Proceedings of the 6th International Conference on Biological Engineering and Medical Science
DOI: 10.54254/2753-8818/2026.38693

Research Progress on the Formation Mechanisms of Ocean Acidification and Its Impacts on Marine Organisms and Ecosystems

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Abstract. Ocean acidification is one of the critical marine environmental issues under global climate change. As the ocean continuously absorbs anthropogenic carbon dioxide (CO_2), re-equilibration occurs in the seawater carbonate system, triggering a series of chemical shifts including declining pH, decreased carbonate-ion concentration and reduced calcium-carbonate saturation state. The magnitude of these changes is modulated by multiple factors such as temperature, salinity, ocean circulation, biogeochemical processes and terrestrial inputs, showing distinct regional heterogeneity. Ocean acidification affects marine organisms via pathways including acid-base balance disturbance, energy redistribution, ion regulation and calcification processes. Responses vary markedly across species and life-history stages. Calcifying organisms such as corals, shellfish, pteropods and calcifying algae have received substantial research attention, while non-calcifying organisms including phytoplankton, zooplankton and fish also exhibit physiological and ecological responses to varying degrees. Effects propagate from individuals and populations to drive community restructuring, altered food-web interactions, modified biogeochemical cycles and degraded ecosystem services. This paper systematically reviews the formation mechanisms and chemical characteristics of ocean acidification, as well as its impacts on representative marine organisms and ecosystems. Major advances regarding multi-stressor interactions, long-term acclimation and ecosystem-scale prediction are summarized. This work aims to support improved understanding of marine ecosystem responses and ecological risks under global change.

Keywords: ocean acidification, carbonate system, marine organisms

1. Introduction

Since the Industrial Revolution, human activities including fossil-fuel combustion, cement production and land-use change have released massive amounts of carbon dioxide (CO_2) into the atmosphere and rapidly elevated atmospheric CO_2 concentrations. Pre-industrial atmospheric CO_2 persisted at approximately 280 ppm, whereas the annual mean concentration recorded at the Mauna Loa Observatory in Hawaii reached roughly 427 ppm in 2025, representing an increase of over 50 % relative to pre-industrial levels. As an essential component of the global carbon cycle, the ocean has

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DOI: 10.54254/2753-8818/2026.38693

absorbed around 29 % of anthropogenic CO_2 emissions over recent decades. While mitigating atmospheric CO_2 accumulation and global warming, such uptake substantially reshapes the seawater carbonate system. Long-term time-series monitoring data continuously record the decadal decline of key carbonate parameters across open-ocean sites, revealing the persistent signal of human-driven ocean chemistry change [1]. After crossing the air-sea interface, atmospheric CO_2 undergoes sequential chemical equilibria with dissolved CO_2, bicarbonate ions (HCO_3^-) and carbonate ions (CO_3^{2-}) in seawater. These reactions raise hydrogen-ion concentrations, lower seawater pH and reduce carbonate-ion concentrations and calcium-carbonate saturation states. This seawater chemical alteration driven by continuous anthropogenic CO_2 uptake is defined as ocean acidification. Notably, even under future negative-emission scenarios, high-latitude regions such as the Arctic will suffer long-lasting acidification due to ocean carbon-cycle hysteresis [2]. Rather than occurring in isolation, ocean acidification co-occurs with other global-change stressors such as ocean warming and deoxygenation, jointly modifying the physicochemical environments inhabited by marine organisms. Elucidating how ocean acidification influences marine organisms and ecosystems has therefore become a key research priority within global-change ecology and marine science.

Growing understanding of ocean acidification has stimulated extensive studies spanning individual, population and ecosystem levels. Feely et al. [3] demonstrated through global-ocean carbonate-system observations that anthropogenic CO_2 uptake has profoundly altered seawater carbonate chemistry and calcium-carbonate saturation, providing foundational evidence for global-scale ocean-acidification risks. Subsequent laboratory-controlled experiments, long-term field observations and field-based investigations indicate that ocean acidification modulates organismal physiology including growth, feeding, photosynthesis, reproduction and survival by disrupting cellular acid-base homeostasis, energy allocation, ion regulation and calcification. For calcifying taxa such as corals, shellfish and pteropods, reduced carbonate-ion concentrations and calcium-carbonate saturation increase calcification costs and impair shell- or skeleton formation. For instance, Bednaršek et al. [4] reported shell dissolution in pteropods exposed to acidified seawater with adverse consequences for survival. Pronounced inter-species and life-stage-dependent sensitivity further reshapes competition, predation and trophic relationships, altering community composition and food-web architecture. Meta-analysis synthesizing large-scale experimental datasets confirms that biological responses under combined warming-acidification stress are highly taxon-specific and cannot be simply extrapolated from single-factor laboratory results [5]. Numerous domestic studies have focused on coastal taxa including phytoplankton, macroalgae and bivalve mollusks. Research from Gao's group shows that elevated CO_2 modulates photosynthetic physiology and growth of marine primary producers, with responses strongly modulated by co-occurring environmental drivers such as light and temperature [6]. These findings illustrate that biological responses to acidification are not uniformly stimulatory or inhibitory but are jointly shaped by species-specific traits, physiological status and ambient environmental conditions. Natural CO_2 vent field surveys further verify trait-based community filtering: only stress-tolerant species maintain dominance under chronically high-CO_2 seawater [7].

Despite important progress, existing research retains notable limitations. Many laboratory experiments adopt short-term, single-factor high-CO_2 treatments to isolate direct biological effects. Natural marine environments, however, are highly complex; ocean acidification co-occurs with warming, deoxygenation, nutrient shifts and terrestrial pollution. Biological responses measured under single-factor acidification cannot fully represent real-world ecological outcomes. Moreover, short-term exposures predominantly reflect acute physiological plasticity. Multi-generational experiments have demonstrated that compound climate extreme events can trigger lasting

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developmental impairment across generations for marine benthic invertebrates, which short-term assays are unable to capture [8]. Natural populations experiencing chronic ocean acidification may modify their responses via acclimation, transgenerational effects or evolutionary adaptation. Expanding from short-term single-factor experiments toward multi-factor and longer-term exposures is critical for robust projections of future marine ecological risks. Disentangling interactions between ocean acidification and co-occurring stressors together with organismal acclimation and adaptation mechanisms improves mechanistic understanding of marine ecological processes under global change and informs projections of coastal-ecosystem stability and biological-resource dynamics.

2. Formation mechanisms and environmental characteristics of ocean acidification

Ocean acidification essentially reflects re-equilibration of the seawater carbonate system driven by sustained exogenous CO_2 inputs. After entering seawater, some CO_2 remains in dissolved form; some combines with water to form carbonic acid (H_2CO_3), which dissociates into bicarbonate ions (HCO_3^-), carbonate ions (CO_3^{2-}) and hydrogen ions (H^+). Rising dissolved CO_2 shifts chemical equilibria toward bicarbonate production, increasing H^+ concentrations while lowering CO_3^{2-} concentrations. Owing to seawater's substantial buffering capacity, changes are not limited to simple pH reduction but encompass persistent shifts in the distribution of all carbonate-system species. Ocean acidification should therefore be interpreted as comprehensive chemical reorganization of the seawater carbonate system marked by elevated H^+ and depleted CO_3^{2-}.

Multiple seawater chemical parameters change synchronously. Dissolved inorganic carbon (DIC) increases with CO_2 uptake, while total alkalinity (TA) generally remains largely unaffected by CO_2 invasion alone under ideal conditions excluding freshwater inputs, evaporation, calcification and organic-matter transformations. Reduced carbonate-ion concentrations further modify thermodynamic conditions for calcium-carbonate mineral formation. Aragonite saturation state ($\Omega arag$) and calcite saturation state ($\Omega calc$) quantify conditions governing calcium-carbonate stability. When Ω exceeds 1, seawater thermodynamically favors calcium-carbonate preservation. As Ω approaches or drops below 1, conditions become unfavorable for calcium-carbonate deposition and existing calcium-carbonate structures face elevated dissolution risk. Integrating pH, partial pressure of carbon dioxide (pCO_2), DIC, TA, CO_3^{2-} concentrations and saturation states provides a far more complete characterization of ocean-acidification severity than pH measurements alone.

Long-term ocean-monitoring datasets reveal consistent trends among these parameters. At subtropical North Pacific time-series stations, surface-water pH, carbonate-ion concentrations and aragonite saturation states have declined for decades, demonstrating decadal-scale modification of open-ocean carbonate chemistry by anthropogenic CO_2. These changes are not globally uniform; rates and magnitudes are modulated by seawater temperature, salinity, water-mass structure, ocean circulation, biological production and air-gas exchange.

High-latitude oceans are particularly sensitive to ocean acidification. Low temperatures enhance CO_2 solubility in seawater, promoting strong oceanic CO_2 uptake. Furthermore, natural carbonate-ion concentrations and calcium-carbonate saturation states are inherently low in portions of the Arctic and Southern Oceans, meaning these regions readily approach calcium-carbonate undersaturation given equivalent CO_2 increases. Sea-ice melt additionally lowers total alkalinity and buffering capacity via freshwater inputs, amplifying local acidification susceptibility. Although tropical surface waters feature higher temperatures and calcium-carbonate saturation states, tropical coral-reef ecosystems reliant on calcium-carbonate deposition still exhibit clear responses to declining saturation.

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Nearshore and estuarine acidification is more complex and variable relative to open-ocean conditions. Terrestrial runoff, eutrophication, organic-matter loading and water-column stratification substantially alter local carbon cycling. Enhanced primary production follows nutrient inputs to coastal waters; microbial respiration and decomposition of sinking organic matter in bottom waters release CO_2 and consume dissolved oxygen, co-generating low-pH and low-oxygen conditions. In estuaries, freshwater inputs modify salinity and total alkalinity and further weaken seawater buffering. Coastal ocean acidification thus exhibits strong seasonality, short-term variability and spatial heterogeneity, with magnitudes often exceeding long-term open-ocean trends.

In summary, ocean-acidification signals are driven by long-term global anthropogenic CO_2 increases and modulated by local physical, chemical and biogeochemical processes. pH decline constitutes only the most visible symptom. More critical are synchronous shifts in DIC, CO_3^{2-} concentrations and calcium-carbonate saturation states alongside pronounced spatial variability across ocean regions. This continuously changing, heterogenous carbonate-system chemistry forms the direct environmental backdrop for physiological, growth, calcification and ecological responses among marine organisms.

3. Mechanisms underlying marine-organism responses to ocean acidification

Marine organisms display pronounced taxonomic variation in ocean-acidification responses stemming from differences in biomineralization modes, acid-base regulatory capacity, metabolism and life-history strategies. Calcifying organisms including corals, shellfish, pteropods and calcifying algae attract major research attention. Reduced calcium-carbonate saturation under acidification elevates physiological costs for maintaining calcifying-fluid chemistry and constructing shells or skeletons. Some species exhibit lowered calcification rates, abnormal shell textures or reduced mechanical strength. Exposed calcium-carbonate structures face higher dissolution risk under severely undersaturated conditions. Nevertheless, responses are not uniform across calcifying taxa. Certain species sustain biomineralization within tolerance ranges by modifying calcifying-site pH, inorganic-carbon supply and ion transport. Sensitivity is therefore jointly controlled by species-specific traits, nutritional conditions and exposure duration.

Non-calcifying organisms exhibit more diverse response pathways. Some phytoplankton utilize elevated CO_2 as an inorganic-carbon source for photosynthesis and show enhanced growth or photosynthetic efficiency under certain conditions. Responses differ among taxonomic groups owing to divergent carbon-concentrating mechanisms and are modulated by temperature, light and nutrient availability. Zooplankton may experience direct or indirect adverse effects from elevated acid-base regulatory costs and altered food quality, with consequences for feeding, metabolism and reproduction. Fish possess relatively robust body-fluid acid-base regulation, yet chronic high-CO_2 exposure can still disturb ion homeostasis, respiratory metabolism and certain sensory-behavioural traits. Recent studies highlight that fish behavioural responses are strongly context- and species-dependent; generalized claims that ocean acidification inevitably impairs sensory performance are unsupported. Ecological effects of ocean acidification lack universal directional outcomes and arise from interactions between organismal physiology and ambient environments.

Despite taxonomic disparities, maintenance of acid-base homeostasis and energy reallocation represent core physiological strategies employed by many marine animals under acidification. Elevated environmental CO_2 diffuses across gills or body surfaces into bodily fluids and triggers intracellular or extracellular acid-base disturbances. Organisms compensate via hydrogen-ion excretion, bicarbonate accumulation and ion-exchange processes involving sodium (Na^+) and chloride (Cl^-) to preserve cellular and tissue function. Such active regulatory processes consume

DOI: 10.54254/2753-8818/2026.38693

extra metabolic energy and reshape individual energy budgets. When stress persists or exceeds regulatory capacity, energy allocated toward growth, immunity, reproduction and tissue repair may decline, altering metabolic performance and stress resistance. Increased reactive-oxygen-species production, modified antioxidant enzyme activity and shifts in gene expression are observed in some taxa, though oxidative stress is not a universal outcome; its magnitude depends on exposure intensity, duration and co-occurring environmental conditions.

Life-history stage is another key determinant of acidification sensitivity. Many marine-invertebrate embryos and larvae feature rapid growth but incompletely developed acid-base regulatory systems and limited energy reserves, rendering them generally more vulnerable than adults. For example, larval bivalves may suffer calcification deficits, reduced shell size or developmental delays during early shell formation. Coral-larval development, settlement and early skeletal growth can also be impaired. However, effects on gamete quality, fertilization and embryonic development are highly species-specific and not universally negative. Intraspecific variation in tolerance among populations and parental lineages indicates that phenotypic plasticity, transgenerational effects and genetic variation contribute to long-term adaptation to ocean acidification.

In natural ecosystems, biological responses are strongly modulated by additional co-occurring stressors. Combined exposures to warming, deoxygenation, food limitation and contaminants produce additive, synergistic or antagonistic outcomes that cannot be predicted by simple linear summation of individual-stressor effects. Warming elevates metabolic demands; combined with energy costs for acid-base regulation, this can further constrain energy available for growth and reproduction. Hypoxia limits aerobic metabolic capacity and complicates internal-homeostasis maintenance for some species. By contrast, sufficient food supply can offset extra energetic costs imposed by acidification and improve organismal tolerance. Individual-level outcomes under ocean acidification ultimately depend on physiological regulatory capacity, resource availability and multiple interacting environmental drivers. Differences in species-specific sensitivity propagate via recruitment dynamics, competition and predation from individuals toward populations, communities and food webs, ultimately reshaping ecosystem structure and function. Assessing ecological risks of ocean acidification therefore requires multi-species, multi-stressor and multi-trophic-level assessments extending beyond isolated physiological metrics.

4. Ecosystem-scale impacts of ocean acidification

Differential species-specific responses to ocean acidification propagate from individuals and populations to reshape community composition and ecosystem function. Shifts in species tolerance, competitive ability and resource utilization redistribute ecological niches and drive community reorganization. Coral-reef ecosystems represent one high-risk example. Sustained net calcification by reef-building corals and other calcifying reef taxa underpins coral-reef formation and persistence. Progressive ocean acidification reduces reef-construction potential and enhances chemical dissolution of carbonate structures. When reef-accretion rates approach or fall below physical and biological erosion rates, reefs transition toward net erosion. Complex three-dimensional reef architecture provides critical habitat, breeding grounds and predation refuges for diverse fishes and benthic invertebrates. Structural simplification reduces habitat heterogeneity and lowers regional species richness and community stability. It should be emphasized that coral-reef degradation is rarely driven by ocean acidification alone; it arises from combined pressures including ocean warming, marine heatwaves and local-scale anthropogenic stressors, with high temperature representing the primary direct driver of mass coral bleaching events.

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Community-composition shifts propagate across trophic levels through predation, competition and trophic transfer. Marine ecosystems do not operate as simple linear food chains, so ocean-acidification effects do not amplify uniformly along trophic gradients. Instead, complex food-web cascades emerge. Shifts in phytoplankton community composition, cell size or nutritional quality modify food quantity and quality available for zooplankton. Altered zooplankton communities in turn influence larval fish, cephalopods and higher-trophic-level consumers. Disparate sensitivities between predators and prey can reshape existing competitive and predator-prey interactions whenever population sizes or functional traits change for any interacting partner. Final ecosystem-level outcomes reflect combined biological responses and species interactions rather than simple summation of individual-species effects.

Beyond food-web restructuring, ocean acidification modifies material cycling and energy flow within ecosystems. Modified phytoplankton community composition alters the quantity, particle size and sinking characteristics of organic material produced via primary production, modifying organic-carbon export toward the deep ocean. Changes in abundance and calcification intensity among calcifying plankton and benthic calcifiers further influence the marine carbonate pump and particle-sinking dynamics. Owing to complex couplings among the organic-carbon pump, carbonate pump and microbial cycling, ocean-acidification impacts on marine carbon cycling lack simple universal trends and vary with biological-community composition and regional environmental backgrounds. Community shifts also alter regeneration and cycling of macronutrients including nitrogen and phosphorus, extending ocean-acidification influences to broader marine biogeochemical processes.

These internal ecosystem modifications ultimately alter marine ecosystem services delivered to human societies. Coral reefs sustain high biodiversity and provide fish nurseries, support fisheries and serve as natural coastal-defense barriers. Reef degradation weakens wave-energy dissipation and coastal-protection capacity. Biogenic habitats such as oyster and mussel reefs deliver important functions including water filtration, nutrient regulation and habitat provision. Their long-term degradation reduces coastal-water purification capacity and negatively impacts shell-fishery and aquaculture industries. For coastal societies reliant on marine biological resources, community reorganization and population shifts triggered by ocean acidification may reduce fishery yields and disrupt associated economic activities.

At the ecosystem scale, ocean-acidification impacts are manifested primarily through community restructuring, modified food-web relationships, altered biogeochemical cycling and degraded ecosystem services. Sensitive populations may decline while tolerant taxa replace them, reshaping community dominance and functional composition. Marked reductions in key foundation or functional species generate effects extending far beyond individual taxa, disturbing habitat structure, resource provision and overall ecosystem stability. Ecological consequences of ocean acidification should therefore be understood as systemic changes arising from interacting biological and environmental processes rather than simple upward amplification of individual-level physiological damage.

5. Conclusions and prospects

Ocean acidification represents an important global-change driver affecting marine organisms and ecosystems, with ecological effects displaying strong species-specificity, environmental dependence and scale-dependence. Despite substantial research progress, critical knowledge gaps remain regarding long-term biological responses, multi-stressor interactions and ecosystem-scale projections. Short-term single-factor laboratory experiments cannot fully reproduce real-world conditions in natural oceans. Future research should prioritize long-term, multi-factor and cross-

DOI: 10.54254/2753-8818/2026.38693

scale integrated investigations combining laboratory-controlled experiments, long-term field observations and ecological-modelling approaches. Special attention should be paid to phenotypic plasticity, transgenerational effects and evolutionary adaptive potential of marine biota. Comparative analyses across different ocean regions and functional groups are required to build comprehensive assessment frameworks linking individual-level responses to population, community and ecosystem-function outcomes. Improved predictive capacity for ocean-acidification-related ecological risks supports marine-biodiversity conservation, fisheries-resource management and marine-ecosystem governance under global change.

References

[1] Caporale, G. M., Gil-Alana, L. A., Carmona-González, J., et al. (2026). Trends and persistence in ocean acidification as measured by station ALOHA. *Frontiers in Marine Science, 13*, 1873334. https://doi.org/10.3389/fmars.2026.1873334.

[2] Terhaar, J., & Frölicher, T. L. (2026). Persistence of Arctic Ocean acidification under negative emissions. *Nature Climate Change, 16*, 448-454. https://doi.org/10.1038/s41558-026-02715-9.

[3] Feely, R. A., Sabine, C. L., Lee, K., et al. (2004). Impact of anthropogenic CO_2 on the $CaCO_3$ system in the oceans. *Science, 305*(5682), 362-366.

[4] Bednaršek, N., Tarling, G. A., Bakker, D. C. E., et al. (2014). Severe dissolution of pteropod shells in the Southern Ocean. *Nature Geoscience, 7*(10), 701-705.

[5] Zhang, Y., Liu, X., Wang, L., et al. (2024). Hidden impacts of ocean warming and acidification on biological responses of marine animals revealed through meta-analysis. *Nature Communications, 15*(1), 2876. https://doi.org/10.1038/s41467-024-47064-3.

[6] Gao, K., Xu, J., Gao, G., et al. (2012). Rising CO_2 and increased light exposure synergistically reduce marine primary productivity. *Nature Climate Change, 2*(7), 519–523.

[7] Gao, K., Xu, J., Wang, Y., et al. (2026). Brown algae as winners: Divergent resilience to high light under acidified conditions shapes macroalgal communities around a carbon dioxide vent. *Limnology and Oceanography*. https://doi.org/10.1002/lno.70435.

[8] Liu, Z., Zhang, B., & Li, Q. (2025). Compound extreme events of ocean acidification and marine heatwave drive transgenerational impairment in Ruditapes philippinarum. *Science of the Total Environment, 913*, 169872. https://doi.org/10.1016/j.scitotenv.2025.169872.