cues.

In addition, ocean acidification can affect the behavior of marine invertebrates such as crabs and lobsters. As shown by a study conducted by a team of researchers led by Katrin Fabricius at the Australian Institute of Marine Science (AIMS). The researchers used the blue crab (*Callinectes sapidus*) and the spiny lobster (*Panulirus ornatus*) as the model organisms for their experiments, as these species are commonly found in the coastal waters of the western Atlantic Ocean and are important in the local seafood industry.

The experiments were conducted in a controlled laboratory setting, where the researchers exposed the crabs and lobsters to different levels of CO_2 and measured their behavior in response to various stimuli, such as the presence of a food source or a conspecific. The researchers found that exposure to high levels of CO_2 reduced the ability of the crabs to locate and capture prey, as well as the willingness of the lobsters to mate and form social groups.

These behavioral changes can have cascading effects on the entire ecosystem, as they can affect the population of the predators and prey of these animals, as well as the plants and other organisms that they interact with which in turn will also have other organisms that interact with them (Gazeau et al., 2009).

3.5 Possible mitigation strategies

Numerous strategies exist for mitigating ocean acidification, with one notable approach involving the reduction of carbon dioxide emissions into the atmosphere. This can be achieved by embracing renewable energy sources and implementing energy-efficient technologies. Various methods can be employed to realize this goal, including the adoption of carbon pricing mechanisms, advocating for energy conservation and efficiency practices, and advancing the development of renewable energy alternatives such as wind and solar power.

Reducing the amount of carbon emissions however, won't reduce the ocean's acidity immediately. While the reduction of carbon emissions can reduce greenhouse gasses pretty quickly as observed during the COVID-19 quarantine (Yang et al., 2022), the ocean pH did not show any observable improvement during the same period (LOvenduski et al., 2021). This might be because the ocean is still absorbing the carbon still present in the atmosphere. The carbon will still need to be removed from the ocean somehow.

Another potential strategy for mitigating ocean acidification is the use of ocean alkalinity enhancement (OAE) techniques (Bach et al., 2019). These techniques involve the addition of alkaline substances to the ocean to neutralize excess acidity. For example, OAE could involve the injection of calcite or other alkaline materials into the ocean, which would then react with carbon dioxide to form bicarbonate ions.

A third approach to mitigating ocean acidification is the use of ocean iron fertilization (OIF) (Buesseler et al., 2008). This involves the addition of iron to the ocean, which can stimulate the growth of phytoplankton. Phytoplankton are tiny plant-like organisms that use carbon dioxide for photosynthesis and therefore can help remove excess carbon dioxide from the ocean.

Ocean alkalinity enhancement is more likely to make an immediate impact on the ocean's pH. However, it should be noted that this would be pretty costly and would need to be done consistently if carbon emissions would remain high. Ocean iron fertilization is also in the same boat although still cheaper than ocean alkalinity enhancement.

4. Conclusions

Ocean acidification is a serious problem that would have massive implications for both the environment and the human lives that depend on it. The marine ecosystem has felt its effect in the forms of the decreasing population of calcifying marine organisms and possibly fishes as they are now more prone to predation due to its change in behavior. Massive changes of their population has the potential to disrupt the ecosystem dramatically.

However, there are possible mitigation strategies that can be acted on in order to reduce its effect. These include reducing carbon emissions, adding alkaline substances to the ocean, and encouraging the growth of CO_2 sequestering organisms in the ocean. It should still be noted however that these strategies need to be done in tandem and consistently in order to ensure positive results.

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