Impact of Ocean Acidification on Fish Health and Marine Ecosystem Dynamics

Maham Riaz[1*], Sajid Abdullah[1], Zain Khalil[1], Mina Jamil[1], Warda Fatima[2], Amna Rasheed[1], Maham Fatima[1] and Sadia Gulshan[3]

[1]Department of Zoology, Wildlife and Fisheries, University of Agriculture, Faisalabad, Pakistan
[2]Department of Biochemistry, University of Agriculture, Faisalabad, Pakistan
[3]Department of Zoology, Government College Women University, Faisalabad, Pakistan
*Corresponding author: mahamalich11@gmail.com

Abstract

Ocean acidification (OA) causes an increase in carbon dioxide (CO_2) and a reduction in the pH of ocean waters. This chapter reviews the current literature to investigate the adverse effects of OA on fish health and marine ecosystem dynamics. OA poses serious threats to marine biodiversity and ecosystem dynamics. Fish experience severe physiological problems such as impaired growth, development, tissue damage, Impaired behavioral changes, sensory and brain functions, and disruption in predator-prey interactions due to acidification with a 74% decline in survival rates of egg and larval stages. Besides affecting fish, OA also affects marine ecosystem dynamics: reducing calcification rates in calcifying species, increasing seagrass production, causing effects on habitat-forming species, and disrupting the food web. Vulnerable species, such as coral reef fish, show high sensitivity, risking the stability of their habitats. The United Nations recognized the OA as a threat to marine biodiversity through the Convention on Biodiversity. The future research needs to focus on understanding fish and marine animals' adaptive mechanisms to OA, its interaction with other stressors, and global collaboration to address the underlying causes of OA.

Keywords: Carbon dioxide emission, Marine biodiversity, Marine Ecosystem, Climate Change, Marine Conservation

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Introduction

Ocean acidification (OA) is a shift in the composition of the ocean caused by the oceanic absorption of chemical inputs from the atmosphere, such as carbon, nitrogen, and sulfur compounds (Dillon et al., 2020) which decreases ocean pH Anthropogenic activities such as fossil fuel combustion, land-use practices, and deforestation are major contributors to elevated atmospheric carbon dioxide (CO_2) levels (Lapola et al., 2014). The ocean has been recognized as a significant sink for anthropogenic CO_2 since the late 1950s. CO_2 levels in the atmosphere are over 410 ppm, about 50% higher than preindustrial levels. These extreme levels and fast growth rates are unparalleled in the previous 55 million years (Gingerich, 2019). Evidence suggests that the ocean absorbs approximately 25% of total anthropogenic CO_2 emissions. Increased CO_2 levels in the ocean cause a change in the acid-base chemistry of seawater, leading to a decline in pH levels, a reduction in carbonate ion concentration, and lower calcium carbonate saturation (Lohbeck et al., 2012; Gruber et al., 2019).

This intake of atmospheric CO_2 has contributed to a 0.1unit reduction in oceanic pH since the Industrial Revolution, and it is predicted to cause an additional 0.3-0.32 unit decline by the end of the century (Gattuso et al., 2015). Changes in pH can cause changes in the amounts of carbonate and bicarbonate ions in saltwater, impacting fundamental organism physiology, such as calcification. Maintaining proper carbonate ion saturation levels is crucial to facilitate calcium carbonate formation, which is vital for the skeletons and shells of many marine organisms, such as corals, shellfish, and plankton (Teixidó et al., 2020). As a result, OA is widely regarded as a major threat to marine biodiversity (Garrard et al. 2013; Harvey et al. 2013). OA damage includes large-scale mortality of oyster larvae due to acidic hatchery water in Oregon and Washington hatcheries in 2007-2008 (Barton et al., 2015). The United Nations' Sustainable Development Goal 14.3 recognizes OA as a worldwide environmental issue. It is also one of the nine planetary limits crucial for maintaining Earth's equilibrium (Rockström et al.,2009). The objective of this chapter is to access the diverse impact of OA on fish health and marine ecosystem dynamics by investigating its potential physiological and behavioral effects on fish and cascading effects on marine food web and stability of marine ecosystem

Natural Ocean Acidification

The dissolution of CO_2 and dissolved inorganic carbon (DIC) in seawater caused by photoinduced and biological mineralization of primary producers (PP) or dissolved organic matter (DOM) reduces pH and alters carbonate chemistry (Sunda and Cai, 2012; Bates et al., 2013; Mostofa et al., 2013a). Surface and subsurface waters exhibit an anticorrelation of pH and CO_2 levels during the diurnal cycle. Enhanced CO_2 levels contribute to greater photosynthesis and may significantly influence net primary production (Cai & Jiao, 2022). Upper ocean species, mostly autotrophs, are carbon-processing machines that may absorb atmospheric CO_2 or CO_2 combined with DIC produced from DOM or PP throughout the day (Mostofa et al., 2013a; Rheuban et al., 2019). Seawater may operate as a CO_2 source at night, due to its higher pCO_2 values than the atmosphere (Dai et al., 2022). Daytime CO_2 intake is mostly owing to primary photosynthesis, which utilizes dissolved CO_2 via ribulose biphosphate carboxylase which directs carbon-concentrating mechanisms (CCMs) (Wang et al., 2022).

Global warming (GW) also considerably impacts the natural ocean acidification process, accelerating the dissolution of CO_2 and DIC from PP and subsequent respiration (Mostofa et al., 2013a; Holding et al., 2015). GW also raises water temperatures boosting respiration rates in natural waterways and influencing phytoplankton metabolism (Toseland et al., 2013). Photoinduced and microbiological products/compounds generated from DOM or PP, such as CO_2, DIC, H_2O_2, NH^{+4}, NO^{-3}, PO^{-4}, CH_4, and autochthonous DOM, may promote photosynthesis and primary production in stratified surface waters (Mostofa et al., 2016).

Anthropogenic Ocean Acidification

The global surface ocean is acidifying due to a swift increase in atmospheric CO_2, mostly caused by fossil fuel consumption. Anthropological emissions of 10 billion metric tons of carbon annually increase by around 2 ppm/year or 0.5%. This expansion occurs quicker than during big glacial-interglacial transitions (Ciais et al., 2014). Increasing dissolution of atmospheric CO_2 into seawater results in decreased pH and a significant alteration of carbonate chemistry, affecting both biogenic and sedimentary calcium carbonate ($CaCO_3$). The net fluxes of CO_2 can fluctuate depending on the time of day and seasonal changes. Throughout the daytime, seawater may either release CO_2 into the atmosphere or maintain a consistent balance during the night. In warmer periods, atmospheric CO_2 tends to sink into surface waters or contribute to them. During colder periods, the seawater may release, sink, or maintain a balance of its CO_2 content in the atmosphere (Figure 1). These scenarios highlight carbon's complex and dynamic exchange nature in marine environments (Beaufort et al., 2011).

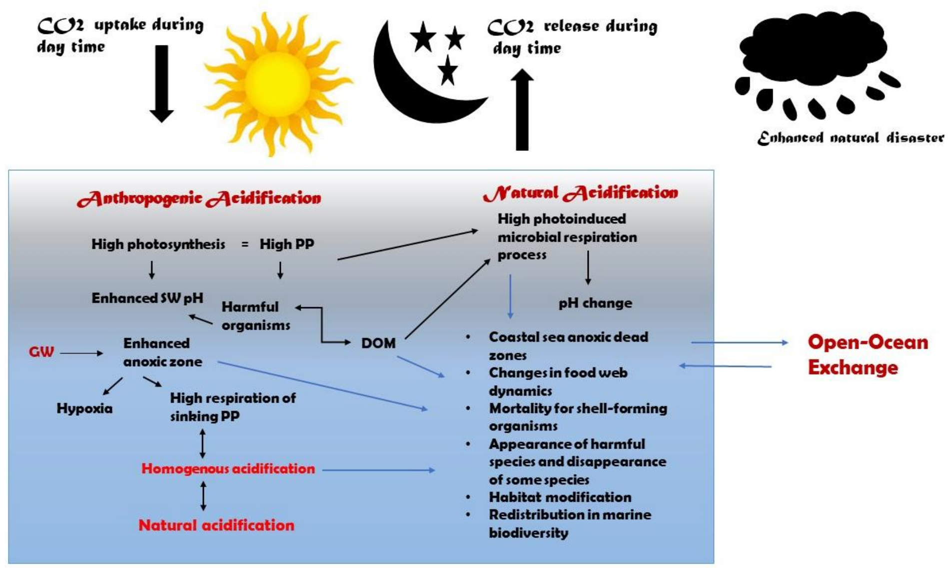

Fig. 1: Overview of natural and anthropogenic acidification

Seawater Chemistry

The addition of CO_2 to seawater forms bicarbonate ($HCO^-{}_3$), and hydrogen ions (H^+) at seawater pH levels

$CO_2 + H_2O \rightarrow HCO_3^- + H^+$.

The formation of H+ increases acidity by lowering seawater pH, and concentration of carbonate ions (CO_3^{-2})

$CO2^-{}_3 + H^+ \rightarrow HCO_3^-$.

The effects of acidification depend on organism responses to multiple, simultaneous chemical changes increasing CO_2, HCO_3^-, and H^+ concentration and decreasing CO_3^{-2} concentration. Many marine animals that make shells and skeletons from calcium carbonate ($CaCO_3$) minerals are susceptible to acidification (Hurd et al., 2019). Oceanic waters exchange CO_2 with the atmosphere, and surface seawater partial pressure, pCO_2, follows atmospheric CO_2 increase throughout much of the world's oceans (Bakker et al., 2016). Surface ocean pH and CO_3^{-2} are decreasing, with an average worldwide reduction of around 0.1 units from preindustrial periods to today in pH, leading to a 30% rise in hydrogen ion concentrations. This acidified ocean situation is compounded by global acidification signals caused by CO_2 emissions. Coastal upwelling systems feature elevated CO_2 levels while reduced O_2 levels owing to the aquatic biological pump, which generates organic materials on the oceanic surface and carries them to the subsurface (Feely et al., 2018). Additionally, low-alkaline freshwater from glacier melt, rivers, and groundwater can cause coastal acidification (Kessouri et al., 2021).

Impact on Fish Health

OA poses a serious risk to marine life, particularly fish.

Physiological Stress

OA causes severe physiological effects to fish by affecting blood CO2 chemistry and disrupting acid-based balance in body. These disruptions are similar across species, but there is significant variation in how various fish species and individuals behave, with some showing resistance and others succumbing to their effects (Green & Jutfelt, 2014; DePasquale et al., 2015). Fish gills play an important role in gaseous exchange and ion movement; nevertheless, gill function may be impaired in acidic environments. This deficiency can cause decreased oxygen consumption and a greater vulnerability to disease (Fonseca et al., 2019). Furthermore, under more acidic conditions tissue damage, impaired growth, and development have been observed in Atlantic cod and Atlantic herring. Early life stages, notably eggs and larvae, are more sensitive to OA, with a 74% decline in survival rates (Frommel et al. 2014; Frommel et al. 2020).

Behavioral Changes

Acidification causes a wide range of behavioral changes in the fish. A study on the sensory systems of tropical coral reef fishes (11 species from six genera) revealed that at high CO_2 levels, larval fish shift in their settlement choices, favoring negative stimuli over positive ones, perhaps leading to lower survival rates and altered ecological interactions. This behavioral shift shows that OA may impair important decision-making processes in fish, possibly impairing their capacity to choose ideal habitats and partners for symbiotic interactions. (Munday et al., 2014). Similar disruptions were seen in larval damselfish settlement behavior and adult five-lined cardinalfish homing abilities. Furthermore, OA impairs larval fish's auditory responses and settling behaviors, limiting their capacity to identify acceptable homes (Radford et al., 2021; Priest et al., 2024). Moreover, increasing CO_2 concentrations cause reef fish to display bolder and riskier behavior, such as increased activity, mobility, and eating (Hannan et al., 2020) Elevated CO_2 levels also impair fish's sensory abilities, including their sense of smell, vision, and hearing. Damselfish showed reduced foraging and movement patterns and exhibited normal anti-predator behaviors (Ferrari et al., 2012).

Predator-prey Interaction

Studies on predator-prey interactions in fish species show that OA significantly influences their behavioral responses. Under normal CO_2 levels, orange clownfish larvae and other fish tend to avoid the odors of predators. However, at elevated CO_2 levels, their ability to differentiate between predator and non-predator odors declines, leading to a surprising attraction to predator scents (Porteus et al., 2021). This behavioral change varies among species and individuals; some fish consistently evade predators, while others are drawn to them in high-CO_2 environments (Munday et al., 2011). Moreover, OA has been associated with impaired sensory abilities in fish, particularly their sense of smell, which can result in higher mortality rates among juvenile prey when they encounter predators indicating that ocean acidification impacts not just individual species but also the broader ecological dynamics of marine ecosystems (Cattano et al., 2020). OA has been found to impact fish brain functions, resulting in increased mortality rates among juvenile prey species when placed with predators. This effect continues to be evident even when fish exposed to high CO_2 levels are returned to coral reefs. Failed lateralization and learning also occur, with ambon damselfish unable to avoid predatory dotty backs (Domenici et al., 2011). The fundamental cause of these alterations in brain function is the activation of neurotransmitters known as g-aminobutyric acid (GABA)-A by increasing CO_2 in larval orange clownfish (Heuer et al., 2019).

Impact on Marine Ecosystem Dynamics

OA is predicted to affect biodiversity and marine ecosystem dynamics.

Disruption of Marine Food Webs

OA is likely to cause significant changes in the structure of plankton communities, which in turn will affect the productivity of the entire food web (Bach et al., 2017). The responses of phytoplankton are influenced by various environmental aspects: nutrient levels, salinity, and temperature (Boyd et al., 2014). OA increased stratification, which leads to shifts in marine microbial community composition (Dutkiewicz et al., 2015). Mesocosm studies have indicated that there might be an increase in productivity at the base of pelagic food webs, which could subsequently enhance productivity at higher trophic levels, including the survival and biomass of larval fish which faces negative effects of OA (Boxhammer et al., 2018). However, this productivity increase is not anticipated to help all zooplankton species. Studies have indicated that the nutritional quality of zooplankton could decline due to OA irrespectively of their abundance and pteropods in acidic waters alongside the California Current could face shell dissolution as in Figure 2 (Rossoll et al., 2012; Bednaršek et al., 2014). OA could also upset oceanic food webs by promoting harmful algal blooms, potentially enhancing the toxic effects of harmful algae, or increasing the predominance of harmful bloom-forming species by changed competitive dynamics (Fu et al., 2012; Riebesell et al., 2018).

Alteration in Habitat Structure

Habitat structure, which is one of the important components of marine ecosystems, is profoundly impacted by ocean acidification. Ocean absorbs a high amount of CO_2 from the atmosphere that alters the chemistry of seawater which affects the ability of marine organisms to make and maintain their shells and skeletons which leads to significant alterations in the physical structure of coastal and offshore habitats, with cascading effects on the overall dynamics of the marine ecosystem (Guan et al., 2020).

Effect on Habitat-forming Species

OA exerts a profound impact on species diversity, with most macroalgae tolerating the effects with a 5% loss in species diversity, but it also causes significant changes in the community composition of algae, impacting coastal habitats (Porzio et al., 2011; Enochs et al., 2015). Undersaturation of carbonate declines the algal coralline thickness forming a rock pavement in the photic zone, enabling other life to establish and grow (Fabricius et al., 2011). Higher accessibility of bicarbonate encourages primary production in wave-sheltered areas, while wave-exposed areas reduce the resilience of coastal ecosystems, leading to only microalgal biofilm and tiny grass algae remaining after storms (Linares et al., 2015; Connell et al., 2018). Many macrofauna are affected by OA, with a nearly 30% decline in animal biodiversity as pH falls from 8.1 to 7.8 at CO_2 seeps due to the high metabolic costs that they require to cope with high CO_2 and high vulnerability to predators (Garilli et al., 2015; Harvey et al., 2018). Corals, sponges, serpulids, vermetids, oysters, mussels, and bryozoans are among the famous habitat-forming marine species that make calcareous seabed habitats. These species decline due to the low tolerance of these species to hypercapnia. Acidification also poses a hazard to maerl beds, a habitat of detached, branching crustose coralline algae (Fabricius et al., 2011; Milazzo et al., 2014; Enochs et al., 2015).

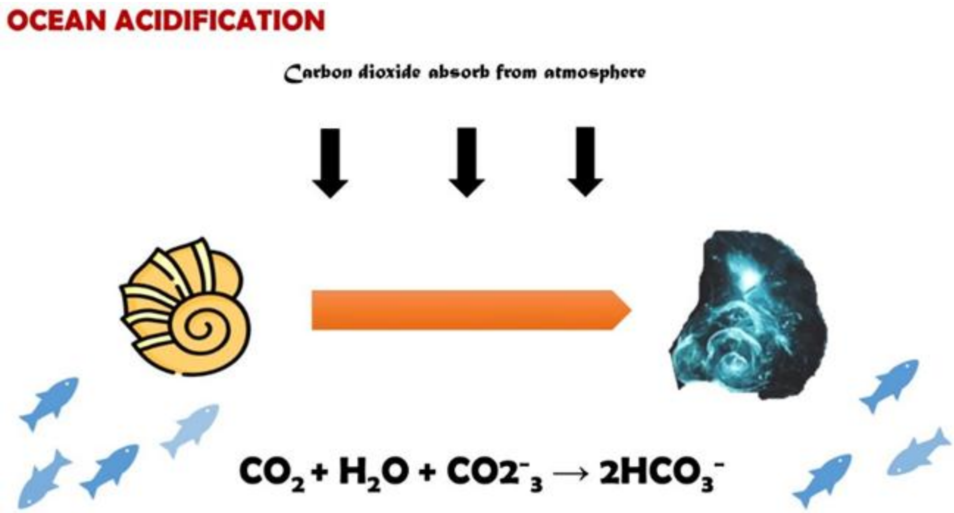

Fig. 2: It shows the dissolution of pteropod shells in low-pH seawater

Effect on Calcifying Species

OA reduces calcium carbonate saturation, which is especially important for calcifying species including mollusks, corals, and certain plankton. Carbonate ions are used by calcifying animals to produce calcium carbonate minerals in shells and skeletons. Hydrogen ions compete with calcium for carbonate ions, reducing calcification rates and adversely impacting growth, survival, calcification, development, and abundance (Kroeker et al., 2013)

Coral reefs may face a 20-60% decline in calcification rates due to a low aragonite saturation state caused by high CO_2 levels, causing low coral reef resilience (Browman, 2016). OA is predicted to enhance the degradation of oyster shells, which form the structure of oyster reefs. High CO_2 levels may dangerously impact oyster larval recruitment (Munday et al., 2014). Fish have calcified structures in their inner ear, otoliths that help them sense sound, navigate, and accelerate the shape of sacculus otoliths are affected by OA. Effects on calcifying animals may disrupt the food web and change the species makeup of marine environments because higher trophic-level organisms rely on calcifying animals for nourishment and refuge (Busch and McElhany, 2016).

Effect on Seagrasses

Seagrasses may benefit from acidification because it reduces the cost of carbon intake for photosynthesis, however, there is little evidence that CO_2 enrichment increases seagrass production (Koch et al., 2013). Acidification can have an impact on related species, as well as community consequences on seagrass meadows. Marine epiphytes and macroalgae that compete with seagrasses may behave differently. Seagrasses are sensitive to both benthic light and water quality, therefore the impacts of acidification on plankton dynamics may be important (Zimmerman et al., 2015). While the number of calcium carbonate-producing epiphytes decreases with acidification, increased seagrass production may safeguard some calcareous species that live near seagrass tissues in low-flow situations (Cox et al., 2017). High pCO_2 benefits fleshy epiphytic algae, and experimental studies show that grazers can regulate epiphytic algae. Many seagrass-dwelling invertebrate grazers are highly acid-tolerant (Eklöf et al., 2015).

International Recognition

The global community appears to understand the threats of the OA to biodiversity. Target 8 set by the Convention of Biodiversity held in December 2022 calls to action to reduce the impact of climate change and ocean acidification on biodiversity (*COP15: Nations Adopt Four Goals, 23 Targets for 2030 in Landmark UN Biodiversity Agreement*, n.d.). United Nations officially recognized the impact of OA on biodiversity loss by adding this target to an international treaty. They obligated the members to introduce legislation regarding OA to reduce its effects. However, only a few countries are taking steps toward this. According to the OA Alliance, only 13 countries made government-level OA action plans.

Conclusion

OA is caused by an increase in CO_2 and a reduction in the pH of ocean waters, which has major consequences for fish health and threatens marine ecosystem dynamics. Fish experience physiological stress, behavioral changes, disruption in predator-prey interactions due to OA. Moreover, OA effects ecosystem by disrupting the food web, and altering habitat structure resulting in lower ecological resilience. By synthesizing the current literature, we come to the conclusion that future studies should focus on the evaluating the long-term effects of OA on fish and marine organisms and understanding their adaptative mechanism to OA. International Organizations should come forward with immediate action plan to reduce CO_2 emissions to addresses this global issue which has been pushed down on priority list due to lack of interest.

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