Nep J Environ Sci (2025), 13(2), 103-122
https://doi.org/10.3126/njes.v13i2.69175
ISSN 2350-8647 (Print) 2542-2901 (Online)

Review Article

Consequences of rising atmospheric CO_2 on ocean acidification and dissolved carbon cycling: A systematic review

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(Received: 27 August 2024; Revised: 29 December 2025; Accepted: 30 December 2025)

Abstract

Increasing atmospheric CO_2 and temperature diminish ocean pH and raise the amounts of dissolved inorganic and organic carbons, causing wide-ranging shifts in marine water carbon chemistry and predicting the impacts on long-term ecosystems. This review aimed to determine the ocean chemistry and spatial variation of CO_2 at a global scale, as well as to predict the influences of anthropogenic and natural changes on marine ecosystems. The literature has demonstrated that the southern polar oceans, Antarctica, and any coastal zone are predominantly susceptible to marine acidification and the dissolved carbon cycle. Based on 355 studies conducted over the last 30 years, this investigation found that marine acidification and the dissolved cycle are complex and poorly understood phenomena. These two facts and climate change are very interrelated, and the potential of these threats is very spatial, seasonal, stratified, and complex also. It was found that the atmospheric CO_2 has increased by about 50% since preindustrial times and excess CO_2 raise the seawater acidity through some equilibrium reactions in aqueous medium. The study observed that over the past half-century, the marine surface water acidity has risen by 30%, and predicted that by 2100, it will increase to 150. Moreover, this study critically reviewed the actual rules of marine dissolved organic and inorganic carbon on the global carbon cycle and marine acidification and vice versa. Such a major change in ocean chemistry will already have wide consequences for marine life and ocean ecosystems.

Keywords: DIC, DOC, ocean carbon cycle, pH, stratification

Introduction

Continuous use of fossil fuels has cumulatively increased the CO_2 level in the atmosphere, and the global climate has incessantly changed for centuries (Zhang et al., 2020). Accordingly, large amounts of CO_2 gas have been mixed with ocean water since the Industrial Revolution (after 1750). When the ocean's water absorbs CO_2, it reacts with water to create a weak acid, carbonic acid (H_2CO_3). This acid raises the water acidity and lowers its pH value. In early 1750, approximately 35% to 50% of this gas released in the atmosphere by manmade actions was absorbed by seawater (Jiang et al., 2019). During this period, observers assessed that the average value of pH in ocean water ranged between 8.19 to 8.05, which is similar to a 30% increase in water acidity (Jewett et al., 2020). Numerous researchers have suggested that since the early 18th century, the rate of marine acidification has been almost 100 times quicker than at any other time through the current 6.5 million yrs (Jagers et al., 2019; Friedlingstein et al., 2020; Ma et al., 2023). Also, they exhibited that the level of air CO_2 from 1000 to 1900 ranged between 275 and 290 ppm (NOAA, 2022). It was found that the typical concentration of this gas was 390 ppm in 2010, and scientists expected the level to rise to 413 and 750 ppm by the next century, depending on the amount of greenhouse gases released (Friedlingstein et al., 2020). If additional CO_2 is absorbed by the ocean, the water pH would decrease further, and the pH would decline from 7.8 to 7.9 by 2100 (Saha et al., 2021). Usually, 30% of air CO_2 is absorbed by the ocean's water, streams, rivers, and lakes (IPCC, 2011; Wang et al., 2025). Doney et al. (2020) stated that as the seawater absorbs excess CO_2, marine chemistry changes, which highly impact the living situations of marine organisms and numerous organisms are invaded, predominantly species that rely on $CaCO_3$ skeletons and shells. So, the global blue economy and the marine biota's food chain have both been significantly influenced by the altered marine chemistry.

The sea surface water pH has now reduced by 0.1 units, rather than the 30% increase in acidity. If current CO_2 emissions continue until the end of this era, CO_2 emissions could be reduced by 0.3 units, thus increasing ocean acidity by just about 2.5 times (Osborne et al., 2019). Because the pH scale is logarithmic, it can be ambiguous, and its units may appear in increments that represent large changes in acidity. For instance, a slight drop in pH of 0.4 more than doubles the acidity of seawater. Over the past 300 million yrs, marine pH has never dropped more than 0.6 below a value of 1750 (Lowe et al., 2019). Nevertheless, if fossil fuel consumption continues at the same rate over the next few centuries, marine pH could fall more than 0.7 units below the 1750 level (Bopp et al., 2013). Free H^+ (from H_2CO_3) lowers the pH of the seawater, causing acidification. A decrease in pH also reduces the level of CO_3^{2-}, the main constituent of calcium carbonate ($CaCO_3$) shells. A diminution in the level of CO_3^{2-} ions affects the carbonate equilibrium reaction and decreases the saturation process of carbonate mineral (Islam and Mostafa 2022). Ocean alkalinity is unchanged by

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acidification, but alkalinity may increase over time due to the dissolution of carbonate minerals and reduced formation of $CaCO_3$ shells (Boudreau et al., 2018).

The water pH and carbonate saturation of the sea surface vary with location and depth. Higher-latitude and colder oceans can absorb more CO_2 (Wallace et al., 2014). Other factors that influence the exchange of CO_2 among the atmosphere and ocean and therefore affect marine acidification include stratification of ocean water, major continental rivers, sea ice melting, atmospheric nitrogen and sulfur deposition, etc. (Jagers et al., 2019). Globally, surface pH varies, and cold, high-latitude oceans have higher CO_2 solubility and lesser bicarbonate (HCO_3^-) saturation, further reducing the dimensions of marine creatures to form hard frames (Wallace et al., 2014). Acidification in the ocean happened early in the history of Earth, and subsequent ecological disruption of the ocean has had continuing belongings on the worldwide climate and overall carbon cycle (Jagers et al., 2019). Lowe et al. (2019) showed that rising acidity is thought to have a variety of possibly detrimental implications for marine creatures, for instance, discouraging rates of metabolism and resistance responses in some biotas. This acidification affects ecosystems in oceanic environments that offer food, transport, recreation, livelihoods, and supplementary ecosystem services for most of humankind. About one billion people depend, in whole or in part, on coral reef ecosystem services for fishing, collecting marine plants, tourism, and coastal management. The excess existence of free protons (H^+) leads to the formation of extra H_2CO_3 in the ocean, eventually converting carbonate ions to bicarbonate ions. An actual diminution in the quantity of available CO_3^{2-} ions makes it more difficult for calcified marine creatures such as corals and planktons to produce biogenic $CaCO_3$, and such structures dissolve (Lowe et al., 2019). Hence, ongoing ocean acidification may jeopardize future food chains leading to the oceans (Friedlingstein et al., 2020).

Marine saturated CO_2 influences the dissolved organic and inorganic carbon (DOC and DIC) cycle in the sea and generates a complicated chemical environment in the oceanic system. This course occurred over a decade or more. The ocean's dissolved carbon pool is a significant factor in the operation of the marine ecosystem. DOC is at the crossing point amongst chemical and biotic functioning; it controls the oceanic food chain and is a key part of global carbon cycle (Grosse et al., 2020). Due to climate change, changes in carbon cycling can result in variations in the sea-atmospheric exchange of CO_2 gas and have the probable to generate substantial feedback on global change itself. Climate change affects the ocean's biogeochemical cycles in the next decades and centuries. Several existing climate models have projected global influences on marine biochemistry, but these influences are associated with huge doubts, dependent on the model setup, and are hampered by the deficiency of actual data (David et al., 2020; US-EPA, 2025). This manuscript focuses on the influences of rising CO_2 and marine acidity on dissolved overall carbon cycling in the upcoming ocean system on broad scales. In particular, this study designates the consequences of global climate change stressors on oceanic DOC and DIC, driving the impending ocean. These climate stressors comprise surface water warming, stratification, deoxygenation, ocean acidification, changed invasion from continental rivers, marine ice-derived material, seawater circulation and upwelling, and wet, dry deposition, etc. (Mayer et al., 2025). These global change strains are anticipated to have a large impact on biogeochemistry, ecosystem operation, and, therefore, marine carbon cycling. Instead, the lower pH or more acidic condition hampered several stages of the carbon cycle and can change the functioning of dissolved carbon in oceanic systems.

Acidification of the ocean is one of the numerous effects of global change on the oceanic systems. The major solution to marine acidity is to drop air CO_2 concentrations. The Inter Academy Partnership (IAP) stated that marine acidification has increased and mentions that by 2050, atmospheric CO_2 release will be abridged by at least 50% corresponding to 1990 (Lowe et al., 2019). The nation has a goal to minimize and address the effects of increased acidification in the oceans (Nina, 2014).

There is an increasing acknowledgment that forecasted marine acidification affects environmental ecosystems from which human civilizations obtain the socioeconomic resources that support our well-being. The key goals and objectives of this review work are to a) detect the actual sources of acidity in oceanic systems, b) correlate the acidification with the marine DOC and DIC cycle, and c) identify the probable influence of acidification on marine species, economy, and ecosystems. In this study, the findings from the critical review of the literature were included, given the probable economic impacts of marine acidification. It recognizes that although this is an area of research, comparatively scarce evaluations have been directed to date, with those that have been done vastly attentive on scopes only. Therefore, this study highlights the existing state of knowledge, major gaps in thought, and approaches that may be utilized in upcoming investigations.

Materials and Methods

Climate variation and deviations in surface water availability and quality were the main topics of numerous international conferences and seminars. Researchers are concerned about the worldwide issue and are actively working to lessen its effects, according to the reflections of published papers, conferences, and meetings on this topic. During the previous three decades, most of the work has been done. The study looked for papers spanning 35 years, from 1990 to 2025, using Web of Science, PubMed, Google Scholar, Scopus, and other sources. Using the Boolean Operators, the succeeding terms were searched ('and' and 'or'): (a) carbon budget and global warming, (b) climate change, (c) change of marine pH, (d) dissolved organic and carbon, (e) dissolved inorganic carbon, (f) marine acidification and oceanic calcifiers, (g) ecological change and marine acidification, (h) marine acidification and green economy, etc. Also, other terms that impact the marine water environment, for example, global warming, sea level rise, marine species, and marine carbon budget searched utilizing similar operators. To begin with, the review study acknowledged over 355 published literature, but lastly counted in 102, which are directly linked to and/or support this study's heading. Now, for every event of inclusion and exclusion measures, this review study pursued the PRISMA Statement (Mengista et al., 2020). Over half of the composed articles were published from 2008 to 2015. Fig. 1 displays a flow diagram of the criteria used to choose the articles for systematic review. The methodology used is accessible in a PRISMA flow scheme (Fig. 1). Intended for comprehensive information on the review guiding principle, source identification, scoping and screening, and literature analysis, refer to the original publication.

The review explored climate change, seawater pH variation, diversity of marine ecosystems, etc., from published works and is systematically described in some figures and tables. Mostly prediction-based investigations concerning the degradation of seawater chemistry with climate change are available now. Numerous data gaps and methodological information were also recognized from the reviewed literature, and guiding principles for future research are deliberated in the end sections of this article.

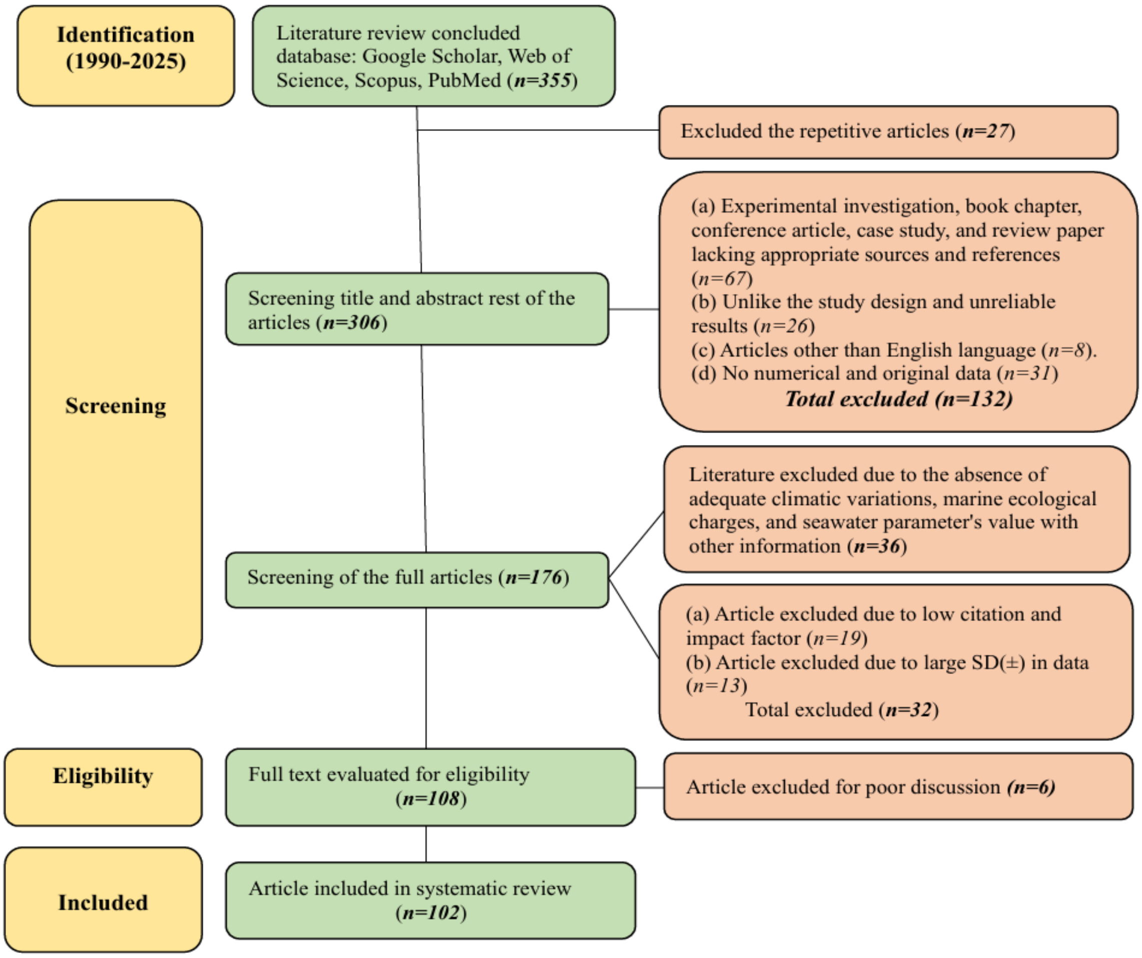

Figure 1. Conditions flow diagram for choosing articles of systematic review (according to the PRISMA method)

Research question

The key research question of this study is: 'How does ocean acidification, driven by increased atmospheric CO_2 absorption by seawater, alter the marine dissolved carbon cycle with marine pH and impact oceanic calcifying creatures, thereby affecting the biological carbon pump?'

The specific research questions are:

a) How does seawater acidification change the microbial loop and rate of DOC decomposition?

b) Are there synergetic or antagonistic effects when acidification interacts with other stressors like stratification, warming, nutrient chain, etc.?

c) What are the consequences for the overall carbon storage capacity in the ocean?

d) How does natural changeability in seawater pH affect the study of the impact of acidification on DOC?

e) Does the chemical composition of DOC change under high-CO_2 conditions?

Hypotheses

The primary hypothesis regarding marine acidification and the DOC cycle is that acidification will change the production, composition, and degradation potential of DOC, which in turn affects the efficacy of the microbial carbon pump and eventually the ocean's capacity to sequester carbon. The major points of the research hypothesis are:

a) Ocean acidification induces the uptake of DIC (carbonate-bicarbonate) by planktons, which leads to vast primary production and a subsequent increase in the release of DOC.

b) Increased pCO_2 will not only affect the DOC quantity but also the specific molecular composition of the released organic substance, making some compounds essentially available for microbial use.

c) The increase in degradable DOC will stimulate microbial growth and respiration. This boosted microbial activity could lead to a lower rate of carbon sequestration if more DOC is taken by CO_2 rather than stored as refractory carbon in the ocean.

d) The interconnection between acidification and the dissolved carbon cycle is highly complex and reliant on several factors.

Background – Carbon budget and global warming

Primarily, atmospheric CO_2 is the key culprit in acidifying seawater. The increase in global temperature is the secondary impacting factor for this natural phenomenon. This global warming potential in the climate systems is definite, with considerable rises in global average air temperature (~+1°C), ocean surface temperature (~+1°C), and sea-level rise (~+15 cm) since 1960 (Pachauri and Reisinger, 2007). As stated by the 4th Assessment Report (AR4) of UN Intergovernmental Panel on Climate Change's (IPCC), the best estimate for a "low scenario" is 1.8 °C, with a probable variation of 1.1 to 2.9 °C, and the best approximation for a "high scenario" is 4 °C, with a predicted range of 2.4 to 6.4 °C (Wuebbles et al., 2017). However, the actual changes in CO_2 gas, which is the primary cause of tricking heat radiating from the earth's surface to space, human activity, and the effectiveness of efforts to regulate releases of this gas and another greenhouse gases (such as CH_4, N_2O, surface Ozone, and chlorofluorocarbons) will determine where temperatures occur within this range. Here, according to the decision of the 6th Environment Action Program, European Environment Agency (decision no. 1600/2002/EC), the study displays the projected temperature rise trends from 2000 to 2100 in Fig. 2.

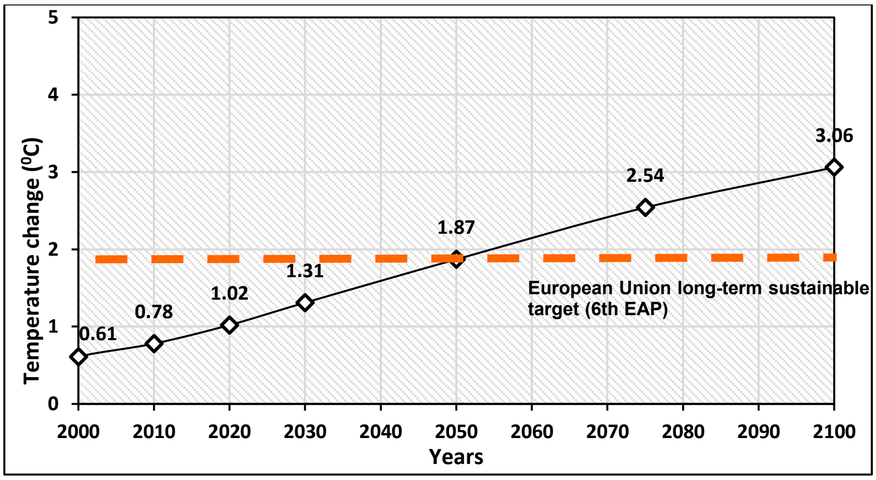

Figure 2. Global temperature rising trends from 2000 to 2100 (projection)

Since 1958, CO_2 levels have been tracked in the Pacific Ocean at Mauna Loa, Hawaii, by the National Centre for Environmental Prediction (NCEP), along with other monitoring sites such as Barrow, American Samoa, Alaska, and the South Pole. Throughout our lives, both the concentration of CO_2 and the pace at which it changes have consistently risen. By 2018, this gas's concentration had risen by approximately 50% compared to preindustrial levels, and in 2013, CO_2 measurements at the Mauna Loa site surpassed 400 ppm for the first time (WMO, 2020). As of October 2025, the current level of this gas stands at 424.87 ppm, which is an increase of 8.46 ppm from the concentration recorded in October 2021 (NOAA, 2025). The ongoing rise in atmospheric CO_2 concentration over time is shown on Fig. 3.

Sources of carbon feedback in the atmosphere are not only human activities, but a big amount of carbon released from the breathing of animals and plants, and the decay of organic substances in soil and surface water bodies (Alonso-Serra, 2021). Carbon sequestration feedback are the effects of the process of eradicating CO_2 from the atmosphere and storing it, which can both increase and counteract sequestration. Positive feedback is that increased atmospheric CO_2 can stimulate plant growth, leading to more carbon being absorbed and stored in soils. Negative feedback is that global warming can increase microbial activity and soil respiration, which releases stored carbon back into the atmosphere (Beer, 2025). In this process, the ocean environment can play a significant role.

Variations of acidification chemistry in seawater

Anthropogenic activities such as excessive burning of fossil fuels and agricultural practices have contributed to disturbances in CO_2 balance in the atmosphere. Of the total CO_2 in the globe, roughly 45% stays in the atmospheric air, approximately 23% absorbed by the oceans, and 32% utilized by terrestrial vegetation (Friedlingstein et al., 2020). The seawater absorbs a larger portion of air CO_2, leading to the acidification of the oceanic water. The acidity of a solution is quantified by its hydrogen ion (H^+) concentration. A higher concentration of H^+ ions in a solution indicates greater acidity, which correlates with a lower pH level. When CO_2 is dissolved in the ocean, it produces H_2CO_3 and releases H^+, which reduces CO_3^{2-} levels and allows for the formation of bicarbonate (HCO_3^-) and calcite (calcium carbonate) (Fig. 4 and Eqns. 1 - 3). Currently, marine waters are significantly enriched with dissolved carbonate minerals. However, as the acidity of seawater increases, the level of CO_3^{2-} ions declines. The uptake of CO_2 by seawater primarily occurs through the gas dissolving in the surface layers of the ocean, and it is also introduced into the water via photosynthesis and respiration of marine plants and microbes. Algae and other photosynthetic marine organisms absorb this gas and stock it in their tissues as carbon. This carbon is then transferred through the food web to plankton and other microorganisms, which can release CO_2 back into seawater by respiration. Additionally, when marine organisms die and gather on the ocean floor, CO_2 is produced during decomposition. Thus, the budget of this gas within the oceanic system is influenced not only by its atmospheric concentration. Overall, all forms of incoming gases can contribute to the acidification process in seawater.

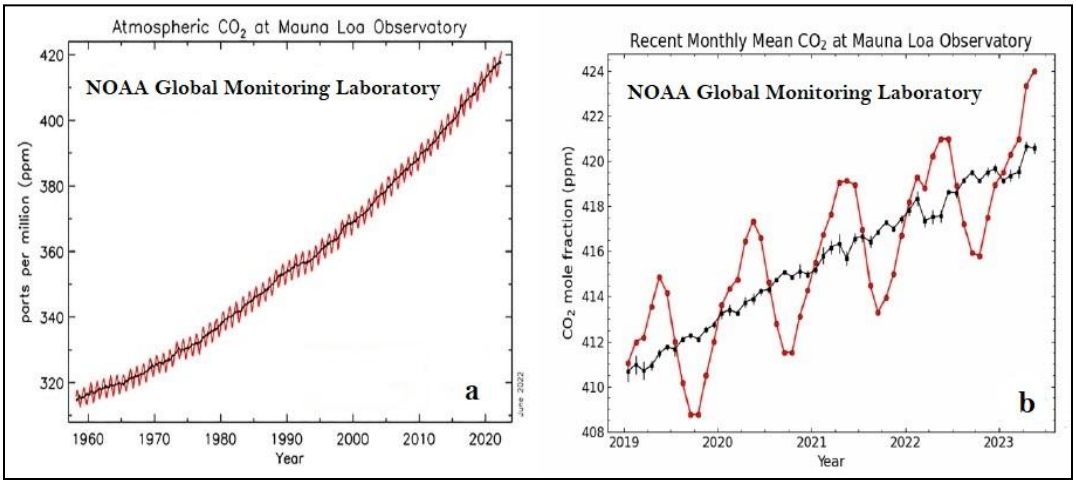

Figure 3. a) The historical concentration of CO_2 gas (1960-Oct 2025), and b) Monthly average CO_2 level (ppm) at Mauna Loa station (Source: Global Monitoring Laboratory-NOAA: https://gml.noaa.gov/ccgg/trends)

The seawater pH will change in the future years through man-made emissions of CO_2 gas; changes in ocean chemistry are incontrovertible. This chemistry is clear-cut but not simple; as man-made CO_2 increases in the air, it dissolutions in the oceanic surface. Then this gas reacts with marine water to produce H_2CO_3, as shown by the reactions 1 to 3 and these reactions are strongly impacted by the local temperature and pH of the aqueous medium.

$$[CO_2]_{aq} + [H_2O] = [H_2CO_3] \quad (1)$$

Carbonic acid decomposes and delivers proton (H^+) and bicarbonate ion (HCO_3^-):

$$[H_2CO_3] = [H^+] + [HCO_3^-] \quad (2)$$

A big portion of the additional H^+ is added with CO_3^{2-} to produce HCO_3^- ions:

$$[H^+] + [CO_3^{2-}] = [HCO_3^-] \quad (3)$$

Thus, the result of dissolved CO_2 in oceanic water is a rise in the levels of CO_2(aq), H_2CO_3, H^+, and HCO_3^- and a decrease in the level of CO_3^{2-}. The water parameter, pH, is distinct as the negative logarithm value of H^+ concentration (pH = - log [H^+]), while % of acidity is a direct measure of the concentration of an acidic substance in an aqueous medium. A change of 1 pH unit signifies a ten-fold change in the concentration of H^+, meaning a lower pH designates higher acidity, but not a straight proportional connection like a percentage would. For instance, an aqueous solution with pH 2 is tenfold more acidic than one with pH 3. It is expected that the pH of the top ocean layer will change with rising man-made CO_2. In shallow coastal and shelf areas, several factors interact to affect air-sea exchange of this gas and the resulting pH variation. These comprise biological courses, such as respiration and photosynthesis, along with water upwelling. Similarly, ecosystem metabolism in water reaching seaside waters can lead to large, but local, pH changes, with the degree of biologically mediated pH change reliant on ambient water temperature, among other factors such as stratification, depth of sea, ice capping, route of stream flow, etc.

Since warm water does not absorb as much CO_2, the above mechanisms may be affected by the degree of ocean surface temperature. Thus, further increases in seawater temperature can limit this gas uptake and cause slight changes in pH even with increased CO_2. Differences in temperature change among basins are one of the key factors for the different rates of acidity at different places. The oceanic surface is currently acidifying at a rate between 0.003 and 0.026 units of pH value per decade. Though this rate is higher in the polar areas with 0.002 to -0.026 than in the tropics with -0.016 to -0.020 units pH per decade (Mora, 2013; Bialik & Sisma-Ventura, 2016).

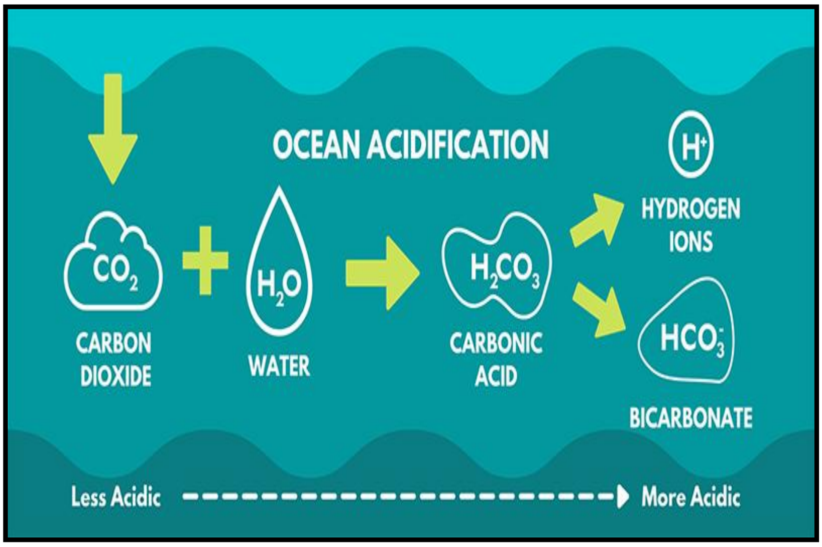

Figure 4. Simple diagram of acidification of marine water through excess air CO_2: production of H^+ and HCO_3 ions (Source: https://rinconeducativo.org/en/recursos-educativos/what-is-ocean-acidification)

Changes in ocean acidification

Past and present trends

Global change is connected to both declining DOC and marine acidification. These perils are highly stratified, seasonal, and spatially potent. It is uncertain how these two factors will be affected by stressors related to global change in the future ocean. According to Caldeira and Wickett (2003), projected pH variations in the seas and surface seawater would likely decrease by 0.77 units by 2300 if the current rate is maintained. According to Wu et al. (2018), the pH of ocean water dropped by 0.1 units over the previous 25 million yrs. However, the UK Ocean Acidification Research Program (2015) revealed that if CO_2 continues at its current rate, marine acidity will rise by over 150% by 2100—a rate that hasn't been observed in at least 400,000 years (AAD, 2011). The pace of change in marine pH from the 18th to the 21st centuries is displayed in Table 1. Table 1 shows the results of several studies, which presented that between the preindustrial era and 2100, the marine pH will drop by –0.355 and the H^+ content will rise by 126.5%. These results are consistent with previous research.

Fig. 5 illustrates that the calculated global seawater pH has decreased from 8.11 in 1985 (345 ppm CO_2 in atm.) to 8.04 in 2024 (422 ppm CO_2 in atm.). Existing rates of seawater acidification have been related to greenhouse effects at the Palaeocene-Eocene age limit (~0.56 billion years past) when the temperature of the sea surface rose by 5–6 °C (Zeebe, 2012). The carbon addition rate to the current air-sea systems is about 10 times higher than the carbon addition rate in the age limits above. Another 2013 study claimed that acidity is increasing ten times faster than other evolutionary catastrophes in the history of Earth (Humphreys, 2016). In a comprehensive statement published in the 'Science' journal in the year 2015, 22 famous ocean investigators found that CO_2 gas from combustion of fossil fuels is altering ocean chemistry faster than at any point in the last 100 yrs (Gulev et al., 2021; Philip et al., 2009). However, current ocean acidification is on track to reach pH levels lower than anything recorded in the last 3 billion yrs. The unprecedented amount of carbon addition makes existing and projected acidification in the geographical record unprecedented (Simmer et al., 2023). A US Research Council study published in April 2010 also decided that seawater acidity is increasing at an unprecedented rate (USNRC, 2010). Between 1995 and 2010 alone, acidity in the upper 100m of the Pacific Ocean from Alaska to Hawaii increased by 6% (Philip et al., 2009; Fiona, 2013). In July 2012, NOAA stated that sea surface waters are changing far faster than preliminary assessments have shown. This institution creates a graph (Fig. 6) for the station of Mauna Loa that illustrates the relationship between marine pH and air CO_2 from 1958 to 2018. This shows that as the partial pressure of marine CO_2 increases (at Aloha station), marine acidification increases continuously.

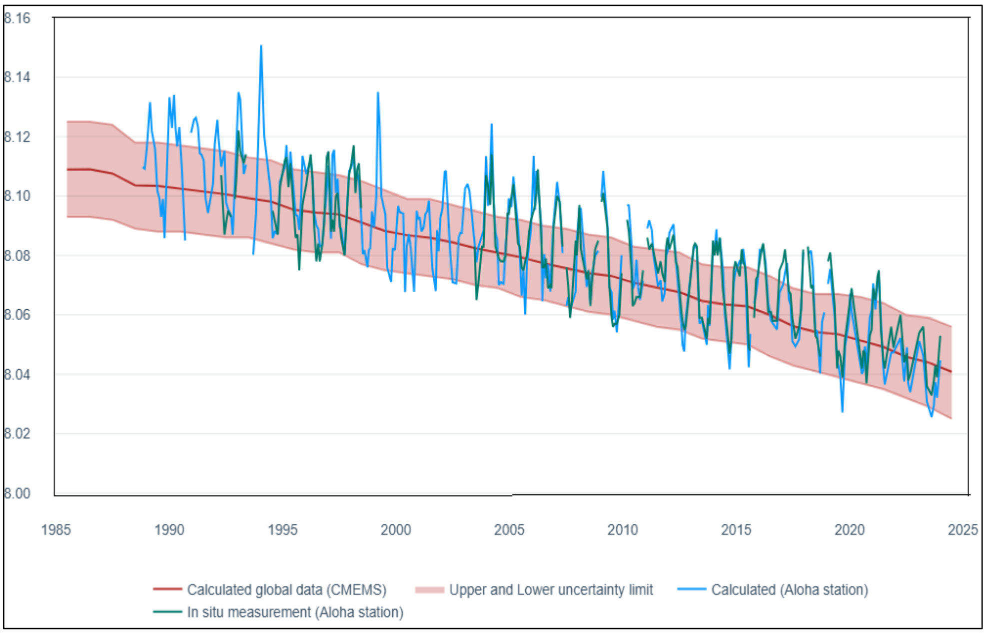

Figure 5. Decline in ocean pH and annual mean seawater pH stated on a global scale from 1985-2024 (Source: EEA, 2025)

Predicted future rates

The Earth System Models (ESMs) predict that seawater acidity will exceed historically similar values by 2008 and, combined with other marine biogeochemical variations, will damage the effectiveness of oceanic ecosystems and interrupt the delivery of many services and goods related to the ocean beginning as early as 2100 (Mora et al., 2013). Model projections show that if 'dealing as usual' models of human activity continue, surface seawater pH could deteriorate by 0.16 to 0.44 units related to today by the end of this century (Flecha et al., 2022). The sea has not experienced this level of acidity in 3 billion years (Grossman, 2009). Moreover, the World Bank's Biodiversity Advisory Committee predicts that marine acidity will more than double over the next 40 years. Besides, they argue that this rate is 100 times faster than the change in marine acidity over the past 0.2 billion years, making it improbable that marine organisms will be able to adapt to that change (Gattuso et al., 2013). By 2100, simultaneous biogeochemical changes affecting the provision of marine products and services are likely to have significant impacts on the well-being of people who depend heavily on oceanic resources for food, occupations, and incomes (Flecha et al., 2022).

Marine DOC, DIC, and acidification

In the ocean, DIC and DOC are the two main forms of dissolved carbon, playing vital roles in the global carbon cycle and marine acidification (Wang et al., 2024). DIC comprises numerous inorganic components like CO_2, HCO_3^-, and CO_3^{2-}. DOC is the most abundant form of organic carbon and originates mainly from biological processes like photosynthesis. Even though connected by the carbon cycle, they differ in sources, cycling times, and chemistry (Grosse et al., 2020).

In marine systems, organic matter (OM) is typically distinguished by its percolation behavior. Particulate organic matter (POM) is material that is retained on a filter of 0.2 to 0.7 μm pore size, whereas DOM is OM that passes through the filter (Verdugo, 2012). Since DOC is very susceptible to climate change, the majority of DOM investigations have focused primarily on the DOC pool. After all, the amount of carbon in the ocean DOC pool is similar to that of CO_2 in the air. Therefore, small variations in DOC cycling can have significant effects on air CO_2 levels and, as a result, the warming and cooling of the Earth's surface over millions of years (Sexton et al., 2011). Changes in ocean DOC cycling may have an impact on the ocean system and air CO_2 levels because, at shorter durations, the amount of DOC injected into the deep ocean (about 2000 mMT per year) is equal to the amount of CO_2 entering the ocean from the air each year (Nicolas, 2011). On the other hand, the DOC release in the oceanic system is mostly influenced by changes in marine acidity.

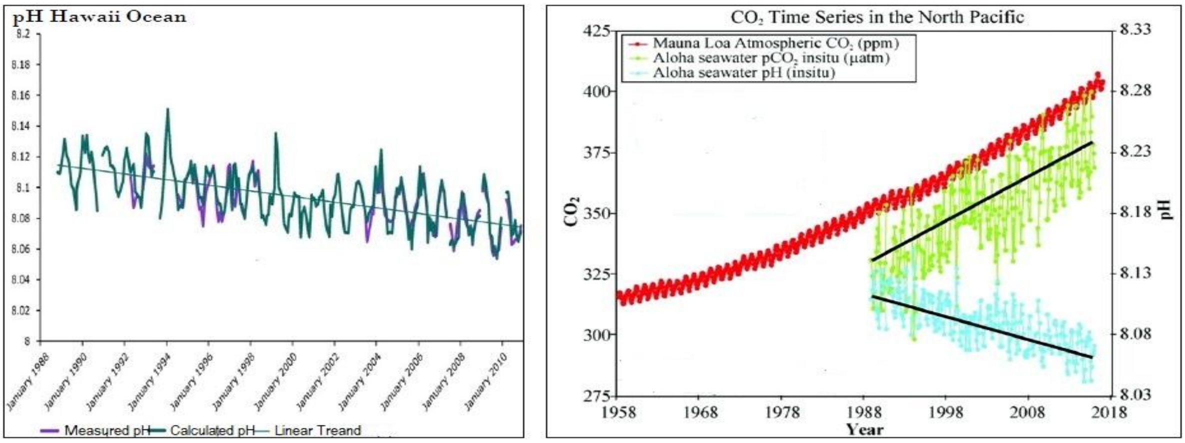

Figure 6. Left: Marine pH changes from 1988 to 2010; Right: Atmospheric CO_2 changes from 1958-2018 and both CO_2 and pH changes between 1988 and 2018 (Courtesy: NOAA Ocean Acidification Program https://oceanacidification.noaa.gov/what-is-ocean-acidification)

Table 1. Seawater pH changes with the time scale

Time	pH	pH changes relative to pre-industrial	H^+ concentration changes relative to pre-industrial	Source	Reference
Pre-industrial (18th century)	8.179	-	-	Field study	AAD (2011)
Near past (the 1990s)	8.104	−0.075	+ 18.9%	Field study	AAD (2011)
Near past (2007)	8.069	−0.11	+ 28.8%	Field study	Hall-Spencer et al. (2008)
Present (2024)	8.040	−0.139	+ 36.4%	Field study	EEA (2025)
2050 ($2\times CO_2$ = 560 ppm) (projected)	7.949	−0.230	+ 69.8%	Model prediction	Key et al. (2004)
2100 (projected)	7.824	−0.355	+ 126.5%	Model prediction	Key et al. (2004)

The amount of CO_2 in the air now is around 40% greater than it was before the Industrial Revolution (Wuebbles et al., 2017). The ocean dissolves between 30 to 35 percent of anthropogenic CO_2, which lowers the pH of saltwater (Nicolas, 2011). Seaweeds and other creatures are often the source of marine organic carbon, which is sunk by a variety of microbial processes. The DOC pool oceanic system was directly impacted by both marine pH and air CO_2 levels. It is anticipated that acidification will mostly impact DOC cycling in the sea surface layer waters since man-made CO_2 enters the ocean primarily through its surface (Piontek et al., 2022). Ocean acidification has been shown to have varying effects on the organic carbon pool. While some researchers found no effect and instead suggested more formation of transparent exopolymeric particles (TEPs), others claimed that increased carbon fixation by plankton boosted the production and storage of DOC (Zark et al., 2015). Increases in DOC levels and changes in the chemical composition were free of CO_2, according to another study that tracked the composition of plankton-formed organic carbon in mesocosm studies exposed to a variety of CO_2 levels (Zark et al., 2015). These kinds of variations between studies could be attributed to (a) variable organic carbon partition between the particulate and dissolved phases, which are influenced by community diversity and the structure of the food chain; (b) quick bacterial breakdown of the extra DOC released; (c) damage of the extra organic carbon as TEP to the sea sediments; and/or (d) different species producing varying degrees of flexibility and responses to pH changes. However, DOC concentrations appear to normally increase with increasing CO_2 levels in most environments without any appreciable effect on molecular composition. Additionally, it has been demonstrated that ocean acidification increases the bioavailability and concentrations of potentially limiting micronutrients (such as iron), which raises primary production and species composition (Gledhill et al., 2015).

On the other hand, DIC is a key factor in ocean acidification, which occurs as the ocean absorbs excess atmospheric CO_2. This absorption increases the amount of DIC, which then moves the balance of the carbonate system, leading to higher concentrations of CO_2 and H^+, and a decrease in pH and CO_3^- ions (Hu et al., 2024). Thus, the ocean becomes more acidic, making it harder for ocean organisms like shellfish and corals to construct skeletons and shells.

Impact of acidification on the marine environment

The community of calcifying animals, coral reefs, and the global blue economy are all directly impacted by the increasing acidity of seawater, which also indirectly contributes to global warming. The maritime and atmospheric environments are affected by acidification in both direct and indirect ways. In addition to financial losses, some effects on marine ecosystems and chemical reactions upset the entire marine biota food chain. Fig. 7 illustrates these direct and indirect influences.

Marine acidification not only impacts the species' growth and reproduction, but it also accelerates the warming processes of the globe. According to marine biologists, declining marine phytoplankton communities brought on by increasing seawater acidity will result in a favorable reaction that intensifies global warming processes (Feely et al., 2020). The primary source of sulfur (S) in the Earth's atmosphere is dimethyl sulfide $(CH_3)_2S$, which is produced by oceanic plankton. Sulfur in the upper atmosphere prevents solar radiation from warming the Earth's surface by replicating some of the sun's incoming heat back into space (Fig. 7). According to several estimates, the production of $(CH_3)_2S$ would decrease by around 18% between 1750 and 2100, resulting in additional radiative forcing equal to a 0.25 °C rise in atmospheric temperature (Middelburg, 2019).

Physiological and ecological effects of marine acidification

Marine acidification disrupts a wide range of physiological and ecological effects, primarily by dropping the availability of CO_3^- ions needed for shells and skeletons, which impairs growth and survival in many organisms like corals and crustaceans (Czaja et al., 2023). These physiological impacts cascade through total ecosystems, threatening food webs that depend on affected species, disrupting nutrient cycling, and increasing the risk of detrimental algal blooms. The physiological and ecological impacts of marine acidification are discussed specifically in the following sub-sections.

Reduced calcification

If ocean acidification rises and CO_3^{2-} levels continue to decrease, the global coral reefs, which provide habitat for many species, may deteriorate or perhaps disappear. Oceanic calcifiers are both large and small creatures that build their skeleton and shells from CO_3^{2-} and Ca^{2+} ions dissolved in marine water. Oceanic calcifiers would have substantially less material to maintain their skeletons and shells due to the reduced concentration of CO_3^{2-} ion (Fig. 8). Because of this, they are more likely to be consumed by predators due to their small size (Hansell and Orellana, 2021). Furthermore, in such a highly acidic environment, the shells of some animals (such as pteropods and sea snails), which are food for whales and krill, dissolve considerably in just 40 days (Lønborg et al., 2021).

Declining growth and reproduction of marine species and food web disruptions

As H_2CO_3 levels rise in their body fluids, larger creatures like fish and squid may also experience the effects of increasing acidity (Nicolas, 2011). This condition, known as acidosis, can make it difficult for animals to breathe, develop, and reproduce. Furthermore, a number of ocean experts stated that the increased ocean acidification that which oyster larvae are subjected is the reason for the notable decline in oyster reefs throughout the United States West Coast since 2005 (Jewett et al., 2020). Some studies have illustrated that the calcite skeleton of marine urchin larvae is smaller under amplified acidity; such a deterioration in general size could make them more edible to predators who would evade them under usual situations (Van de Waal et al., 2013). Animals that consume pteropods (sea snails), foraminifera (a technical word for internal shells), and coccoliths (individual plates of calcium carbonate) would be forced to move to different prey if their quantity declined (Figuerola et al., 2021). Many marine biologists fear that if ocean acidification continues at its current rate, many marine species may become extinct because they won't have enough time to adjust to the chemical changes in saltwater.

Metabolic and physiological disruptions

Dissolved CO_2 in blood controls the pH through buffering action in any animal body. A high concentration of this gas can readily cross biological membranes and pass into the blood and intracellular spaces (Wanjeri et al., 2023). The only quick fix for limiting pH variations in the body is passive buffering. The anaerobic metabolic enzyme activity in the locomotory muscles of active animals, such as cephalopods and epipelagic fish, is high. This means that the muscles can withstand pH fluctuations that are caused by anaerobic burst locomotion with great efficiency. Intracellular pH will fluctuate more in organisms with poor buffering ability than in those with higher capacity during hypercapnia. As per Seibel and Walsh (2003), an epipelagic fish like tuna that is active may only experience a 0.02 pH unit drop in response to an increase in seawater CO_2 that is enough to lower intracellular pH by 0.2 units in a lethargic benthic fish. In certain situations, the production of HCO_3^- from the breakdown of $CaCO_3$ stores or exoskeletons such as shells or tests can also offer extracellular fluid buffering, as will be covered in the section that follows.

Marine stratification and coral reefs disappearing

In the ocean, the physiological effects of marine acidity vary. Because CO_2 that dissolves on the surface travels downward with density through the thermohaline circulation, the deeper waters of the sea are often more acidic than the sea surface (Feely et al., 2008). A barrier known as the "saturation horizon" or stratification separates the sea's more acidic lower layers from its less acidic higher layers. The water over this horizon has enough CO_3^{2-}ions to support coral ecosystems. Tropical coral reefs are rarely found below 100 meters; however, a variety of cold-water coral communities can be found closer to the poles at depths between 40 and 1,000 meters (Jewett et al., 2020). By 1800, the study revealed that in semipolar and midlatitude regions, rising acidity had extended the saturation horizon by roughly 50 to 200 m (NOAA, 2020). This variance is enough to endanger coral colonies in cold water, and some researchers, e.g., Pilly et al. (2024) and Raick et al. (2025) worry that as the horizon boundary gets closer to the sea's top, more communities will be at risk. Coral reef structure would deteriorate as a result of a decline in cold-water sea calcifiers, and other marine biota that depend on corals for food and habitat would also decline (Raick et al., 2025). Additionally, Walker et al. (2024) stated that warm-water coral reefs, which are frequently the source of food and tourism income for those who live nearby, would suffer similar fates if ocean acidification were to increase globally.

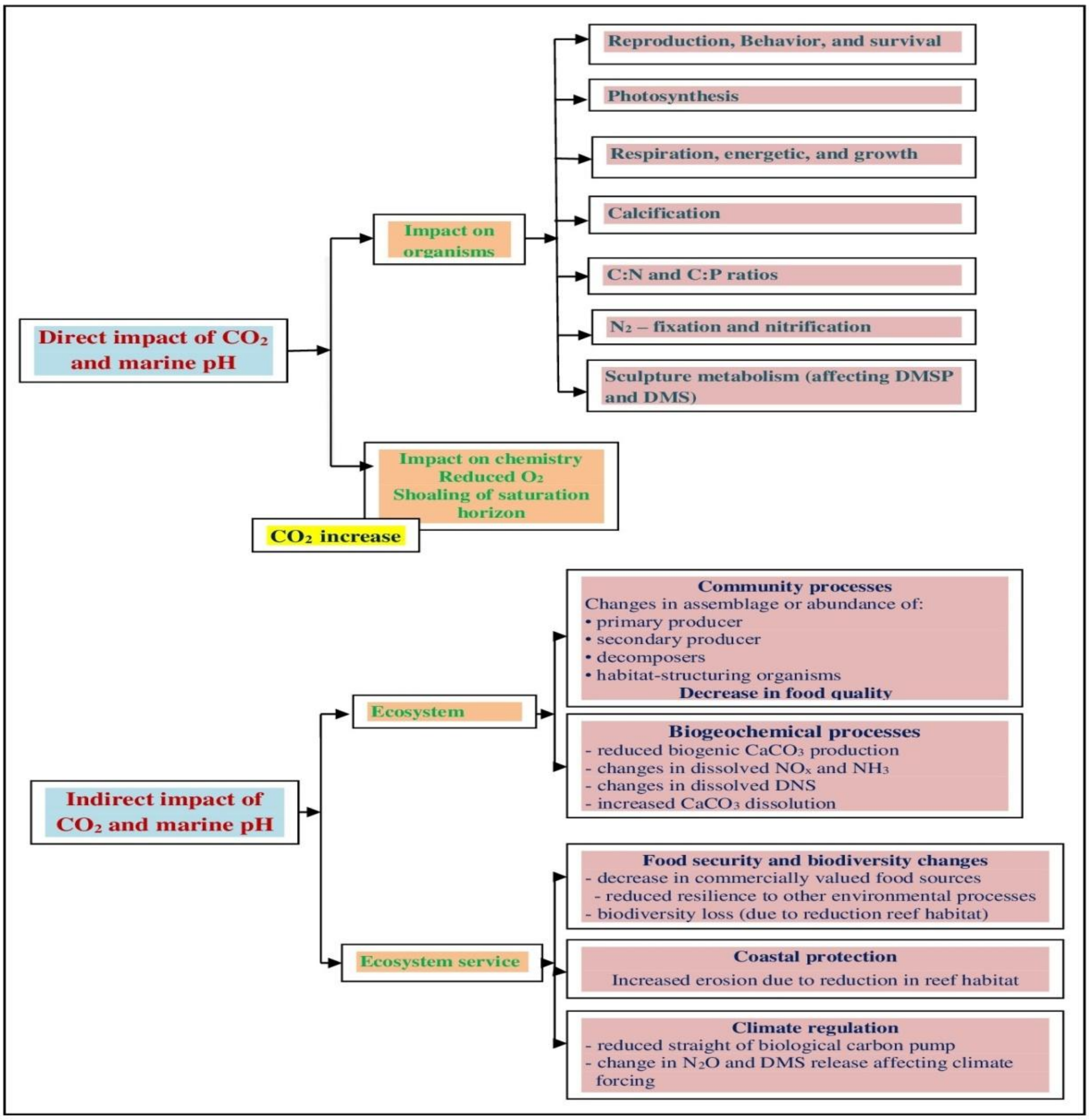

Figure 7. Major impacts of marine acidification on the oceanic and atmospheric environment

It was found that many researchers deny the aforementioned impact of acidification on marine physiology. The impact of ocean acidification has been the subject of numerous experimental studies, but they have usually concentrated on short-term single-species trials (Riebesell et al., 2018). These studies have suggested that ocean acidification has neutral, positive, and negative effects on species physiology, demography, and ecology. Research examining the effects of decreasing pH on marine bacteriological communities reveals alterations in the composition, growth, and cell size of phytoplankton and bacterial populations (Walker et al., 2024). However, the impact on the plankton community is uneven. For example, some phytoplankton species may have lower growth rates, such as $CaCO_3$ shell-producing phytoplankton, but may not be affected, as primary phytoplankton production is generally not limited by current CO_2 levels (Xu et al., 2022). Overall, it is difficult to generalize about impacts, as different species, communities, and environments respond differently to increased CO_2. On the other hand, some populations of species may adapt over time through genetic variation and non-genetic mechanisms like phenotypic plasticity. Kim et al. (2024) stated that this adaptive capacity is not general and is threatened by the present environmental change. The best way to prevent further damage is to reduce CO_2 emissions, but local management efforts can also improve seawater quality and reduce other stressors on marine environments.

Figure 8. Impacts of marine acidification on oceanic calcifiers: a pteropod shell is revealed to be dissolving over time in the ocean with a lower pH. (Courtesy: Ocean Acidification: NOAA, https://www.noaa.gov/education/resource-collections/ocean-coasts/ocean-acidification)

Calcification

Figure 8 illustrates how variations in the carbonate chemistry of the ocean cause marine calcifiers to shift (from healthy to smaller). As was previously mentioned, the reaction of CO_2 with marine water (Eqs. 1 - 3) decreases the availability of CO_3^{2-} ions, which are essential for the production of calcite ($CaCO_3$) shells and skeletons by oceanic calcifying creatures, such as corals, echinoderms, crustaceans, and mollusks (Leung et al., 2022). The $CaCO_3$ saturation index (Ω), which is calculated by dividing the concentrations (mg/L) of Ca^{2+} and CO_3^{2-} by the solubility product (Ksp) for calcite or aragonite (two forms of carbonates typically produced by marine creatures), primarily affects these animals:

$$\Omega = \frac{[Ca^{2+}][CO_3^{2-}]}{K_{sp}} \quad (4)$$

where $[Ca^{2+}]$ is measured from the salinity, and $[CO_3^{2-}]$ is computed from the DIC and total alkalinity (TA) of seawater. Rising CO_2 levels in the air, and consequently in the surface seawater (pCO_2), will lead to a decrease in the CO_3^{2-} concentration in the upper part of the sea, dropping $CaCO_3$ saturation levels through the following reaction:

$$CO_2 + CO_3^{2-} + H_2O = 2HCO_3 \quad (5)$$

The formation of shells and skeletons in calcified animals is preferred in regions where $\Omega_{aragonite}$ or $\Omega_{calcite}$ is larger than 1. Marine water is corrosive to $CaCO_3$ at values less than 1, and dissolution will start in the absence of protective measures (Fabry et al., 2008). Because the degree of solubility of $CaCO_3$ increases with lowering temperature (inverse solubility) and increasing air pressure, saturation conditions are typically lowest at high latitudes and highest in tropical regions. Because DIC levels are higher than TA at shallow sea depths, there is significant shoaling of the calcite ($CaCO_3$) saturation horizons in the Pacific Ocean north of 40°N (Keeling et al., 2010). Fabry et al. (2008) demonstrated that these are caused by enhanced upwelling, which sustains high animal biomass and transports nutrients and DIC-rich subsurface waters to the upper ocean. The calcite saturation depth shoals from 1000 meters around 30°S to 300 meters at the equator when heading north. On the other hand, the calcite saturation horizon in the North Pacific is currently moving upward at a rate of 1-2 m/y due to man-made CO_2 acceptance (Feely et al., 2004).

The amount of DIC (μmol/kg), seawater pH values, and calcite and aragonite saturation states (Ω) of the mean value of the sea surface water pCO_2 levels (ppm) during glacial age, pre-industrial age, present day, two and three times pre-industrial CO_2 concentration are presented in Table 2 (adapted from: Feely et al., 2004 and Kleypas et al., 2005). The last column in the table presents the changes from the preindustrial levels to three times the air CO_2. Table 2 clearly shows that the saturation index values (Ω) for marine carbonate minerals are steadily declining with glacial age to date.

Table 2. Present and predicted dissolved inorganic carbon (DIC), pH, and $CaCO_3$ saturation state (Ω) values.

Factor	Glacial age	Pre-industrial age	Present day	Projected: $2\times CO_2$	Projected: $3\times CO_2$	Changed from pre-industrial to $3\times CO_2$
DIC (μmol/kg)	1952	1970	2026	2090	2144	8.8%
pH	8.32	8.16	8.05	7.91	7.76	-0.4%
$\Omega_{cal.}$	6.63	5.32	4.46	3.52	2.77	-48%
$\Omega_{arag.}$	4.26	3.44	2.90	2.29	1.81	-47%

Some studies have suggested that several biotic and abiotic factors may have contributed to the formation of the solid parts of $CaCO_3$ in different collections of fauna at various periods in the history of evolution (DeCarlo et al., 2019; EPA, 2025). Most of the calcifying organisms investigated to date prove abridged calcification in response to the amplified pCO_2 in marine water and reduced CO_3^{2-}, $CaCO_3$ saturation index (**Ω**), and oceanic pH (Guinotte et al., 2008). The literature review distinguished that the majority of studies have been carried out on warm-water corals and *coccolithophorid (unicellular)* algae. Evidence recommends that the rate of calcification in corals is controlled by the calcite saturation state ($\Omega_{calcite}$), instead of the water pH or other parameters of the seawater (Armstrong and Bahr, 2025). Because the Ca^{2+} concentration in the sea is around a constant, changes in the carbonate levels are directly affected by changes in the $CaCO_3$ saturation index. Both Tyrrell & Zeebe (2004) and Ridgwell & Zeebe (2005) support the idea that the $CaCO_3$ saturation state is the key constituent of the seawater carbonate systems that control the rate of calcification. These investigations demonstrated that the partial pressure of oceanic CO_2 and the acidification of seawater had a mutually negative impact on the growth of calcifying organisms. Similar to Fig. 8, Fig. 9 also shows the changes in marine life with changes in marine carbonate chemistry.

Effect of marine acidification on blue economy

Marine acidification has substantial socioeconomic implications, mainly through negative effects on aquaculture, fisheries, marine minerals, and tourism, which influences food security, food web, livelihoods, and coastal economies (Kurniawan et al. 2026). The damage also comprises the loss of vital ecosystem services, such as storm protection from coral reefs, and can excessively harm developing nations that rely heavily on these marine resources. However, major policy and research gaps in the impact of marine acidification include the lack of coordinated local and global legal agendas, inadequate understanding of how several stressors relate at the ecosystem levels and deficient data on the exact regional vulnerability of species and potential for adaptation (Gourvenec et al., 2025).

The sustainable use of marine and coastal resources for economic expansion, improved living standards, and employment while preserving the health of ocean ecosystems is known as the blue economy. Research on the potential economic effects of ocean acidification is relatively new. Our theme was initially recognized in scholarly publications in 2007, and by 2025, our investigation had found more than 100 publications on the subject. The relationship between ocean acidification and the economic repercussions of saturated marine CO_2 was covered in most of this research. However, because multiple disciplines were involved, a number of difficulties were noted while evaluating these implications. The complicated nature of this matter is the connection between subjects, precisely biology and economics, which is recommended to be the weakest section of evaluation (Falkenberg and Tubb, 2017). Up to now, assessments have characteristically linked this gap by abridging the predictions of biotic responses to change in vital physiological factors revealed in a few meta-analyses and scientific studies, which are presented in Table 3.

Table 3 shows that only one assessment of this research finds favorable economic consequences, and most studies predict negative repercussions from ocean acidification. These detrimental effects are likely observed because most studies focus on calcifying organisms and the habitats they create (such as mollusks, crabs, corals, and other invertebrates), which are expected to respond more adversely to ocean acidification than noncalcifying organisms that might respond favorably (such as seagrasses and algae). This assessment acknowledged that many of the ecosystem services provided by oceanic species and habitats to human civilizations may be impacted by ocean acidification. The environmental services provided by fish, mollusks, crustaceans, and coral reefs have been assessed in several studies.

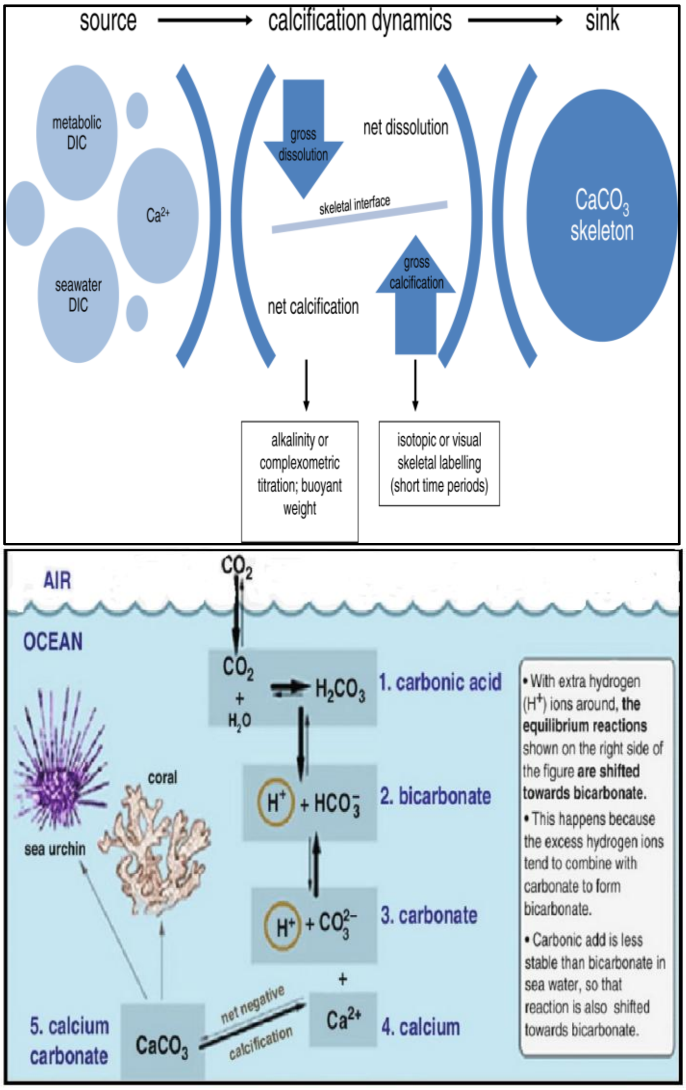

Figure 9. Influences of ocean carbonate chemistry on the calcification of marine organisms (Source: Cohen et al., 2017)

In the majority of studies, the forecasted impact of ocean acidification is negative, and only one evaluation of this review identifies positive economic effects (Table 3). These negative influences are probably observed because most investigations focus on calcifying organisms and the habitats they form (e.g., mollusks, crabs, corals, and other invertebrates), which are predicted to respond negatively to ocean acidification, somewhat more than noncalcifying organisms that may respond positively (e.g., seagrasses and algae). Oceanic species and habitats offer a range of ecosystem services to human civilizations, and this review recognized that many of these services may be influenced by ocean acidification. Many studies have measured the ecosystem services of marine animals and their outputs provided by mollusks, crustaceans, fish, or coral reefs. The assessment, which took into account global, national, sub-national, and regional scales, replicates the potential economic effects of marine acidification on a range of geographical regions.

Table 3. Economic impacts of ocean acidification at various future timescales

Timescale /Time series	Species/ habitat	Spatial scale	The biological response included in the analysis	Ecosystem services	Economic forecasting factors[a,b]	Economic effect	Reference
2060	Mollusks	National and subnational	Calcification	Marine animals and their outputs	Net present value, economic profit losses	Negative	Cooley and Doney (2018)
2100	Mollusks	Global and regional/ National	Calcification and survival	Animals from in situ aquaculture, marine animals, and their outputs	Total economic cost, producer and consumer excess	Negative	Narita et al. (2012)
Through 2100	Coral reefs	Global	Area	Wild animal and their outputs, experiential use, physical use, preserving nursery populations and habitats inheritance	Annual economic damage and net present value	Negative	Brander et al. (2012)
2050	Fish and invertebrates	Regional and national, and subnational	Metabolic rate, larval and adult mortality	Marine animals and their outputs	Total revenue, fishers' incomes, total fishing cost, economic impacts, income impacts, economic rents, landed value	Negative	Lam et al. (2016)
2100	Seagrass beds	Global and National	Biomass	Global climate guidelines for a decrease in greenhouse gases	Carbon sequestration, net present value	Positive	Garrard and Beaumont (2014)
Through 2100	Red king crab	Local	Juvenile survival	Marine animals and their outputs	Maximum economic productivity and income	Negative	Punt et al. (2014)
2100	Norwegian coastal cod	Local	Larval mortality	Wild animals and their outputs	Total incomes	Negative	Voss et al. (2013)
Through 2100	Mollusks	National	Growth rate	Wild animals and their outputs	Net present value, and corresponding surplus from avoided ocean acidification, compensative surplus	Negative	Edwards et al. (2015)
2100	Marine Seal	Global and National (Baltic Sea)	Population (Due to a disturbed food web)	Provide nutrient cycling by transporting nutrients, top predators, and regulating prey populations to maintain the ecosystem.	Indirect economic impact	Negative	Mangi et al. (2018)

Note: (a) A variety of response variables, such as net revenue flow, present value, and consumer welfare values, were employed in the study that evaluated the possible economic implications of marine acidification; (b) According to the IPCC report, using different economic forecasting scenarios, e.g., SRES (A1, A2, B1, B2), IS92, RCP, etc.

DOC and ecosystem responses in the ocean environment - a summary

The marine DOC pool is one of the prime collections of organic substances on the planet (Guo et al., 2025). It is a critical constituent of the Earth's carbon cycle and a primary energy source for marine food webs. Lonborg et al. (2020) stated that ecosystem responses to changes in the marine DOC pool are highly complex and often driven by global change stressors such as oceanic warming, deoxygenation, and acidification, which alter the production, degradation, and transport of DOC. It has not only regulated marine acidification or chemistry, but DOC also acts as a global change stressor that impacts both the primary production and the consumption, leading to numerous ecosystem responses (Guo et al., 2025). The complex interactions between these stressors mean that ecosystem responses vary locally, and the overall outcome for the global ocean DOC pool remains an area of active research. These responses are summarized in Table 4.

Table 4. Impact **of** global change stressors on the dynamics of DOC, leading to ecosystem responses, with a relevant research gap.

Stressor	Impact on DOC cycling	Resulting ecosystem responses	Research gap
Increased CO_2 and ocean acidification	- Increases both the creation and degradation rates of DOC - Increased DOC accumulation with elevated CO_2 - Potentially reduce photochemical degradation of marine DOC - Microbial destruction of DOC exhibited increases with raised CO_2 and acidity	Loss of higher trophic organisms (e.g., fish) from oxygen-deficient zones, a shift toward microbial-dominated systems, and potential release of iron and phosphorus from sediments, impacting primary production.	Vital research gaps concerning marine DOC and ocean acidification center on understanding the complex, variable, and interactive effects of reduced pH on DOC production, composition, and its eventual fate in the marine carbon cycle.
Ocean heat-up	Degradation rates of DOC and increased microbial respiration potentially led to a net loss of carbon from the sea to the air.	Changes the size of phytoplankton community and composition; reduced carbon sequestration to the deep ocean; mass mortalities of some marine life during heatwaves.	Key research gaps regarding the impact of ocean heat-up on DOC cycling primarily revolve around the increasing effects of multiple stressors**,** regional variability, and the need for updated data to refine climate models.
Ocean deoxygenation	Shifts DOC degradation to less effective anaerobic procedures, which is suggested to slow degradation and potentially cause DOC accumulation, particularly in coastal dead zones.	Loss of higher trophic organisms and a shift towards microbial-dominated food chains; release of iron and phosphorus from sediments.	The primary research gaps regarding the link between ocean deoxygenation and DOC center on understanding the accurate mechanisms and rates at which changes in DOC cycling affect, and are affected by, reduced oxygen levels, mainly in the open ocean.
Increased stratification	Prevents the vertical exchange of DOC and nutrients between the surface and deeper layers of seawater.	Decline in primary production in surface water because lack of nutrients; gathering of carbon-rich DOC at the surface layer; and increased exposure of DOC to sunlight.	Key research gaps concerning the effect of increased ocean stratification on DOC cycling mostly center on the need for detailed studies on the combined effects of warming and stratification.

Research needs

Maximum research work on the influences of marine acidification on ocean biology and the carbon cycle in the oceanic environment at climate-relevant atmospheric CO_2 concentrations has explored the calcification of corals and calcifiers. Evidence on the sublethal calcification and energetic reactions of a miscellaneous range of micronekton and zooplankton is vital. The biotic effects of seawater acidification on marine life are only now commencement to be appreciated, and the fluctuations in seawater chemistry over the majority of the ocean are well-considered owing to the seawater uptake of excess human CO_2 gas. It will take innovative technologies and advancements, along with coordinated, interdisciplinary efforts from chemists, biologists, analysts, and modelers to measure the impacts of marine acidification on oceanic creatures and variations in ecosystem environment and occupation. However, there is enough data to say with confidence that during the next century, significant changes to marine ecosystems are anticipated and that harmful effects on specific marine species are certain. Some specific facts are needed for a thorough investigation into where multiple investigators should be involved.

For critically affected species and in sensitive areas, it is essential to track the abundance and depth distribution of calcifying and non-calcifying organisms, determine calcification and changes in the metabolic rate of these species, and correlate these data with variations in the reactions involved in the CO_2 chemistry of marine water layers. Continuing monitoring programs at suitable spatial and temporal scales to detect potential changes and discriminate between human- and natural-variability-induced changes will be needed for these purposes.

Sensitive regions for investigation take in high-latitude areas, which may become under-saturated regarding aragonite and calcite by 2050, and areas with definite O_2 minimum columns (coastal hypoxia), which are still categorized by high CO_2 levels and may be mostly at risk, due to the mutual consequences of low O_2 with raised CO_2, eutrophication, and warming.

Utilizing increased CO_2 data expected to happen in the following century, laboratory experimentations are required to explore the calcification and dissolution responses, recognize physiological catalogs suitable for forecasting CO_2 acceptance, regulate the costs of the acid-base directive, and measure delicate energetic courses, e.g., reproduction, tissue and skeletal growth, and metabolism for sensitive life stages of crucial organisms.

Conclusions

Over the past three decades, there has been a noteworthy advancement in both scientific and field studies on the changes in marine water chemistry caused by rising air CO_2 and the susceptibility of oceanic life to increased marine acidity. According to the study, air CO_2 concentrations have increased from 3 to 4 ppm in recent years. By 2100, the pH of marine water would have dropped from 7.9 to 7.8 due to additional CO_2 entering the oceans. The ocean has been absorbing more CO_2 since the Industrial Revolution, and marine chemistry, especially carbonate chemistry and dissolved carbon cycling, has changed dramatically. The partial pressure of saturated CO_2 and the pH of oceanic water sustain this organic carbon, which controls the life of calcified species. Coastal human communities are suffering financial losses as a result of decreased calcification, reduced shellfish harvests, and coral reefs' inability to defend coastal areas. With little to no modification, several current regulations used to manage seawater quality and protect marine life can also aid in addressing acidification. This study found that many similar adaptive measures were employed in other nations to deal with other problems, such as bolstering the shellfish aquaculture sector as a whole, which may help mitigate acidification. Certain species, such as corals, may struggle to survive in existing ecosystems when $CaCO_3$ saturation levels decrease. A top priority for policymakers is to improve knowledge and public awareness about ocean acidification and its potential impacts on marine ecosystems and the dissolved global carbon cycle.

Author Contributions: MSI: Conceptualization, methodology, investigation, writing – original draft; MGM: Supervision, formal analysis, investigation, writing – review & editing.

Conflict of Interest: The authors declare no conflict of interest.

Data Availability: Data will be available through the corresponding author upon reasonable request.

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