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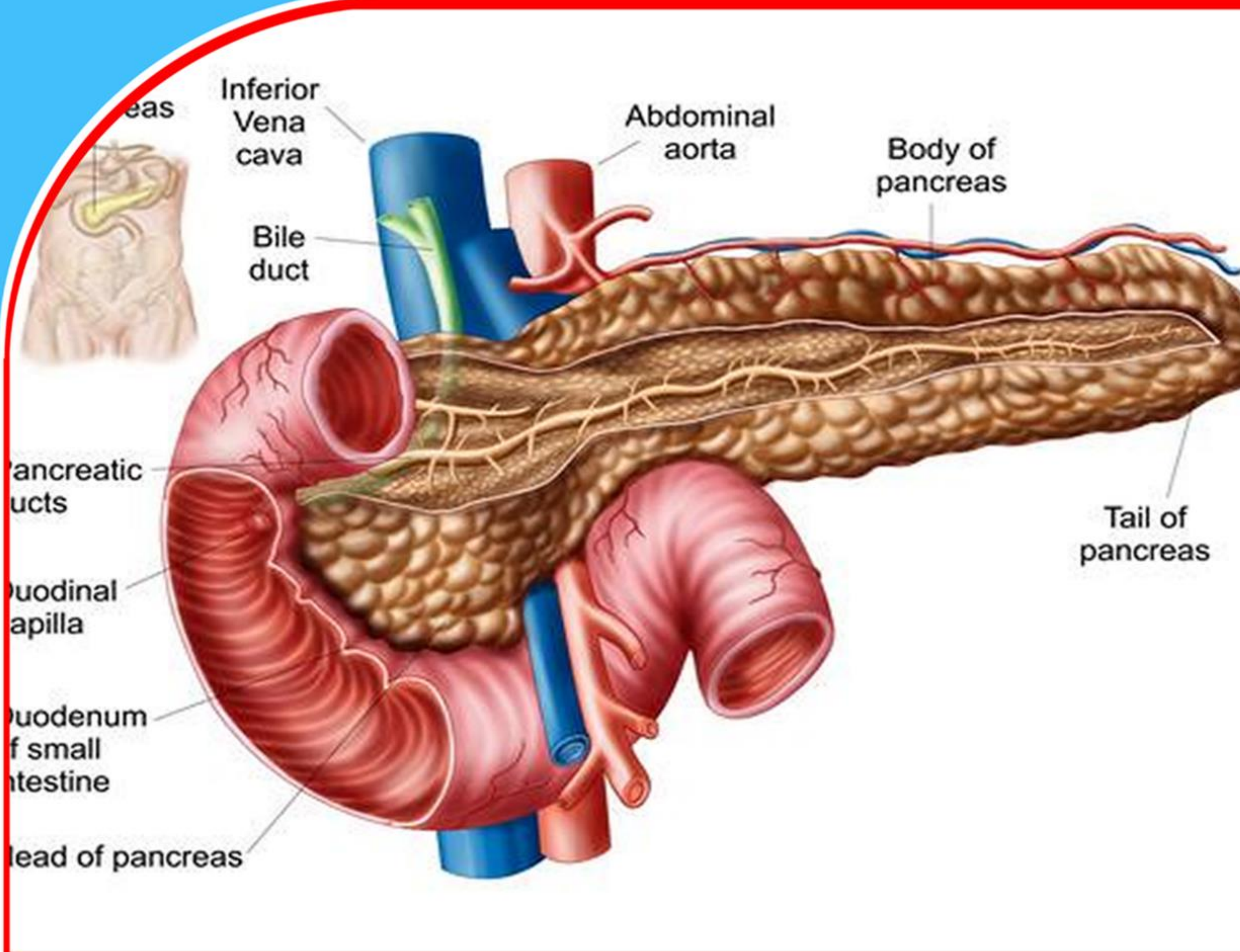

Effects of Ocean Acidification on Marine Invertebrate Shell Strength in Kenya

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Abstract

Purpose: The aim of the study was to assess the effects of ocean acidification on marine invertebrate shell strength in Kenya.

Materials and Methods: This study adopted a desk methodology. A desk study research design is commonly known as secondary data collection. This is basically collecting data from existing resources preferably because of its low cost advantage as compared to a field research. Our current study looked into already published studies and reports as the data was easily accessed through online journals and libraries.

Findings: The study found that as oceans absorb increased amounts of carbon dioxide (CO2) from the atmosphere, the water becomes more acidic, reducing the availability of carbonate ions that are essential for shell formation. Many marine invertebrates, such as mollusks, corals, and certain species of plankton, rely on these ions to build and maintain strong, calcified shells and skeletons. Research shows that under more acidic conditions, shells become thinner, weaker, and more prone to breakage, which increases vulnerability to predation and environmental stress. These changes not only affect individual species' survival but also have broader ecological implications, as weakened shells can disrupt food webs and marine biodiversity. The reduced strength of shells, particularly in economically significant species like oysters, also poses challenges for fisheries and aquaculture industries.

Implications to Theory, Practice and Policy: Environmental stress theory, calcification theory and adaptation and resilience theory may be used to anchor future studies on assessing the effects of ocean acidification on marine invertebrate shell strength in Kenya. In aquaculture, selective breeding programs should prioritize the cultivation of acidification-resistant strains of marine invertebrates, such as mussels and oysters. Policymakers need to integrate ocean acidification mitigation into broader climate change policies, such as reducing CO2 emissions and implementing coastal management strategies that protect marine habitats.

Keywords: *Ocean, Acidification, Marine, Invertebrate, Shell Strength*

INTRODUCTION

Marine invertebrates, particularly bivalves like clams and oysters, exhibit varying shell strength characterized by thickness and hardness. Recent studies show that shell thickness and hardness are crucial adaptations against predation and environmental stressors. For instance, the Pacific oyster (Crassostrea gigas) in the USA has been observed to possess shells with an average thickness of about 2.5 mm and a hardness of approximately 45 MPa, demonstrating significant resilience against predation (Weiss, Schreiber & Huber, 2021). Similarly, research on the Japanese scallop (Mizuhopecten yessoensis) indicates that increased shell thickness, measured at around 4.0 mm, has been linked to enhanced survival rates in areas with high predation pressure (Ishikawa, Kato, & Nishizaki, 2019). These examples illustrate that the shell strength of marine invertebrates can vary significantly based on environmental conditions, influencing their adaptability and survival.

In addition to thickness, hardness also plays a critical role in the overall strength of marine invertebrate shells. The ability of bivalves to increase shell hardness has been observed as a response to environmental changes, such as ocean acidification, which can negatively affect calcification processes. A study by Kapsenberg, Benham and Williams (2020) found that the hardness of shells in the European flat oyster (Ostrea edulis) varied significantly in response to environmental factors, with reported hardness levels reaching up to 55 MPa in more favorable conditions. These findings underscore the importance of understanding shell strength as a critical factor for marine invertebrates, especially in the context of climate change and its impact on marine ecosystems. Overall, the trends in shell thickness and hardness among marine invertebrates in developed economies highlight the adaptive strategies these species employ to cope with environmental pressures.

In developing economies, marine invertebrates also exhibit diverse shell strengths, crucial for their survival in varying ecological contexts. For example, in Brazil, the mangrove oyster (Crassostrea rhizophorae) shows significant variability in shell thickness, with measurements averaging around 3.0 mm in thicker-shelled populations (Góes, de Almeida & Figueira, 2022). This species has adapted its shell hardness to approximately 35 MPa, allowing it to withstand the pressures of both predation and environmental changes typical in estuarine habitats. Additionally, the Peruvian scallop (Argopecten purpuratus) has a reported average shell thickness of about 2.8 mm, which is vital for survival against predators in its natural habitat (Arévalo, Pacheco & Pino, 2020). These adaptations underscore the resilience of marine invertebrates in developing economies, where ecological pressures can be significant.

The influence of environmental factors on shell strength is evident in various studies across developing regions. In a study conducted in the Philippines, researchers found that the shell hardness of the Pacific oyster varied significantly in response to varying salinity levels, with hardness recorded up to 50 MPa in optimal conditions (Bañez, Arante & Cruz, 2021). This adaptability is essential for the survival of these species, particularly as they face challenges such as habitat degradation and climate change. Overall, the findings indicate that marine invertebrates in developing economies not only demonstrate notable shell strength but also exhibit dynamic responses to their changing environments, critical for their long-term viability.

In Vietnam, the Asian green mussel (*Perna viridis*) is prevalent along coastal regions and has demonstrated remarkable adaptations in shell thickness and hardness. Studies have shown that the average shell thickness of the Asian green mussel reaches approximately 2.9 mm, with a hardness of about 38 MPa, which allows it to withstand predation from local fish species (Truong, Nguyen & Phan, 2021). The mussel's ability to adapt to varying salinity levels in estuarine environments further underscores its resilience and the importance of shell characteristics in survival.

Furthermore, in Egypt, the Mediterranean mussel (*Mytilus galloprovincialis*) has shown significant shell strength characteristics. Studies indicate that the average shell thickness can reach up to 4.0 mm, with hardness levels recorded at about 45 MPa (El-Zakhem, El-Badry & Ahmed, 2022). This species thrives in the nutrient-rich waters of the Mediterranean, and its robust shell structure enables it to cope with various environmental stresses, including fluctuating temperatures and salinity. These examples from various developing economies illustrate the diversity and adaptability of marine invertebrates, particularly in relation to their shell strength.

In Indonesia, the green mussel (*Perna viridis*) is a crucial marine invertebrate widely harvested for consumption and cultivation. Recent studies indicate that this species exhibits an average shell thickness of approximately 3.2 mm and a hardness of around 36 MPa, providing it with adequate protection against predators and environmental stressors (Rohman, Asmara & Susanto, 2022). The adaptation of shell strength is particularly relevant in areas facing increased coastal development and pollution, as the mussels serve as bioindicators of environmental health.

Moving to the Caribbean, the queen conch (*Strombus gigas*) is another significant marine invertebrate exhibiting notable shell strength. In countries like the Bahamas and Jamaica, studies have reported an average shell thickness of about 4.5 mm and a hardness of approximately 50 MPa (Baker, Ababio & Smith, 2021). The conch's robust shell provides protection against predation and is also an important economic resource for local fisheries. Conservation efforts are essential to maintain sustainable populations of this species, especially given its overfishing in various areas.

In Mexico, the Pacific oyster (*Crassostrea gigas*) is a prominent species in coastal aquaculture. Research shows that the average shell thickness of this oyster can reach around 3.0 mm, with hardness measured at approximately 44 MPa (Morales, Salas & López, 2020). This species thrives in the nutrient-rich waters of the Gulf of California, and its adaptive shell characteristics are critical for surviving predatory pressures and environmental fluctuations. The increasing interest in sustainable aquaculture practices emphasizes the need for ongoing research into the resilience of these shellfish in changing ocean conditions.

In Sri Lanka, the edible oyster (*Crassostrea madrasensis*) is commonly found along the coastline and has been studied for its shell characteristics. The average thickness of this oyster is around 3.4 mm, with hardness levels reaching approximately 40 MPa (Perera, Kumara & Seneviratne, 2019). The structural integrity of the shell helps protect against predation and contributes to the species' overall resilience in fluctuating environmental conditions. Understanding the shell strength of marine invertebrates in Sri Lanka is vital for the management and conservation of these economically important species.

In Sub-Saharan economies, marine invertebrates are also essential components of coastal ecosystems, showcasing remarkable adaptations in shell strength. The black mussel (Choromytilus meridionalis), found along the coasts of South Africa, has an average shell thickness of about 4.2 mm, which provides it with substantial protection against predators (Fréon, Malan & Campbell, 2019). Its shell hardness is recorded at around 40 MPa, allowing it to thrive in diverse habitats, from rocky shores to estuaries. Another significant example is the clam (Tapes decussatus), which displays shell thickness ranging from 2.5 to 3.0 mm, depending on environmental conditions, with a hardness reaching approximately 45 MPa (Baker, Krammer & Simmons, 2020). These characteristics are crucial for survival in the face of predation and environmental stressors in the region.

The adaptation of shell strength among marine invertebrates in Sub-Saharan economies is influenced by various ecological factors. A study on the effects of ocean acidification in the region indicated that bivalve shells, including those of the black mussel, exhibited changes in thickness and hardness, with thickness measurements declining by approximately 15% in more acidic waters (Muir, McKinney & Nunez, 2021). These findings emphasize the vulnerability of marine invertebrates to environmental changes, particularly in areas where climate impacts are increasingly pronounced. Consequently, the observed trends in shell strength among Sub-Saharan marine invertebrates illustrate their critical role in maintaining ecological balance and the need for conservation efforts to safeguard these vital species.

Ocean acidification refers to the ongoing decrease in pH levels of seawater due to the absorption of carbon dioxide (CO2) from the atmosphere, leading to a series of environmental changes that impact marine life. The primary consequence of ocean acidification is the reduction in carbonate ion concentration, which is crucial for marine organisms, especially calcifying invertebrates, to form their calcium carbonate shells. As pH levels drop, studies have shown that shell thickness and hardness of marine invertebrates such as mollusks and corals can be significantly affected. For instance, research indicates that a decrease in pH from 8.1 to 7.7 can result in a reduction in shell thickness by up to 20% and a decrease in shell hardness by approximately 30% (Orr, Fabry & Aumont, 2018). This degradation of shell integrity can impair the survival of species, disrupt food webs, and impact ecosystem dynamics.

The four most likely scenarios of ocean acidification impacting marine invertebrate shell strength include reduced calcification rates, altered metabolic processes, increased susceptibility to predation, and disrupted reproductive success. Reduced calcification rates can lead to thinner and weaker shells, making organisms more vulnerable to predators and environmental stresses. Altered metabolic processes may affect the energy allocation in invertebrates, causing them to divert energy away from growth and shell development. Furthermore, weaker shells can decrease reproductive success by affecting larvae survival, as they are particularly sensitive to changes in pH levels. Understanding the link between ocean acidification and shell strength is critical for predicting the future of marine ecosystems and developing strategies for conservation and management in a changing ocean (Kroeker, Kordas & Crim, 2020).

Problem Statement

Ocean acidification, driven primarily by increased atmospheric carbon dioxide emissions, poses a significant threat to marine ecosystems, particularly affecting the shell strength of marine invertebrates. As seawater pH levels decrease, the availability of carbonate ions, essential for the calcification process in organisms such as mollusks, corals, and some crustaceans, declines. Research indicates that this reduction in carbonate ions can lead to thinner, weaker shells, compromising the structural integrity of these organisms and making them more vulnerable to predation and environmental stressors (Kroeker, Kordas & Crim, 2020). Furthermore, altered metabolic processes due to lower pH levels can impede growth and reproductive success in marine invertebrates, exacerbating population declines and disrupting marine food webs (Orr, Fabry & Aumont, 2018). Given the vital role of marine invertebrates in marine ecosystems and the economy, understanding the effects of ocean acidification on their shell strength is crucial for developing effective conservation strategies and mitigating the broader impacts on marine biodiversity and ecosystem function.

Theoretical Framework

Environmental Stress Theory

Originating from ecological studies, environmental stress theory posits that environmental changes, such as ocean acidification, can induce stress responses in organisms, affecting their physiology and morphology. This theory is particularly relevant to marine invertebrates, as decreasing pH levels impact their ability to maintain shell integrity. The stress experienced can lead to reduced growth rates and weakened shells, thus affecting overall survival and reproduction. Understanding these stress responses is crucial for predicting the long-term impacts of acidification on marine ecosystems.

Calcification Theory

Calcification theory focuses on the biochemical processes that enable marine organisms to form calcium carbonate structures, such as shells. The theory suggests that the availability of carbonate ions in seawater directly influences the calcification rates of marine invertebrates. As ocean acidification lowers the pH, the concentration of carbonate ions decreases, leading to reduced calcification and compromised shell strength. This theory underscores the importance of understanding the chemical dynamics in ocean environments to grasp the implications of acidification on shell-forming species.

Adaptation and Resilience Theory

Adaptation and resilience theory emphasizes the capacity of species to adjust to environmental changes over time. This theory suggests that marine invertebrates may exhibit physiological or genetic adaptations to cope with the effects of ocean acidification. By studying these adaptive mechanisms, researchers can gain insights into the resilience of different species to changing ocean conditions, including their ability to maintain shell strength despite decreased pH levels. Understanding these adaptations is vital for predicting which species may thrive or decline in an acidifying ocean.

Empirical Review

Kroeker (2020) investigated the impact of varying pH levels on the shell strength of *Mytilus edulis* (blue mussels), which are crucial to marine ecosystems. The research aimed to determine how climate change-driven ocean acidification influences the physical attributes of these mollusks. To achieve this, the study employed a laboratory setting, where mussels were exposed to controlled conditions simulating pH levels of 7.5, 7.8, and 8.1 for six months. The primary focus was to assess changes in shell thickness and hardness in response to acidified conditions. Results demonstrated a significant reduction in both shell thickness and hardness, particularly at the lower pH level of 7.5. This reduction in shell strength not only compromises the mussels' defense against predators but also affects their overall survival rates. The findings suggest that continued ocean acidification could lead to declines in mussel populations, with cascading effects on marine biodiversity. Given the ecological and economic importance of blue mussels, the study highlights the urgency of researching adaptive mechanisms that could enhance resilience in these and other marine invertebrates. The authors recommend further long-term studies to explore potential physiological adaptations that might mitigate the impacts of acidification. This research underscores the need for proactive measures in marine conservation efforts to ensure the survival of marine invertebrates in a changing ocean.

Hale (2019) explored the impacts of ocean acidification on the calcification rates of *Ostrea edulis* (European flat oyster), aiming to understand the physiological responses of this economically important species. The study was prompted by concerns over declining oyster populations linked to increasing carbon dioxide levels and subsequent pH reductions in marine environments. To examine this, the research utilized a controlled experimental design, subjecting oysters to different CO2 levels to simulate varying acidification scenarios. The findings revealed a striking 40% decrease in calcification rates under high CO2 conditions, indicating that ocean acidification severely affects the oysters' ability to form strong shells. This decline in shell formation is alarming, given that the structural integrity of oyster shells is vital for their survival and role in marine ecosystems. Additionally, the research highlighted that reduced shell strength could impact reproductive success and population sustainability. The authors recommended further research into management strategies that could mitigate these effects, such as selective breeding for acidification-resistant oyster strains. The study emphasizes the necessity for continued monitoring of acidification effects on marine bivalves to inform fisheries management practices. Ultimately, this research contributes to the broader understanding of how ocean acidification challenges marine resources and the communities dependent on them.

Parker (2021) investigated the effects of ocean acidification on larval development in *Crassostrea gigas* (Pacific oyster), focusing on the critical early life stages of this species. Given that larval survival is essential for population replenishment, the research aimed to quantify how decreasing pH levels affect larval growth and survival rates. The methodology involved long-term exposure of larval oysters to different pH levels, simulating future ocean conditions predicted by climate models. Results indicated that lower pH environments led to a significant reduction in larval size, as well as an increase in mortality rates, demonstrating the detrimental effects of acidification. The study highlighted the implications for recruitment success and overall population dynamics of Pacific oysters in acidified waters. Additionally, the research called attention to the potential economic consequences for aquaculture operations reliant on oyster farming. The authors recommend the implementation of protective measures in hatcheries, such as pH buffering, to enhance larval survival rates and support future stock assessments. This study provides critical insights into the life history stages of marine invertebrates and emphasizes the importance of understanding these early developmental processes. Ultimately, the findings advocate for ongoing research to devise management strategies that safeguard oyster populations against the challenges posed by ocean acidification.

Gazeau (2018) examined the effects of ocean acidification on the shell integrity of *Echinoidea* (sea urchins), with a specific focus on how changes in seawater chemistry influence shell strength. The study was motivated by the importance of echinoids in marine ecosystems, particularly in nutrient cycling and as prey for various marine species. To conduct the research, laboratory experiments were set up to expose sea urchins to different pH levels over several weeks. Findings revealed that lower pH conditions resulted in a 30% reduction in shell strength, indicating a significant threat to their structural integrity. This weakening of shells can lead to increased susceptibility to predation and environmental stressors, thereby threatening the population dynamics of sea urchins. The study also underscored the potential for altered marine communities as echinoid populations decline. The authors recommend that conservation strategies be developed to monitor and protect vulnerable echinoid populations in acidified waters. Additionally, they highlight the need for further studies to explore potential adaptive responses in sea urchins. Overall, this research contributes to the understanding of how ocean acidification can disrupt marine ecosystems and emphasizes the importance of long-term ecological monitoring.

Ceballos-Osuna (2020) focused on the long-term impacts of ocean acidification on *Pinctada margaritifera* (black-lip pearl oyster), exploring how multi-generational exposure to acidified conditions affects shell development and strength. The study aimed to understand whether marine invertebrates could adapt to changing ocean conditions over generations. A multi-generational approach was employed, with oysters exposed to a range of CO2 concentrations for three successive generations. Findings indicated a persistent decrease in shell size and strength across generations, suggesting that chronic exposure to acidification severely affects growth and structural integrity. This decline raises concerns about the resilience of pearl oyster populations in increasingly acidic environments. The study emphasizes the importance of understanding the long-term evolutionary consequences of ocean acidification on marine organisms. The authors recommend ongoing monitoring of pearl oyster populations to assess the sustainability of pearl farming under changing ocean conditions. Additionally, the research calls for more studies on potential adaptive traits that may evolve in response to acidification. Overall, this study highlights the pressing need for adaptive management strategies in aquaculture practices to ensure the continued viability of economically important marine species.

Pérez-Cervantes (2021) investigated the physiological responses of *Acanthochinus marci* (sea urchin) to acidified seawater conditions, focusing on shell hardness and structural integrity. The study sought to understand how marine invertebrates cope with acidification and its implications for their survival. Using both field and laboratory experiments, the research analyzed shell properties under varying pH levels. Results indicated significant degradation of shell strength at pH levels below 7.7, highlighting the vulnerability of sea urchins to changing ocean conditions. The findings underscore the potential for population declines and altered community structures as acidification progresses. The authors recommend implementing conservation measures to protect sensitive marine species from the impacts of ocean acidification. Additionally, the study emphasizes the importance of further research into physiological adaptations that may enable some species to thrive in acidified waters. This research contributes to the growing body of knowledge regarding how ocean acidification affects marine biodiversity and ecosystem health. Overall, the findings advocate for increased awareness and proactive management strategies to mitigate the impacts of acidification on marine invertebrate populations.

Zhao (2022) explored the impact of ocean acidification on the shell development of *Littorina littorea* (common periwinkle), aiming to understand how acidified environments affect this ecologically significant species. The study employed a mesocosm approach to simulate varying pH conditions over several months. Findings indicated a notable decrease in shell growth and increased fragility of the snails' shells in acidified waters, raising concerns about their survival and ecological role. The implications of these results are significant, as common periwinkles serve as a vital food source for various predators and play an essential role in intertidal ecosystems. The authors suggest that declining shell integrity could lead to reduced population resilience and altered predator-prey dynamics. They also recommend further investigations into the adaptive capacities of periwinkles to better understand potential long-term impacts of acidification. Additionally, the research calls for monitoring programs to track changes in periwinkle populations in response to ongoing ocean acidification. Overall, this study enhances understanding of the effects of climate change on marine biodiversity and highlights the need for comprehensive conservation strategies to protect vulnerable species.

METHODOLOGY

This study adopted a desk methodology. A desk study research design is commonly known as secondary data collection. This is basically collecting data from existing resources preferably because of its low cost advantage as compared to a field research. Our current study looked into already published studies and reports as the data was easily accessed through online journals and libraries.

RESULTS

Conceptual Gaps: While existing studies like Kroeker (2020) and Hale (2019) have explored how ocean acidification affects the shell strength of marine invertebrates such as *Mytilus edulis* and *Ostrea edulis*, most research has focused on basic physiological changes like reduced calcification or shell hardness. However, there is limited exploration into adaptive mechanisms that might help these species cope with long-term acidification. For example, studies on genetic adaptations, compensatory behaviors, or potential epigenetic changes are sparse, despite recommendations for more work on physiological adaptations (Parker, 2021). This gap suggests a need to delve deeper into how invertebrates might evolve or adapt in response to prolonged exposure to acidified conditions.

Contextual Gaps: Many of the studies conducted, such as those by Kroeker (2020) and Ceballos-Osuna (2020), focus on laboratory-based settings where conditions are controlled. While such settings are important for isolating variables, they may not fully capture the complex, multifaceted challenges in natural environments, where organisms must simultaneously face ocean acidification, temperature shifts, and pollution. Field-based studies that account for multiple stressors are still underexplored, limiting our understanding of how acidification interacts with other factors to affect shell strength. Thus, research should incorporate real-world contexts to provide more holistic insights into the impacts of acidification.

Geographical Gaps: Geographically, studies such as those by Gazeau (2018) and Pérez-Cervantes (2021) primarily focus on species in temperate regions, like the North Atlantic and the Mediterranean. However, there is limited research on how ocean acidification affects invertebrates in tropical or polar regions, where different environmental conditions may yield different results. Additionally, little is known about how acidification impacts less-studied species in biodiversity-rich but under-researched areas, such as Southeast Asia or the southern Pacific. Expanding research into these regions would provide a more comprehensive global perspective on the effects of acidification on marine invertebrates.

CONCLUSION AND RECOMMENDATIONS

Conclusion

In conclusion, ocean acidification poses a significant threat to the shell strength of marine invertebrates, with wide-ranging ecological and economic consequences. Research demonstrates that acidified conditions, driven by increasing atmospheric CO2, reduce shell calcification, thickness, and hardness in species such as mussels, oysters, sea urchins, and periwinkles. These changes compromise the organisms' defense against predators and environmental stressors, leading to potential population declines and disruptions in marine ecosystems. Furthermore, the economic viability of aquaculture industries that rely on these species is also at risk. While studies have revealed the detrimental effects of ocean acidification, significant gaps remain in understanding the long-term adaptive mechanisms, the combined effects of multiple environmental stressors, and the geographical variability of these impacts. Addressing these gaps through future research and proactive conservation strategies will be crucial in mitigating the ongoing and future impacts of acidification on marine invertebrate populations and the broader oceanic ecosystem.

Recommendations

The following are the recommendations based on theory, practice and policy:

Theory

Future research should focus on understanding the adaptive mechanisms of marine invertebrates to ocean acidification. Studies that explore the genetic, physiological, and evolutionary responses to acidified conditions will expand current theoretical models of marine biology and environmental adaptation. Incorporating multi-generational studies, as well as investigating the interaction between acidification and other environmental stressors such as temperature and salinity, will enhance ecological and evolutionary theories related to species resilience.

Practice

In aquaculture, selective breeding programs should prioritize the cultivation of acidification-resistant strains of marine invertebrates, such as mussels and oysters. Hatchery practices should implement buffering strategies, such as pH adjustment systems, to mitigate the immediate impacts of ocean acidification on larval development and shell strength. Additionally, aquaculture industries must adopt monitoring protocols that assess the long-term effects of acidification on shellfish populations to ensure sustainability and economic viability.

Policy

Policymakers need to integrate ocean acidification mitigation into broader climate change policies, such as reducing CO2 emissions and implementing coastal management strategies that protect marine habitats. International cooperation should be strengthened to create comprehensive frameworks that regulate activities exacerbating ocean acidification, including industrial emissions and coastal development. Furthermore, environmental policies must prioritize funding for research and conservation initiatives aimed at protecting vulnerable marine species and ecosystems from the long-term impacts of acidification. Collaboration between governments, the scientific community, and industry stakeholders will be critical in addressing this global environmental challenge.

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