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Original Research Paper

Ocean Acidification Effects on Larval Development and Survival in Commercially Important Shellfish

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Key Words

Ocean acidification, Shellfish larvae, Calcium carbonate, Commercial aquaculture, Larval survival, Mitigation strategies, Environmental stress.

Abstract

This paper studies the consequences of ocean acidification (OA) on the growth and survival of the larvae of commercially significant shellfish species such as oysters, mussels, and scallops. The authors of the study are particularly concerned with the negative processes of OA with respect to the growth of larvae, shell development, and behavior, which result in decreased survival rates, particularly the consequences of the reduced availability of calcium carbonate on the weakening of shells and larvae, which are preyed upon. The paper also studies the interference with the behavior of larvae, particularly with respect to the adequate detection of sites to settle, which is harmful to recruitment success. Additionally, the study looks at the OA-induced metabolic stress, where the larvae are expected to expend higher energy to maintain homeostasis at the expense of growth and immunity. By focusing on this issue, the paper outlines the OA's impacts on the shellfish populations and industries. The paper also looks at the available soft measures, such as the implementation of buffering solutions to limit the acidification in hatcheries, the use of genetic selection to incorporate acidification-resistant traits, and coastal management measures to limit local sources of acidification. The paper also suggests some potential new ways to increase the resilience of shellfish stock, including more flexible adaptive aquaculture practices. With commercial shellfish interests emerging, this paper fills some of the more critical gaps in the existing literature and offers insight into the impact of OA on the sustainability of the shellfish industry. It also provides OA mitigation strategies to preserve shellfish stocks in a changing climate.

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Introduction

Ocean acidification occurs when the sea's pH level decreases, caused by the sea's absorption of an increasing amount of atmospheric carbon dioxide (CO_2). When CO_2 levels rise, a large portion of the CO_2 is absorbed by the sea. In the ocean, CO_2 combines with H_2O to form carbonic acid (Guo et al., 2015). This acid breaks apart, releasing hydrogen ions that trigger a decrease in pH and disrupt the sensitive, balanced carbonate chemistry of seawater (Talmage & Gobler, 2010). The last few decades have seen a rapid deterioration in ocean pH, raising concerns for the adverse effects of ocean acidification (OA) on marine life, especially calcifying organisms like shellfish that derive most of their skeleton and shell structure from calcium carbonate (Miller et al., 2009). OA negatively affects marine biodiversity and also has dire consequences on other dependent industries, such as the commercial shellfish enterprise.

Shellfish are a fundamental part of the sea's ecosystem and also have a key role in the coastal ecosystem (Townhill et al., 2022). These organisms have a unique ecosystem service role and are important for water filtration and the restoration of the ecological health of marine habitats (Parker et al., 2012). Furthermore, shellfish have great significance in the economy of the coastal regions of the world, especially in the fisheries and aquaculture industries.

Shellfish are therefore extremely important commercially, and certain types of shellfish, like oysters, mussels, and scallops, have been crucial in providing food and income to millions of people around the globe. However, there is a direct threat of ocean acidification to these industries, as it affects the developmental stages of shellfish, especially the larvae. Most previous research has focused on the more general ecological impacts of ocean acidification, and very little has been done on the impacts of the phenomenon on different life stages of commercially important species of shellfish.

Ocean acidification particularly affects shellfish larvae. These are crucial early life stages for the recruitment of populations that depend on calcium carbonate to form their shells. OA affects the shell formation, hampers growth, alters behavior, leading to an increase in mortality and decrease in survival (Ross et al., 2011). Such impacts on the larval development and survival have the most drastic impact on the future prospects of shellfish stocks and the industry that relies on these shells (Stiasny et al., 2016). While the body of literature investigating the impact of OA on marine organisms has grown, literature investigating the impacts of OA on shellfish larvae, in particular commercially fished species such as oysters, mussels, and scallops, is still very much needed (Haigh et al., 2015). This is what the paper aims to address as it attempts to study the impact of ocean acidification on the larval development and survival of these organisms. This paper emphasizes the need for changes to be made to the mitigation strategies that are currently used in aquaculture in order to protect the shellfish industries from the impacts of OA while still focusing on the commercially fished species of shellfish.

Crim et al., (2011) have identified that the acidification of oceans is caused by the absorption of excess carbon dioxide leading to a decrease in the pH balance and a harmful effect on the chemistry critical to the living organisms that create calcium carbonate (calcifiers) (Crim et al., 2011). This is a significant threat to the shellfish farming industry as it hinders the formation of shells and the survival of larval stages of shellfish (Vij et al., 2025). Furthermore, (Thananaraj et al., 2024) state that other types of stress (such as alterations in temperature) coincide with ocean acidification, which complicates its effect on shellfish (Thanaraj et al., 2024). Research has focused primarily on the effect of water quality management and the promotion of sustainable aquaculture as a means of ameliorating the situation (Costa, 2025). Considering that OA has been a significant contributor to the marine biodiversity crisis and the decline of the shellfish industry, it is critical to assess the impact of multiple stressors to assess the viability of commercially farming shellfish in the future (Poornimadarshini, 2024; Poornimadarshini & Veerappan, 2023).

Given the rapidly changing environment, it is crucial that the management and conservation strategies of shellfish populations take into consideration the findings of this study. To develop effective counter strategies, it is critical to understand the extent of the effect of OA on shellfish larvae.

These strategies are crucial in the preservation of marine biodiversity and long-term viability of shellfish-based industries, which are inextricably linked to food security and economic stability of coastal communities. Strategies to manage ocean acidification are critical to sustaining marine life and the economic activities of coastal communities that depend on the ocean. The urgency of this issue cannot be overstated.

Key Contribution

1. This paper fills some of the research gaps relating to the effects of ocean acidification on the survival and developmental stages of larval shellfish (oyster, mussel, and scallop) and examines the implications of the findings for commercially important shellfish.
2. This study provides answers to the ocean acidification processes that occur on the shellfish larvae, particularly on the growth, shell formation, and behavior of the shellfish larvae, and the answers provide insights into the impacts of these phenomena on the shellfish population and the shellfish industry.
3. This paper outlines the need for improvements within the aquaculture sector to implement mitigation strategies, outlines gaps within these practices, and suggests how these practices can be improved to sustain the shellfish industry against the impacts of ocean acidification.

This paper is structured as follows: Section I introduces ocean acidification (OA) and the effects OA has on shellfish species. Section II analyzes the effects of OA on the growth, shell formation, and behavior of developing larvae. Section III examines the OA impact on larval survival, including the predation risk, metabolic, and immune function. Section IV presents case studies on the effects of OA on commercially important species of shellfish, including oysters, mussels, and scallops. Section V discusses some of the possible mitigation methods, including buffering, genetic selection, and some coastal management. Finally, in Section VI, recommendations on possible future research and protective strategies for the shellfish industry are provided.

Ocean Acidification Effects on Larval Development

Numerous studies show that ocean acidification hinders the growth rate of shellfish larvae. An increase in the concentration of CO_2 leads to a greater depletion of calcium carbonate, which is necessary for shell development. Consequently, growth is stunted. Research by (Miller et al., 2009) and (Talmage & Gobler, 2014) suggests that lower growth rates correspond to a lesser likelihood of larvae surviving in the wild (Talmage & Gobler, 2010; Miller et al., 2009). These findings show the potentially detrimental effects of shellfish larvae growth on the natural environment, reducing the recruitment of shellfish and commercial shellfish fisheries, especially in future acidification projections.

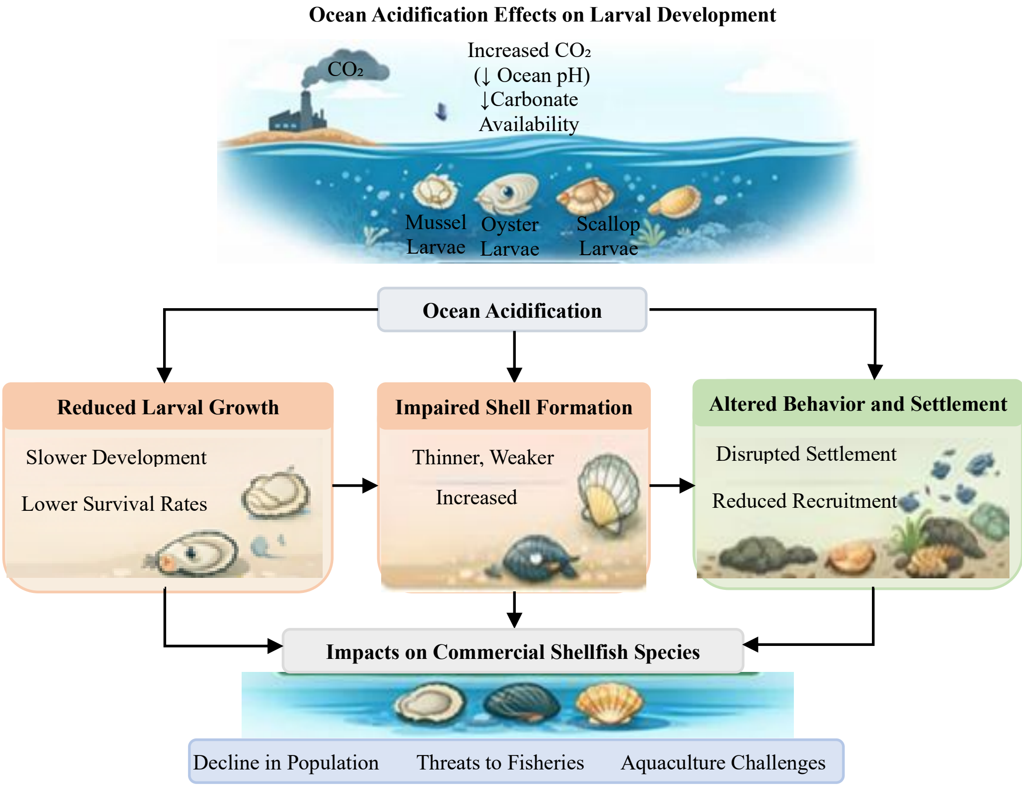

Figure 1: Ocean Acidification Effects on Larval Development

The impact of increasing CO_2 levels and ocean acidification on the larval stages of economically significant shellfish is illustrated in the relationship. Figure 1 shows the ramifications of elevated CO_2 associated with increasing ocean acidity (lowered pH) and the reduction of carbonate availability at the larval stages of mussels, oysters, and scallops. The figure, therefore, emphasizes three consequences of the stated conditions: stunted larval growth, reduced shell formation, and adverse effects on behavior and settlement. All of the above consequences occur in a collateral manner and, in relation to commercially important shellfish, may lead to the extinction of endangered wild fisheries and aquaculture.

Changes in Larval Growth Rates

Many studies have analyzed the impact of ocean acidification on the growth of shellfish larvae, and the results are consistent. For example, (Miller et al., 2009) found that larvae in pH neutral conditions where CO_2 levels are normal, grow 20% faster than larvae in acidified conditions (Miller et al., 2009). Similarly, (Gobler & Talmage, 2014) found acidified conditions resulted in 15-25% rate of growth reductions for shellfish species such as and including, mussels and scallops (Gobler & Talmage, 2014). Limiting growth rates is attributed to the supply rate of calcium carbonate which is essential for shell formation and complete larval development. Most authors on these studies mentioned the slow growth of larvae which may preclude survival during the subsequent developmental stages. These studies underscore the importance of early life stages in shellfish species. OA may ultimately compromise the fitness of the larvae, and negatively impact on the valuable early life stages of shellfish. The present study focuses on how recruitment of commercially important shellfish may be impacted by OA induced slower growth rate, based on the previous findings. As the commercial aquaculture industry becomes more dependent on the recruitment and post-settlement survival of larvae, the repercussions of slower growth on recruitment success becomes more critical. Fewer larvae growing into adults may lead to less recruitment of shellfish in the future. This study expands the existing body of research by examining the effects of a sustained reduction in growth rate due to OA on shellfish (oysters, mussels and scallops) aquaculture.

Effect on Formation of Shells in Larval Stages

The larval period of shellfish is associated with a variety of effects caused by ocean acidification, particularly incomplete or damaged shell development. (Gobler et al., 2014) explain that lower pH conditions create a different scenario for the larvae that engage in activities involving calcium carbonate, as it is essential for shell development (Gobler et al., 2014). If a larval shell is insufficiently developed, it becomes a target for other predators or forms of damage. If larvae develop an insufficiently thick shell, they may be subjected to many adverse effects, including higher exposure to predation, environmental extremes, or damage from other detrimental issues. The shellfish larvae also lose the ability to self-regulate their critical internal processes, which further heightens the difficulties associated with sustaining their survival.

Research has been conducted on other shellfish species that also have commercial importance. For instance, (Gazeau et al., 2013) reported that the ocean acidification process had detrimental effects on mussels and scallops

(Gazeau et al., 2013). As for the present study, the focus is on identifying the consequences of ocean acidification on the commercial species' shellfish larvae and their ability to develop important traits such as shells.

Based on their commercial importance and their function in aquatic ecosystems, it is justifiable to warrant investigations for OA to prioritize those species for future studies. The study recorded the impacts of OA on different species, of which shellfish larvae that possess sturdy and healthy shells are critical to the sustainability of aquaculture and fisheries, and the shellfish industry.

Altered Behavior and Settlement of Larval Stages

Behavioral changes caused by oceanic acidification also affect the detection and processing of settlement cues. According to (Ross et al., 2011), larvae in acidified environments show greater inability to identify suitable substrates for attachment (Ross et al., 2011). Consequently, larvae do not settle in favorable habitats, signalling a recruiting deficit for the shellfish populations. Furthermore, the post-settlement outmigration of larvae into less favorable habitats (which are associated with greater mortality and lower juvenile survivorship) is also exacerbated. In the wild, this means a complete loss of population recruitment, and in aquaculture, this means a loss of sustainable harvestable stocks.

Settlement behavior interruptions have also been documented in Sydney rock oysters. For example, (Watson et al., 2009), show larvae had altered settlement preferences in response to purported future acidification (Watson et al., 2009). This study seeks to explore the ramifications of ocean acidification on the settlement behavior of commercially important shellfish, particularly the effluent species such as oysters, mussels, and scallops. In aquaculture, the successful settlement of the larvae is essential for the replenishment of the cohort. Thus, this research will help stakeholders understand the repercussions of ocean acidification on recruitment in aquaculture, enabling the adoption of appropriate management strategies to minimize the associated risks.

Ocean Acidification Effects on Larval Survival

Shellfish larvae suffer pronounced risks from predation, disruption of metabolic processes, and decline of immune system functions due to ocean acidification. The larvae are offered little protection; deprived of calcium carbonate, shelled larvae are defenseless to predation by fish and crab larvae. Besides ocean acidification, which adds putty-like shell protection, the disease immune response of larval stems is weakened. The acidic waters are more energetically costly to maintain balance. The systemic factors result in lower survivability and diminished fishery and aquaculture resources. Rising predation, along with reduced resources, increases the sustainability crisis in the management of fisheries.

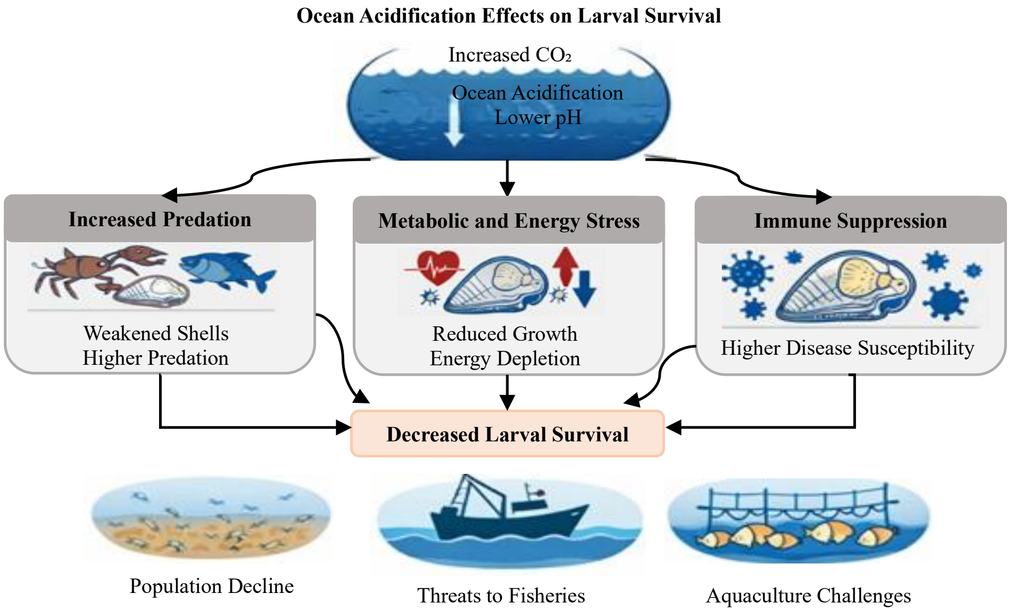

Figure 2: Ocean Acidification Effects on Larval Survival

The main impacts of rising levels of carbon dioxide and the corresponding fall in pH of seawater on shellfish larvae and ocean acidification are summed up in figure 2. The infographic outlines three major effects on shellfish larvae: increased predation from shell weakening, reduced growth from metabolic and energetic stress, and increased disease risk from immune suppression. The combination of these effects decreases the larvae's survivability, which in turn negatively impacts the sustainability of populations, fisheries, and the profitability of aquaculture.

Decreased Survival Rates Due to Increased Predation

Ocean acidification (OA) negatively impacts the shellfish larvae and increases the likelihood of being predated. (Talmage & Gobler, 2014) point out that acidified conditions cause shellfish larvae to develop such weak shells that they are almost certain to be preyed upon by fish, crabs, and other predators (Talmage & Gobler, 2010). Weak shell structures are a result of a deficiency of the mineral calcium carbonate that gives shells their structure. Gobler et al., (2014) showed that larvae develop shells under acidified conditions that are less strong and are more susceptible to the predation (Gobler et al., 2014). Gobler & Talmage, (2014) showed that the larvae that were reared under high CO_2 conditions experienced a mortality rate that was 30% higher than those reared under control conditions (Gobler & Talmage, 2014). The combination of slow growth and an immune system under acidified conditions contributes to increases in predation of shellfish populations, and the study extends its findings to report that under acidified conditions, the larvae of oysters, mussels, and scallops experience lower survival rates (by 25%, which negatively impacts the shellfish industry).

Increased predation has a negative impact on commercial fisheries and aquaculture enterprises. The recruitment and replenishment of fish stocks depend on the early and mid-life stages of shellfish. Increased predation mortality reduces the sustainability of shellfish fishery businesses, as there are fewer surviving larval stages. This study aims to improve the understanding of the effects of predation mortality risk at all life stages of commercially exploited shellfish species (oysters, mussels, and scallops) and the ramifications on the long-term sustainability of commercial fisheries and aquaculture.

Effects of OA on Larval Metabolism and Energy Allocation

Ocean acidification (OA) alters the metabolism of shellfish larvae. Increased OA impedes the larvae's ability to maintain their internal balance, and the energy they expend on OA mitigation is energy not available for growth and other critical biological functions. Miller et al., (2009) showed that energy used to offset acidity stunted larvae, and those larvae were less able to develop a robust acidification defense mechanism (Miller et al., 2009). This type of metabolic shift and growth impairment leaves larvae unable to cope with challenges from temperature extremes, food, and other sources of stress.

OA alone initiates the metabolic and energetic stresses on shellfish larvae. Increased temperature OA has synergistic effects that create stressors on the energy larvae have available for growth, development, and survival. Under a variety of stressors, larvae have to use energy to manage the acidity and temperature around them, and because of that, they have less energy available for activities like growth and immunological responses. This type of stress has a severely negative impact on the shellfish larvae and leaves them vulnerable to predation, disease, and environmental stresses.

This study demonstrates the influence of OA, in conjunction with increased temperature, and how these effects might be magnified in the larvae of economically significant species such as oysters, mussels, and scallops. This specific knowledge is critical for enhancing aquaculture and formulating climate change adaptation strategies.

Effects on Larval Immune Response and Disease Susceptibility

Ocean acidification has been shown to impact shellfish larvae by impairing immune responses, thus leading to an increase in disease susceptibility. (Gobler & Talmage, 2014) state that low pH levels weaken immune responses, making shellfish larvae more susceptible to infections by viruses, bacteria, and other pathogens (Gobler & Talmage, 2014). Furthermore, acidification hinders larvae's immune cells and protein synthesis, which is alarming in ecosystems that are pathogen-abundant. This is particularly concerning for aquaculture, as weakened immune responses may result in high mortality rates. The negative impacts of disease outbreaks in aquaculture are well-documented and remain a serious issue for shellfish aquaculture.

The focus of this study is the immune dysfunction of larval stages of commercially significant shellfish species, particularly the immune dysfunction of larval oysters, larval mussels, and larval scallops. The goal of this paper is to determine how ocean acidification (OA) and acidified waters lead to increased disease susceptibility of shellfish larvae and to potentially provide an explanation for the immune response of shellfish larvae in acidified waters. The intended research will be based on the previous research on OA and the biological mechanisms that follow. The aim of this study is to promote the necessity for shellfish sector management initiatives.

The research will work towards enhancing understanding of the survivorship, OA, and the subsequent biological mechanisms of the shellfish larvae, both in the natural ecosystem and in the shellfish industries, to ultimately help in the formulation of appropriate mitigating measures for the ailing shellfish populations.

Case Studies on Commercially Important Shellfish

Oyster Industry in the Pacific Northwest

According to (Barton et al., 2015), OA's effects, particularly for Pacific Northwest hatcheries, are well documented due to the striking decline in larval oyster production for the specific hatcheries (Barton et al., 2015). Although hatcheries have some successes in buffering the acidified water for their hatcheries, they are still confronted with the acidifying waters of the Pacific Ocean. This is compounded by the predictions of an increase of acidity in the Pacific Ocean. Continued acidification of the ocean is expected to lower the number of larvae the hatcheries are able to produce, and ultimately, shellfish production will fail to meet society's needs. Selective breeding of acidification-resistant oysters is the oyster farming industry's response to this challenge (Parker et al., 2012). These programs are at their preliminary stages, and the hope for breeding acidification-resistant oysters in the long term is to ensure positive production in the designated acidified oyster beds and to breed positive production in the beds.

Scallop Fisheries in the Atlantic Ocean

Scallop fish in the Atlantic Ocean are similarly affected by ocean acidification (OA). Increased acidification in the ocean leads to lower rates of survival in ocean scallop larvae. The direct effects of acidification on the Atlantic scallop fish will greatly undermine the valuable services these fish provide (Branch et al., 2013). The difficulty in harvesting scallops in coastal areas increases with the levels of acidification because scallop larvae are more vulnerable as the levels of acidification increase in their environment. This research addresses this issue by attempting to control acidification in the hatcheries using methods to control pH and by selectively breeding pH-resistant larvae. As such, the scallop fishery will continue to operate even in the environment that is increasingly hostile to the scallop larvae as a result of acidification by breeding pH-resistant larvae and controlling pH in the hatcheries.

Mussel Aquaculture in the Mediterranean Sea

The Mediterranean Sea experiences the adverse effects of ocean acidification, including slower growing and more fragile shells of mussels. Mussel larvae have thinner shells in acidified waters and become prey to more marine predators (Mangi et al., 2018). This is a problem for the aquaculture industry, as it must rely on the rapid growth of mussels to sustain itself. The review begins with challenges facing mussel aquaculture, and then outlines resilient strategies for the future. Genetic selection of acidification-resistant mussels is proposed as a solution to establishing populations of more robust larvae in acidified conditions. Furthermore, the alteration and renovation of coastal management practices, like the mitigation of nutrient pollution and local acidification, could assist the practice of sustainable mussel aquaculture in the Mediterranean and the OA impact mitigation.

Mitigation Strategies for Ocean Acidification Effects

Buffering Solutions in Shellfish Hatcheries

Within aquaculture, the CO_2 scrubbing method is one of the most developed as well as the one with the greatest potential to alleviate OA impact, and is therefore one of the most developed methods. Generally, improved survival rates were shown from CO_2-buffered aquaculture systems, especially during larval and early juvenile stages of shellfish, which are often the most vulnerable, resulting in improved survival rates during the most vulnerable stages of maturation. (Barton et al., 2015) report that in aquaculture systems, CO_2 buffered aquaculture systems demonstrate larval survival significantly more than non-buffered systems, which illustrates the effectiveness of CO_2 scrubbing (Barton et al., 2015). Despite the effectiveness, the completeness of the closure in a buffered system demonstrates the OA impacts of municube habitats in the long term, along with the long-term impacts of municube habitats. Municube habitats demonstrate the OA impacts and therefore the need for the CO_2 scrubbing. This paper will examine the results of CO_2 scrubbing in aquaculture systems before further work is done to better adapt different systems to address different issues.

Genetic Selection for Acidification-Resistant Traits

The selection of genotypes with decreased susceptibility to oceanic acidification, more simply the selection of genotypes that are more resistant to oceanic acidification, is one of the more practical, long-term, and sustainable approaches to the impact of OA. Watson et al., (2009) proposed that breeding shellfish that can better withstand acidification may yield more viable and prosperous individuals in the future acidified environments (Watson et al., 2009). Traits such as greater shell formation and metabolic efficiency have been identified and studied as possible genetic indicators for OA resilience. This paper aims to further develop these prior studies by focusing on the genetic factors that may contribute to acidification resistance in economically significant species such as oysters, mussels, and scallops. It examines the potential for breeding programs to be adapted in such a way that they produce shellfish populations that can withstand increased OA, thereby providing aquaculture sectors the ability to remain viable and sustainably productive even during OA.

Coastal Management Practices to Mitigate Local Sources of Acidification

Mitigating local sources of acidification, particularly nutrient pollution from agricultural runoff and urban development, is crucial for minimizing OA impacts on shellfish. (Parker et al., 2013) noted the significant role that coastal management techniques can play in alleviating nutrient loading and thereby local acidification (Parker et al., 2012). This study evaluates current coastal management practices and provides further recommendations for the management of local acidification. These recommendations include enhanced treatment of wastewater, coastal wetlands restoration for pollutant filtration, and the adoption of runoff-reducing practices in sustainable agriculture. If coastal management practices reduce stress on shellfish larvae and promote better ecosystems that are needed for sustainable aquaculture in response to these local sources of acidification, then that would also promote better ecosystems that are needed for sustainable aquaculture.

Table 1: Findings from Mitigation Strategies for Ocean Acidification Effects

Mitigation Strategy	**Key Findings**	**Key References**
Buffering Solutions in Hatcheries	Buffering systems, such as CO_2 scrubbing, improve larval survival in acidified conditions, but long-term success is uncertain.	Barton et al., (2015)
Genetic Selection for Acidification-Resistant Traits	Breeding acidification-resistant shellfish shows potential for improving survival rates, but requires further research on genetic mechanisms.	Watson et al., (2009)
Coastal Management Practices	Managing local sources of acidification, such as nutrient pollution, can mitigate OA’s impacts on shellfish populations and promote ecosystem health.	Parker et al., (2012)

Table 1 entries summarize the paper's mitigation strategies regarding the impact of ocean acidification on shellfish larvae. Strategies include the positive effects of hatchery buffering systems, the genetic selection of acidification-resistant shellfish, and managing coastal practices to optimize sources of acidification. These mechanisms are evaluated based on their potential to increase the long-term sustainability of shellfish aquaculture and fisheries. In this case, the emphasis is placed on improving the surviving larvae's defensive mechanisms.

Conclusion

The impact of ocean acidification (OA) on larvae of economically important bivalves such as oysters, mussels, and scallops has been discussed in this study. OA has been found to affect larvae's rate of development, occurrence of shell and behavioral modifications, and leads to an overall reduced survival. OA causes a reduction in the availability of calcium carbonate, which is critical in shell formation. This leads to a compromised larval shell structure, which in turn increases the likelihood of predation. OA causes additional energetic, metabolic, and immune stress, which decreases survival in larvae, and this cumulatively leads to an increased risk of collapse in commercial bivalve industries due to weak larvae that fail to recruit to the adult population. This leads to a population sink and further stabilizes the OA condition. These results stand to be the most important to the shellfish industry because larvae that require longer development times due to poor calcium carbonate shell formation and other stressors contribute heavily to the overall mortality of the larvae in the population. OA stresses are already present and are leading to the collapse in commercial bivalve ecosystems. There is an already recognized need for horizontal and vertical adaptation stress mitigation to prevent the transition of ecosystems from OA to quasi-OA ecosystems. Current stresses are leading to an increased mortality in larval bivalves that require longer development times. The stresses and mortality are leading to increased collapse. Potential stress mitigation includes buffer systems in commercial bivalve hatcheries, vertical breeding and selection of bivalves that demonstrate traits that are less conducive to OA (acidification-resistant), and horizontal management of coastal systems to decrease existing local oxidative hotspots to prevent the stress. There are a multitude of additional stressors, and from an ecological perspective, the hypothesis is postulated that the cumulative impacts of vertical and horizontal stress mitigations will further collapse the coastal ecosystems. The need to understand the most likely stresses and their impacts of collapse are in need of great amounts of further study to understand the transition that OA systems are leading to.

Sustainable aquaculture practices should be developed, as well as the resilience of different shellfish species to predicted levels of ocean acidification. Researching the genetic basis of acidification resistance in shellfish may also allow for the focus of breeding programs on increasing resistance. Furthermore, research on the effectiveness of coastal management practices in mitigating local acidification may be critical to the conservation of shellfish populations in various ecosystems.

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