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Assessing the Influence of Ocean Acidification on Calcification Patterns in Non-Coral Marine Invertebrates

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Abstract: Ocean acidification, which consists in the changes in carbonate chemistry of the seawater and in the reduction of calcium carbonate availability, is defined as one of the major challenges facing marine species nowadays. Although the topic of coral calcification received a lot of attention from scientists, it is necessary to conduct the comparative study of how other non-coral marine invertebrates, such as molluscs, echinoderms, crustaceans and bryozoans, respond to the changes in the chemical composition of the seawater. This necessity is associated with the increase in the quantity of the carbon dioxide in the atmosphere and potential consequences for marine biodiversity and the process of the shell and skeleton development in marine organisms. The distinctive feature of the proposed research is the attempt to find the approach to establish the correlation between the seawater carbonate parameters and the species-specific patterns of calcification and organism reactions to it. It implies laboratory exposures, assessment of the physicochemical parameters of seawater, shell and skeletal assessment and comparative biological analysis. The research is focused on the difference in the calcification process in various conditions of acidification. The results expected from this research are to understand better the impact of ocean acidification on the formation and structure of calcium carbonate in marine invertebrates that do not include coral reefs. This research shall bring out the significance of marine invertebrates that are not corals in maintaining the stability of the marine ecosystem. The changes in the organism growth rate, formation of the skeleton, and physiological tolerances due to the changes in the carbonates shall be emphasized. Such information could assist in determining which organisms are more susceptible and resistant to acidification. In addition, the research results shall form an important scientific base for the future monitoring programs for marine ecosystems.

Keywords: Ocean Acidification; Marine Invertebrates; Calcification Patterns; Calcium Carbonate; Seawater Chemistry; Shell Dissolution; Skeletal Development; Marine Biodiversity.

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I. Introduction

Ocean acidification is one of the effects brought about by rising carbon dioxide concentration in the atmosphere, thus changing the composition of the ocean water (Webb et al., 2024; Hošeková et al., 2025). With dissolution of carbon dioxide in the ocean water, chemical reactions occur between the dissolved carbon dioxide and water leading to formation of carbonic acid, which causes high levels of hydrogen ions in the seawater. The change in composition of the seawater causes depletion of carbonate ions in the water, thus affecting the calcifying marine organisms that use calcium carbonate in formation of shells and skeletons (Gómez-Gras et al., 2025; Leung et al., 2022). While corals have been identified as sensitive to ocean acidification, there exist non-corals invertebrates that depend on biomineralization of calcium carbonate (Schubert et al., 2023). The molluscs including oysters, mussels, clams, and snails have protective shells, whereas the echinoderms such as sea urchins and starfishes have calcium carbonate skeletal structures (Xu et al., 2025). The biological reactions to acidification vary because each organism has unique mineral content, physiological control, habitat preference, and tolerance (Whiteley, 2011). For example, while some organisms can regulate their calcification via physiological adaptations, other organisms exhibit reduced mineralization or increased shell dissolution. Temperature, salinity, nutritional sources, and time of exposure may also affect their reactions. The understanding of these differences is essential for predicting the possible consequences of changes in the chemical composition of the seas on their ecology. The current research proposes an integrated approach to evaluating the carbonate and calcification state in non-coral marine invertebrates (Masanja et al., 2024).

Problem Statement

Ocean acidification brings about changes in the chemistry of carbonates in seawater, which leads to lowering of the pH levels, thus affecting the availability of carbonates that can affect the process of calcium carbonate formation in non-coral invertebrates in the ocean. Ocean acidification can lead to different effects in molluscs, echinoderms, crustaceans, and bryozoans, depending on the biomineralization abilities of the organisms. Nevertheless, discrepancies between calcification rate, shell dissolution, skeletal structure, and adaptation of non-coral marine invertebrates are still not sufficiently included in ecological comparisons. Consequently, there is a need for an extensive study of changes in calcification and structural integrity caused by the alterations in the seawater chemistry. In addition, limited long-term experimental data makes prediction of specific response and ecological effects problematic. Thus, systematic comparative studies are crucial for understanding the changes in mineralization, identifying susceptible species, and developing an approach to marine biodiversity protection in continually changing marine environment.

Organization of the Investigation

The initial step of the research is literature review on the ocean acidification, carbonate chemistry, and marine biomineralization. The methodology presents the suggested experimental design, selected organisms, and environment measures. The main part of the assessment focuses on the analysis of calcification and structural changes in non-coral marine invertebrates. Comparative analysis, discussion, future recommendations, and challenges conclude the research. In addition, the study investigates the impact of environmental variability on the biology of organisms belonging to different groups of marine invertebrates. The results will provide information that helps identify species' sensitivity, tolerance, and susceptibility. It will also provide insights into the areas where further research is needed and the methods that should be used in conservation. In addition, it is important to understand the role of chemical changes in seawater as far as the stability of marine ecosystems is concerned. Special emphasis is being laid on different variations of mineral precipitation, shell dissolution, calcification, and physiological effects of the species when exposed to various levels of acidification. The findings from this comparison shall serve as a basis for the identification of differences in biological tolerance of certain selected organisms. Moreover, the importance of continuous monitoring of the environment and advancements in experimental techniques for making correct observations is stressed by the research. The findings from this research shall be helpful in conducting future scientific studies and preservation of biodiversity in the marine environment.

II. Literature Review

Ocean acidification has emerged as a significant topic within marine ecology due to its effect on marine carbonate chemistry and marine biomineralization. Carbon dioxide uptake in the oceans alters the chemical equilibrium of dissolved carbon dioxide, bicarbonate ions, carbonate ions, and hydrogen ions. This process causes a decrease in carbonate ion concentrations, which might affect marine organisms that utilize calcium carbonate to build and retain protective shells or skeletons. In addition, non-coral marine invertebrates vary in terms of their calcification processes and mineral content. For instance, mollusks such as oysters, mussels, clams, and gastropods form their shells mainly from calcium carbonate in the form of aragonite and calcite. Echinoderms, such as sea urchins and starfish, form their skeleton mainly for the purpose of supporting the body and protecting it. Finally, crustaceans have exoskeletons made up of chitin and calcium carbonate. Calcium carbonate shells are produced by some species of Bryozoans. Ecological studies have already established that lower carbonate saturation is responsible for higher energy demands related to the process of calcification and formation of mineral structures. The growth rate of the shell, its density and dissolution, and even abnormalities in development are observed in some species. Yet the reactions vary depending on the species' physiology, type of minerals involved, their life stage, and environment exposure. Some species are capable of regulation of acid-base balance and continued calcification in a somewhat altered environment, while others are more sensitive to these changes. Factors such as temperature, salinity, dissolved oxygen, and food availability additionally affect the reaction of organisms to acidification. This makes it necessary to study calcification in an integrative manner. Comparative experimental work with

different types of invertebrates will help achieve this goal. In addition, knowledge of these biological reactions is vital when it comes to foreseeing any future alterations in marine environments. Decreased calcification may impact the ability of organisms to survive and reproduce; it will impact their habitat and interactions within marine food chains. Acidified water in the long run may impact the population structure and biodiversity. Hence, studying different species of marine invertebrates under laboratory conditions will be helpful in determining their response mechanisms and structures. Such comparative studies will increase ecological knowledge and help formulate proper conservation practices.

Research Limitations and Unexplored Areas

However, while numerous studies have been carried out on ocean acidification effects, there is a need for a comprehensive comparative analysis of calcification in non-coral marine invertebrates, since many investigations focus on one species at once. It should also be noted that it is necessary to study the effect of carbonate saturation along with temperature, salinity, and availability of food for shell formation and skeletal maintenance. Moreover, it is important to consider simultaneously the reduction of mineral deposition and shell dissolution. Such issues outline the necessity to develop an integrative framework considering seawater chemistry, mineral composition, calcification rates, and skeletal integrity.

III. Methodological Framework

Proposed Experimental Architecture

This experimental architecture includes seawater chemistry monitoring, exposure of organisms to acidification, and comparative assessment of calcification process. Chosen non-coral marine invertebrates are kept under controlled conditions with a specific pH and carbonate saturation level. Although water chemistry will be observed in the process of the experiment, growth, deposition, and mineral thickness of skeletal formations are also studied. Biological and physicochemical results are obtained by means of the comparative statistical analysis. Also, it is important to note that there will be control groups with regular sea water used in order to provide standards of comparison. It is possible to make observations several times in order to observe any changes in the composition of minerals, structure, and organism growth. Some other parameters that might be included are the rate of survival, growth, shell mass, bone density, and abnormalities. All of these factors serve as the means of evaluation of the biological effects of the different levels of acidification. The experimental data should be collected regularly in order to observe gradual changes and differences between species. In addition, some environmental factors, such as temperature, salinity, and dissolved oxygen content, should be monitored as well in order to decrease variability of the experiments. It is possible to organize the results of the experiments using statistics in order to find relations between carbonate chemistry and calcification reaction.

Experimental Design and Evaluation Parameters

The experiment employs a comparative experimental design involving a group of marine non-coral invertebrates that are representative.

- Species selection: Species selected are representative organisms such as oysters, mussels, marine snails, sea urchins, crustaceans and bryozoans. These are some of the main considerations that are considered during the process of selecting species.
- Experimental treatments: In this regard, the organisms are subjected to acidified seawater treatments such as the control treatment and other treatments where the pH levels of the seawater are reduced. The actual values of pH and carbonate saturation need to be determined.
- Physico-chemical measurements: The physico-chemical parameters involved include the measurement of seawater pH, temperature, salinity, dissolved inorganic carbon content, total alkalinity and carbonate saturation state.
- Calcification measurements: Shell growth, shell mass, skeletal mineralization, thickness and structural integrity are measured.

- Biological measurements: These include measurements such as growth rate, survival and physiological response to the changes.
- Statistical analysis: Analysis of variance, correlation analysis and regression modeling are utilized.

Research Workflow Architecture

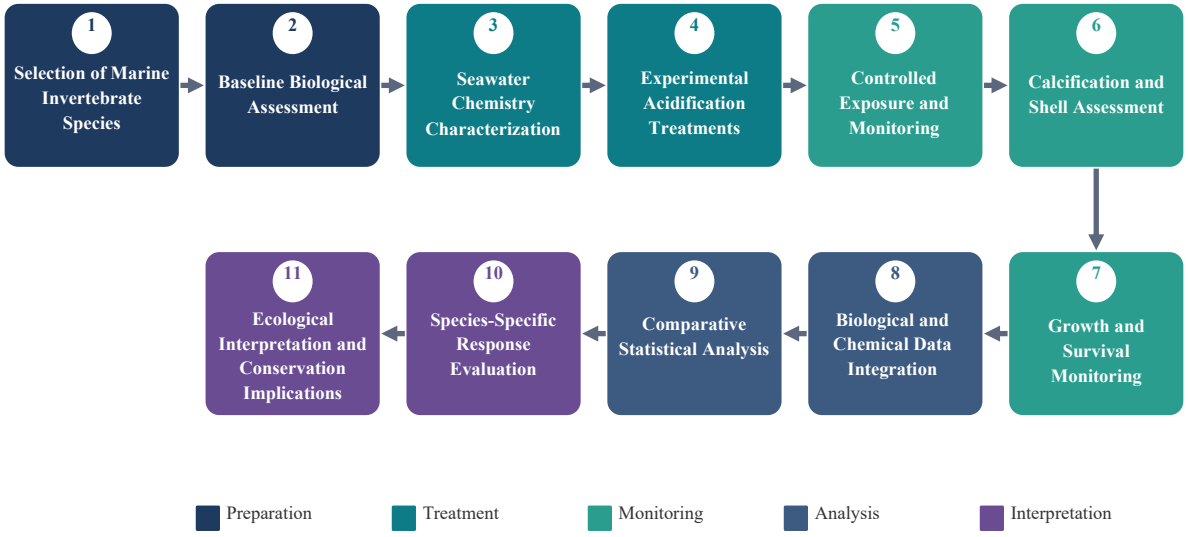


Figure 1: Experimental Workflow for Evaluating Ocean Acidification Effects on Non-Coral Marine Invertebrates

The Figure 1 starts by choosing marine invertebrates from the non-coral group for testing and carrying out the biological characterization. The seawater chemistry is assessed, determining the carbonate system before performing acidification experiments. Organisms are exposed to treatments with simultaneous monitoring of parameters such as calcification, shell traits, growth, and mortality. Both biological and chemical data sets are combined and analyzed using comparison-based statistics to determine the response of each organism. The results are then explained ecologically, demonstrating vulnerability trends.

IV. Calcification Responses and Environmental Mechanisms

Changes in Calcium Carbonate Formation and Structural Development

Precipitation of calcium carbonate is an important biological process amongst several others involving non-coral marine invertebrates. The molluscs develop shells that act as a defense against any predators. Typically, the mollusc shells consist of either aragonite or calcite. The minerals differ by their chemical stability in the changing conditions of seawater. Ocean acidification makes carbonate ions less available and lowers the saturation states of the minerals involved, making the formation of the shell costlier in terms of energy. Echinoderms, such as sea urchins and starfish, build up internal or external skeletal system, which includes calcium carbonate. The development of the echinoderms' skeleton depends on the controlled mineralization and physiology. The limited carbonate availability may hinder the larval skeletal formation, growth, and maintenance of the structure. Crustaceans have exoskeletons of chitin and calcium carbonate. Ocean acidification can affect the process of mineralization and exoskeleton maintenance and the physiology of molting process. However, the extent of the impact varies between different species because of the mineralization process peculiarities in the crustaceans. Bryozoans also take part in the creation of marine carbonate skeletons through formation of mineralized skeletons. Aside from the formation of mineral deposits, there is shell dissolution. If there is a reduction in the saturation state of the water with regard to calcium carbonate, then the minerals may become susceptible to dissolution. Structural changes, thus, could be a result of decreased calcification, dissolution, or both. It is essential to determine the impact of each factor separately on structural development. Formation of calcium carbonate is critical for the

strength of the structure of marine invertebrates. There are differences among various species in their mineral contents, rate of calcification, and development of skeleton. The lack of carbonates due to ocean acidification increases the energy cost of mineralization and leads to the dissolution of shells. It may impact the protection function, development and even survival of these organisms. So, it is crucial to understand the equilibrium between mineralization and dissolution processes. Furthermore, variation in the skeletal composition can play an important role in the resistance of marine invertebrates to the acidified water environment. Depending on the mineral content organisms may respond differently by increasing the thickness of the shell, the skeleton strength and mineral production. This can have an impact on the protection system, mobility, feeding, and reproduction. Thanks to the examination of these variations in structure via microscopic and imaging techniques, those can get information about the mineral concentration and the decay of the skeleton. Thus, it will be possible to understand what organisms are endangered by ocean acidification.

Species Sensitivity and Biological Adaptation Under Acidification

Variations in reactions of marine invertebrates to acidification of oceans can be attributed to physiological factors, habitats, minerals used, and regulatory biology. For instance, some mollusks respond to elevated carbon dioxide levels by reducing shell formation and increasing shell dissolution whereas others have shown partial resistance through physiological adaptation. In the case of echinoderms, acidification affects larvae, skeleton formation, and the way metabolic energy is utilized. The lack of carbonate ions makes the effort for internal chemical regulation and skeleton formation difficult. Reactions from crustaceans depend on the composition of the exoskeleton, frequency of molting, and acid-base balance. Some species can balance their reactions to the changes in chemistry in the external environment while other species may face an increased need for energy or mineral precipitation. In case of bryozoans, the reaction also depends on the characteristics of the species and exposure to the environment. Biological adaptation involves alteration of ion regulation, metabolism, formation of organic matrix of shells, and behavior. Yet, physiological adaptation within a short period of time does not necessarily imply evolutionary adaptation. The availability of food, temperature, salinity, and other habitat conditions can either aggravate or mitigate the consequences of acidification. Different marine invertebrates show varying sensitivities to ocean acidification due to different physiological processes, environmental factors, and mineral structures. While some species have physiological systems that control the pH balance within them and produce minerals, others have slower rates of growth and suffer from physiological stresses. Adaptation in this case may be through metabolic, ion regulation, and energy allocation processes. These, however, vary between different species and developmental stages. The study of these variations is important in determining vulnerable marine life and the impacts of ocean acidification. Moreover, variations in the genetic makeup of organisms and prior environmental exposure may affect the ability of marine invertebrates to withstand changes in the environment of seawater. Organisms subjected to varying environmental factors may adapt physiologically in order to enhance their tolerance in the short term. But prolonged acidification may lead to increased metabolism and reduced energy for growth and reproduction among others. It is only through studying the reaction of organisms through several generations that it is possible to know whether it is adaptation or mere acclimatization.

Comparative Evaluation of Calcification Responses

Table 1 represents comparative study of various types of marine invertebrates, which are not corals, considering their mineral content in the body and their possible responses to changes in the chemical composition of sea water. The table provides several biological features, which can be useful to measure the effectiveness of calcification process. It should be emphasized that acidification will affect these species differently because of their different minerals, physiology, and construction.

Table 1: Non-Coral Marine Invertebrate Groups and Potential Calcification Responses to Ocean Acidification

Marine organism group	**Mineralized structure**	**Potential acidification response**	**Important assessment**
Molluscs	Aragonite/calcite shells	Reduced shell growth and dissolution	Shell thickness and mass
Echinoderms	Calcium carbonate skeleton	Altered skeletal development	Skeletal density and growth
Crustaceans	Chitin-mineral exoskeleton	Changes in mineralization and molting	Exoskeleton composition
Bryozoans	Calcified protective structures	Reduced skeletal deposition	Mineral density and colony growth
Gastropods	Calcium carbonate shells	Increased vulnerability to dissolution	Shell integrity and extension

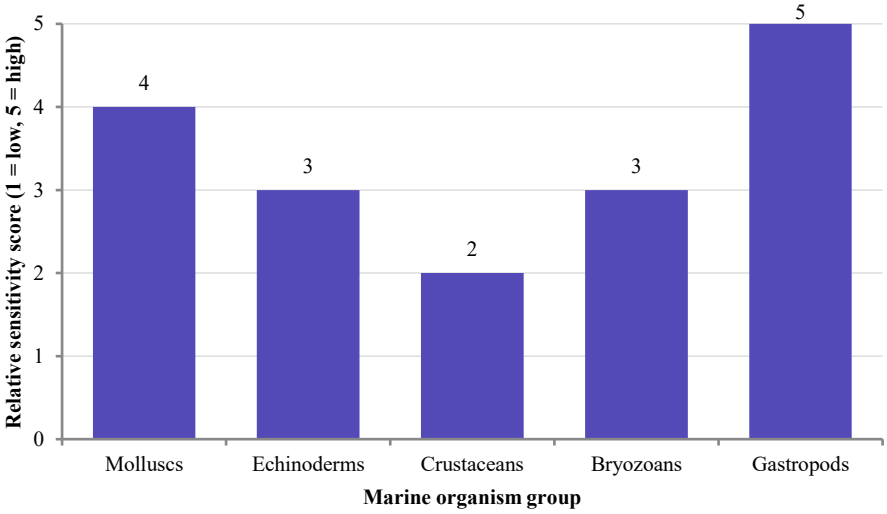


Figure 2: Relative Sensitivity of Calcification to Ocean Acidification in Non-Coral Marine Invertebrates

Figure 2 highlights the degree of sensitivity of calcification in five non-coral invertebrate species of the sea towards acidification. The gastropods are the most sensitive owing to dissolution of their shells while the molluscs have low shell formation rates. The echinoderms and bryozoa are moderately sensitive because of skeletal formation and mineral deposition respectively. Crustaceans are relatively the least sensitive since they have changes in mineralization and molting only.

V. Discussion

The study will help in understanding how the carbonate chemistry of seawater controls the process of calcification in marine invertebrates that do not belong to coral reef (Semmler et al., 2025; Cornwall et al., 2021). Decreased carbonate supply can affect the process of calcification, formation of the shell, the condition of the skeleton, as well as physiological costs. But depending on the type of the organism, minerals used, as well as tolerance, this effect can be manifested to various extents. Comparative approach will consider mollusks, echinoderms, crustaceans, and bryozoans as a basis for making connections on an ecological level. The given chart shows one of the ways how comparison of calcification efficiency can be done. Moreover, the results from comparative analysis have revealed that it is necessary to take into account specific biological features of particular organisms when discussing the effects of ocean acidification. The molluscs might suffer from thin shells and enhanced erosion, while the echinoderms would demonstrate

development problems and alterations in the skeleton formation process. The crustaceans will find it difficult to maintain exoskeleton mineralization during their molting stage, while the bryozoans would show changes in their skeleton development and structure. It is obvious that there are no similar effects of ocean acidification on different marine invertebrates. Thus, the environmental factors, such as temperature, salinity, and oxygen content, will also be taken into account.

Future Research Directions

Further investigation should focus on the long-term effects of acidification on various species of marine invertebrates in diverse geographic regions and developmental phases. It is essential to take into account several stressors, including elevated water temperatures, changing salinities, and low oxygen concentrations. New techniques with the use of imaging and micro-computed tomography will help to evaluate the robustness of the shells, skeletal density, and structure. Further molecular analysis will allow establishing the physiological processes underlying the resilience of invertebrates to acidification. Multi-generation experiments should be conducted in order to distinguish between acclimation and adaptation to the stressor. In addition to the abovementioned recommendations for the future research on the topic, it will be useful to extend the scope of experiments to include both real-life observation and mesocosm experiments, which would better simulate the reality of environmental change. Standardization of experiment procedures and data banks where all the collected information will be stored in a readily available form will assist in comparison and synthesis of the data gathered by other scientists concerning species-specific responses. Modeling future scenarios based on carbonate chemistry, physiology, and population dynamics will help predict changes in the communities of invertebrates in connection with further emissions.

Experimental Limitations and Environmental Challenges

Assessment of the effects of ocean acidification is associated with numerous difficulties. First, continuous maintenance of a stable value of pH and carbonate chemistry of the sea water in an experiment is needed. Differences in physiological properties of organisms used, their stage in the life cycle, as well as their mineral composition are some of the factors that make the comparison complex. Moreover, it is impossible to create natural marine conditions in an experiment, since there are multiple factors influencing each other in nature. Shell thickness, formation and dissolution have to be determined precisely. Lack of long-term biological studies may not allow drawing conclusions on adaptation. Researching conditions, including lack of financial means and access to advanced equipment, may influence the result of an experiment. Different seawater composition, exposure period, and other environmental conditions may lead to inconsistent results. Thus, it is also quite difficult to separate the direct effect of acidification from indirect one through interactions in an ecosystem.

VI. Conclusion

The main objective of this study is to estimate the effects of ocean acidification on calcification process in marine invertebrates excluding corals and investigate possible consequences for the shell and skeleton formation and general ecological equilibrium. The novelty of this study lies in the attempt to develop a comparative theoretical framework which will unite carbonate chemistry of seawater, mineralization, properties of structure and biological reactions of different types of marine invertebrates. Research methodology will be based on controlled experiments with acidification, physicochemical analysis of seawater parameters, evaluation of shells and skeletons, biological observations and comparative statistics. Different kinds of mollusks, echinoderms, crustaceans, and bryozoans will be chosen as categories of marine invertebrates to compare calcification process and sensitivity to environmental factors. Such an experimental approach establishes a direct connection between seawater parameters and biological reactions. Conceptual analysis shows that decreasing of carbonate ions concentration may make the formation of calcium carbonate and its structure harder. The biological responses could be reduced shell growth, changes in skeleton formation, greater dissolution of minerals and physiological energy needs. The

criteria for evaluation are indicated in comparative table; the sample of graphical assessment of calcification is shown. These patterns are research predictions and not the experimental results. The predicted result will be increased understanding of species-specific calcium carbonate formation and the necessity of proper marine carbonate chemistry for the ecology. Further research using prolonged exposures, modern mineralogy techniques and multi-generational observations will contribute to increased validity of these predictions. Overall, it is necessary to learn the vulnerability and adaptability of non-coral marine invertebrates.

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