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The Role of Shellfish Aquaculture in Coastal Habitat Restoration

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Abstract Shellfish aquaculture plays a crucial role in coastal habitat restoration. As coastal habitats globally continue to degrade, the ecological functions of shellfish, such as oysters and mussels, are receiving increasing attention. Through filtering water, improving water quality, stabilizing substrates, and forming new habitats, shellfish significantly contribute to restoring biodiversity, enhancing the resilience of coastal ecosystems, and promoting carbon sequestration. This study reviews the multiple ecological functions of shellfish aquaculture in coastal restoration and analyzes successful case studies to explore its application potential. Additionally, the study examines the environmental, socio-economic, and regulatory challenges encountered when integrating shellfish aquaculture with habitat restoration and proposes future directions for technological advancements. This research aims to provide theoretical support and practical guidance for coastal ecological restoration, emphasizing the importance of shellfish aquaculture in addressing global climate change and ecological degradation.

Keywords Shellfish aquaculture; Coastal habitat restoration; Biodiversity; Ecosystem resilience; Carbon sequestration

1 Introduction

Coastal habitats such as mangroves, coral reefs, salt marshes, and seagrass beds are among the most critical ecosystems on Earth, providing invaluable ecological, economic, and social benefits to both humanity and nature. However, over the past century, more than 50% of the world's coastal wetlands have been lost due to land reclamation, urbanization, and industrial activities (Li et al., 2018). Additionally, nutrient pollution, overfishing, and climate change have further accelerated the degradation of these ecosystems (Lefcheck et al., 2018). This degradation not only threatens biodiversity but also undermines the essential ecosystem services these habitats provide, such as shoreline protection, carbon sequestration, and support for fisheries (Nichols et al., 2018).

Shellfish, particularly bivalves like oysters, mussels, and clams, play a crucial role in maintaining the health and functionality of coastal ecosystems. Shellfish not only improve water quality through filtration and nutrient cycling but also provide habitat for various marine species. Research has shown that when sustainably managed, shellfish aquaculture can significantly enhance the services provided by coastal ecosystems, such as increasing the abundance and diversity of wild, mobile macrofauna, and supporting the reproduction and survival of fish and invertebrates through the creation of artificial reefs (Theuerkauf et al., 2021). Therefore, shellfish aquaculture is considered a potentially effective tool for restoring degraded coastal habitats.

This study systematically analyzes existing scientific literature to evaluate the role of shellfish aquaculture in the restoration of degraded coastal habitats, exploring its positive impacts on ecosystems and the mechanisms through which it operates, while also examining the challenges and limitations that may arise during its implementation. Through this research, the goal is to provide valuable guidance to policymakers, conservationists, and aquaculture practitioners on effectively integrating shellfish aquaculture into coastal habitat restoration strategies.

2 Shellfish Aquaculture and Its Ecological Functions

2.1 Filtration and water quality improvement

Shellfish aquaculture plays a significant role in improving water quality through the filtration activities of bivalves such as mussels and oysters. These organisms feed by filtering plankton and other particles from the water, which can lead to substantial reductions in water turbidity and nutrient levels. For instance, the ribbed mussel (*Geukensia* *demissa)* has been shown to clear large volumes of water daily, removing significant amounts of particulate matter and sequestering nitrogen in their tissues and shells, which helps mitigate nutrient over-enrichment in coastal and estuarine ecosystems (Galimany et al., 2017). Similarly, the inshore aquaculture of suspension-feeding cockles (*Cerastoderma edule*) has demonstrated improvements in water quality by reducing sediment loads and stimulating pelagic microalgal growth, which in turn enhances the growth and meat content of the cockles (Philippart et al., 2020). These filtration activities not only improve water clarity but also contribute to the overall health and resilience of aquatic ecosystems.

2.2 Substrate stabilization and habitat formation

In addition to water filtration, shellfish aquaculture contributes to substrate stabilization and the formation of new habitats, which are crucial for coastal habitat restoration. The cultivation of bivalves such as oysters and mussels provides structured habitats that support diverse faunal communities. For example, suspended or elevated mussel and oyster cultures have been associated with increased abundance and species richness of wild, mobile macrofauna, thereby enhancing the ecological value of these aquaculture sites (Theuerkauf et al., 2021). The physical structures created by shellfish farms, such as rafts and cages, offer surfaces for the settlement of various marine organisms, promoting biodiversity and ecosystem complexity.

Moreover, shellfish aquaculture can play a role in stabilizing sediments and protecting shorelines. The co-restoration of shellfish and other marine habitats, such as kelp forests, can synergistically stabilize sediments and accelerate ecosystem recovery, providing a more resilient and productive coastal environment (McAfee et al., 2022). This multi-habitat approach to restoration leverages the positive interactions between different species and habitats, enhancing the overall ecological and socio-economic benefits of restoration efforts.

Shellfish aquaculture not only improves water quality through filtration but also contributes to substrate stabilization and habitat formation, making it a valuable tool for coastal habitat restoration and the enhancement of ecosystem services. By integrating these ecological functions, shellfish aquaculture can support the recovery and sustainability of coastal ecosystems, providing both environmental and socio-economic benefits.

3 Contributions of Shellfish Aquaculture to Coastal Restoration

3.1 Restoring biodiversity

3.1.1 Habitat creation for marine species

Shellfish aquaculture plays a significant role in creating habitats for various marine species. The cultivation of bivalve shellfish, such as mussels and oysters, has been shown to increase the abundance and species richness of wild, mobile macrofauna. This is primarily due to the structured habitats provided by the aquaculture setups, which offer shelter and breeding grounds for fish and invertebrates (Figure 1) (Theuerkauf et al., 2021). Additionally, the presence of these structured habitats can enhance reproduction and recruitment, further supporting biodiversity (Theuerkauf et al., 2021).

Shellfish farms provide complex substrate structures that allow fouling organisms to grow, offering breeding grounds, refuges, and resting areas for fish and invertebrates. These structured habitats not only increase species abundance and diversity but also promote the overall health of marine ecosystems. Figure 3 clearly demonstrates the important role of shellfish aquaculture in enhancing and restoring marine habitats, aiding in the understanding of its contributions to biodiversity restoration.

3.1.2 Supporting trophic interactions

The introduction of shellfish aquaculture into coastal ecosystems can support trophic interactions by providing food resources for various marine species. Bivalves, for instance, filter feed on plankton, which can help control plankton populations and improve water quality. This, in turn, supports higher trophic levels, including fish and other predators that rely on these resources (Theuerkauf et al., 2021). Moreover, the presence of shellfish can enhance the overall productivity of the ecosystem, creating a more robust and interconnected food web (McAfee et al., 2022).

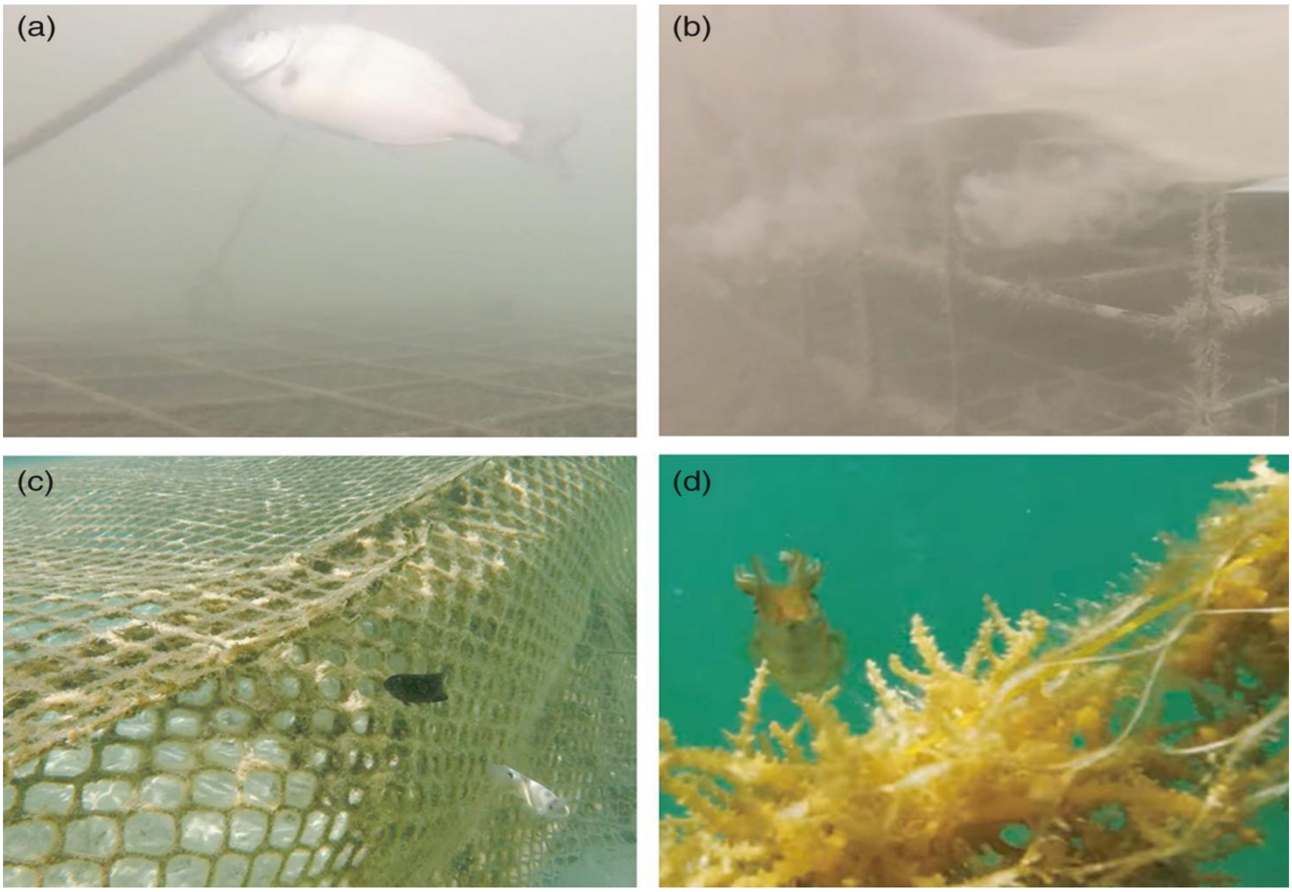

Figure 1 Reported examples of habitat value provided by bivalve and seaweed aquaculture, including (A) gear providing substrate for fouling organisms that provide forage resources for fish (subtidal oyster cage within Long Island Sound, USA), (B) structured habitat for fish reproduction (subtidal oyster cage within Long Island Sound, USA), (C) refuge habitat for juvenile fish (giant clam grow-out cage within Nikko Bay, Palau) and (D) resting habitat for fish and invertebrates (subtidal raft culture for seaweed in *Turneffe Atoll*, Belize) (Photo credit: NOAA Fisheries and The Nature Conservancyhot)

3.1.3 Protecting endangered species

Conservation aquaculture has been identified as a valuable tool for the recovery of endangered marine species. For example, the cultivation of Olympia oysters (*Ostrea lurida*) has been strategically planned to promote their recovery along the west coast of North America. This approach not only supports the species' population growth but also enhances genetic diversity and resilience to environmental changes (Ridlon et al., 2021). By focusing on the recovery of endangered species, shellfish aquaculture contributes to the broader goal of biodiversity conservation.

3.2 Enhancing coastal resilience

Shellfish aquaculture can enhance coastal resilience by stabilizing sediments and reducing erosion. The physical structures created by shellfish farms, such as oyster reefs, can act as natural barriers that protect shorelines from wave action and storm surges. This stabilization effect is crucial for maintaining the integrity of coastal habitats and preventing land loss (McAfee et al., 2022). Additionally, the presence of shellfish can improve water quality by filtering out excess nutrients and pollutants, which further supports the health and resilience of coastal ecosystems (Clements and Comeau, 2019).

Through the synergistic restoration of oyster reefs, seagrass beds, and kelp forests, these habitats collectively reduce hydrodynamic energy and stabilize sediments, thereby enhancing the coastal region's ability to withstand environmental pressures such as erosion, storm surges, and sea-level rise. Multi-habitat restoration can significantly improve the overall stability and functionality of ecosystems, making it an important strategy for enhancing the resilience of coastal ecosystems (Figure 2).

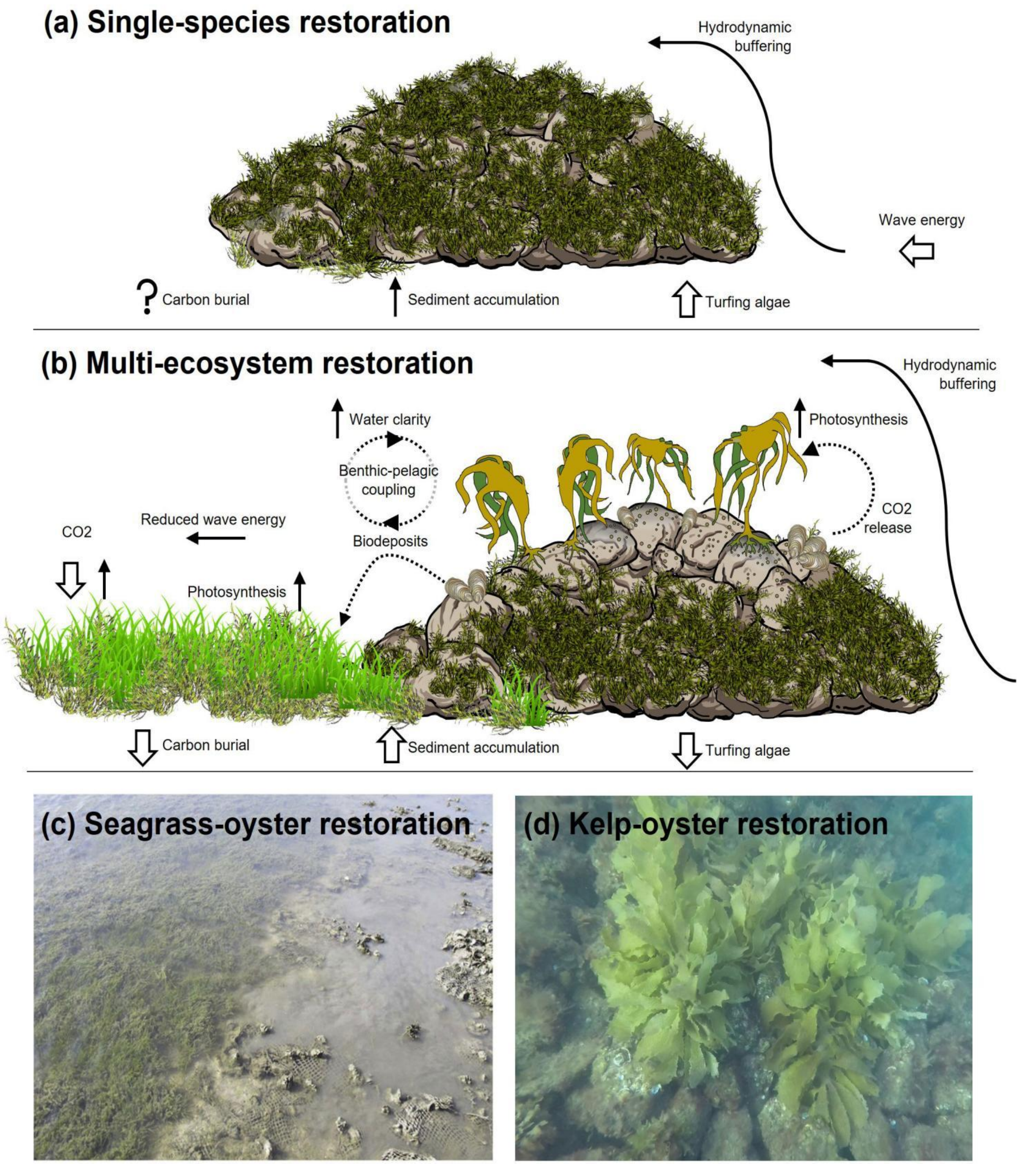

Figure 2 Restoration practice commonly focuses on (a) single-species approaches to habitat restoration, such as constructing reefs to restore oysters, whereas a (b) multi-habitat approach could utilise constructed reefs to recover multiple lost habitat-types (oysters, seagrass, kelp). Examples of multi-habitat restoration in practice demonstrate the facilitative benefits of co-restoration, including (c) constructed oyster reefs that buffer hydrodynamics and stabilise sediments to promote seagrass recovery, and (d) kelp transplants atop constructed reefs that maintain substrata free of turfing algae to facilitate understory oyster recruitment (South Australia) (Adopted from McAfee et al., 2022)

3.3 Promoting carbon sequestration

Shellfish aquaculture contributes to carbon sequestration by incorporating carbon into the shells and tissues of bivalves. This process helps mitigate the effects of climate change by reducing the amount of carbon dioxide in the atmosphere. For instance, the farming of mussels and oysters has been shown to remove significant amounts of nitrogen and carbon from the marine environment, thereby contributing to nutrient cycling and carbon storage (Clements and Comeau, 2019). Furthermore, the restoration of mangrove forests, often associated with shellfish aquaculture, can enhance blue carbon sequestration, providing additional climate change mitigation benefits (Ahmed and Glaser, 2016).

In summary, shellfish aquaculture offers multiple ecological benefits that contribute to coastal habitat restoration. By creating habitats, supporting trophic interactions, protecting endangered species, enhancing coastal resilience, and promoting carbon sequestration, shellfish farming plays a vital role in maintaining and restoring the health and functionality of coastal ecosystems.

4 Case Studies of Successful Shellfish Restoration Projects

4.1 Oyster reefs in the chesapeake bay

The Chesapeake Bay has been a focal point for oyster restoration efforts, particularly with the native eastern oyster, *Crassostrea virginica*. One notable project involved the deployment of a concrete modular reef in the Rappahannock River, Virginia. This artificial reef, covering a surface area of 75 m² over 5 m² of river bottom, was established in October 2000. By May 2005, the reef had achieved remarkable success, with densities of 1085 oysters and 8617 hooked mussels (*Ischadium recurvum*) per square meter of river bottom, the highest recorded for artificial oyster reefs. The population structure indicated four year classes of oysters, with over half being more than one year old and of reproductive age. The biomass and condition index of the oysters were high, while parasite prevalence and intensity were low, indicating a healthy and thriving reef system (Lipcius and Burke, 2018).

The success of this project highlights the potential of artificial structures in supporting oyster populations and enhancing biodiversity. The positive correlation between oyster and mussel densities suggests that such reefs can support diverse and abundant faunal communities. This case study underscores the importance of innovative restoration techniques and long-term monitoring to ensure the sustainability and effectiveness of restoration efforts (Lipcius and Burke, 2018).

4.2 Mussel beds in european coastal waters

In European coastal waters, the restoration of mussel beds has shown promising results, particularly with the European native oyster, *Ostrea edulis*. The Loch Ryan oyster fishery in Southwest Scotland employs a rotational harvest system, where different areas are fished each year and then left undisturbed for six years. This system provided a unique opportunity to study the effect of oyster reef development on biodiversity. Surveys conducted using SCUBA revealed significant differences in oyster shell density, percent cover, and macrofaunal biodiversity between treatments harvested one, two, and six years prior. The highest values were observed in the six-year treatment, with shell density 8.5 times higher and biodiversity metrics significantly improved compared to the one-year treatment (Kennon et al., 2023).

The findings from Loch Ryan indicate that the provision of increased structural complexity through live and dead oyster shells enhances macrofaunal biodiversity. The study projects that full recovery of biodiversity would take approximately ten years, with diversity potentially doubling in that time. This case study demonstrates the biodiversity benefits of oyster habitat restoration and provides a cost-effective metric (shell density) to judge progress in restoration projects (Kennon et al., 2023).

These case studies from the Chesapeake Bay and European coastal waters illustrate the significant ecological benefits of shellfish restoration projects. By enhancing habitat complexity and supporting diverse faunal communities, these projects contribute to the overall health and resilience of coastal ecosystems.

5 Challenges in Integrating Shellfish Aquaculture with Habitat Restoration

5.1 Environmental and ecological considerations

Integrating shellfish aquaculture with habitat restoration presents several environmental and ecological challenges. While shellfish aquaculture can provide valuable ecosystem services, such as habitat provision for fish and invertebrates, it can also contribute to environmental stressors. For instance, aquaculture activities can lead to habitat degradation and increased nutrient loading, which may negatively impact coastal ecosystems (Holden et al., 2019; Theuerkauf et al., 2021).

Moreover, the success of integrating aquaculture with habitat restoration depends on understanding the specific ecological interactions and the potential for aquaculture to support or hinder restoration goals. For example, the metabolic activities of macroalgae in co-culture systems can buffer ocean acidification, potentially benefiting calcifying organisms like shellfish. However, the effectiveness of this buffering capacity is site-specific and depends on local hydrodynamic conditions and community structure (Fernández et al., 2019).

Additionally, the presence of aquaculture structures can alter the habitat use patterns of marine species. For example, mussel farms have been shown to attract common bottlenose dolphins due to the aggregation of prey species around the aquaculture structures. This interaction highlights the need to consider the broader ecological impacts of aquaculture on marine species and their habitats (López and Methion, 2017).

5.2 Socioeconomic and regulatory challenges

The integration of shellfish aquaculture with habitat restoration also faces significant socioeconomic and regulatory challenges. One of the primary issues is balancing the economic benefits of aquaculture with the need to protect and restore coastal habitats. In regions like British Columbia, the expansion of shellfish aquaculture must be carefully managed to ensure it is socially, environmentally, and economically sustainable. This involves considering the interactions between aquaculture, existing industries, and local communities, including First Nations (D'Anna and Murray, 2015; Holden et al., 2019).

Public perception and acceptance of aquaculture activities can also pose challenges. While some stakeholders may recognize the economic benefits of aquaculture, others may have concerns about its environmental impacts and effects on their lived experience. This variability in perceptions underscores the importance of engaging with local communities and addressing their concerns through transparent and inclusive planning processes (D'Anna and Murray, 2015).

Regulatory frameworks play a crucial role in facilitating the integration of aquaculture with habitat restoration. Effective marine spatial planning and adaptive management strategies are essential to ensure that aquaculture activities align with conservation and restoration objectives. This includes developing clear and measurable indicators of success to evaluate the ecological benefits of aquaculture and prevent potential greenwashing (Overton et al., 2023).

Integrating shellfish aquaculture with habitat restoration requires addressing both environmental and ecological considerations, as well as navigating complex socioeconomic and regulatory landscapes. By adopting a holistic and adaptive approach, it is possible to harness the potential benefits of aquaculture while mitigating its challenges and ensuring the sustainability of coastal ecosystems (Xu and Wang, 2014).

6 Advances in Shellfish Aquaculture Techniques for Restoration

6.1 Selective breeding and genetic enhancement

Selective breeding and genetic enhancement have emerged as pivotal techniques in shellfish aquaculture, particularly for restoration purposes. Advances in genomics and bioinformatics have significantly accelerated the genetic improvement of aquaculture species. For instance, genomic selection combined with biotechnological innovations such as genome editing and surrogate broodstock technologies can expedite genetic improvement, optimizing traits like growth rate and disease resistance (Houston et al., 2020). Selective breeding has also been shown to enhance resilience to environmental stressors, such as ocean acidification. For example, selectively bred Sydney rock oysters have demonstrated altered biomineralization pathways, promoting resilience to acidification (Fitzer et al., 2019). These genetic advancements not only improve the sustainability of shellfish aquaculture but also contribute to the restoration of degraded coastal habitats by producing more robust and adaptable shellfish populations (Azra et al., 2022).

6.2 Innovative farming practices

Innovative farming practices are crucial for enhancing the ecological benefits of shellfish aquaculture. Techniques such as suspended or elevated mussel and oyster culture have been associated with significant increases in wild macrofaunal abundance and species richness, thereby providing structured habitats and food resources for various marine species (Theuerkauf et al., 2021). Additionally, the integration of aquaculture-based enhancement with habitat enhancement offers a remarkable opportunity for future research and development. This approach involves using quantitative tools and pilot-scale enhancement scenarios to evaluate and optimize release strategies before full implementation, ensuring that aquaculture practices contribute positively to ecosystem services (Taylor et al., 2017). Furthermore, the nitrogen removal potential of different shellfish farming methods has been studied, revealing that suspended mussel culture provides the greatest nitrogen removal per hectare, thereby mitigating nutrient pollution in coastal waters.

6.3 Monitoring and adaptive management

Effective monitoring and adaptive management are essential components of successful shellfish aquaculture for restoration. The development of a scientific framework for conservation aquaculture, as demonstrated in the case of Olympia oyster restoration in central California, highlights the importance of long-term monitoring and data-driven decision-making. This framework involves tracking the growth and survivorship of hatchery-raised juveniles, assessing natural recruitment limitations, and deploying outplanted oysters in optimal intertidal zones to maximize survival and reproductive success (Wasson et al., 2020). Additionally, the use of social and economic studies to evaluate the outcomes of aquaculture-based enhancement projects ensures that these initiatives are not only ecologically beneficial but also socially and economically viable (Taylor et al., 2017). By continuously adapting management practices based on monitoring data, shellfish aquaculture can effectively contribute to the restoration and sustainability of coastal habitats.

7 Applications Beyond Habitat Restoration

7.1 Integrated multi-trophic aquaculture (IMTA)

Integrated Multi-Trophic Aquaculture (IMTA) is a sustainable aquaculture practice that involves the co-cultivation of species from different trophic levels within the same system. This method aims to enhance the ecological and economic sustainability of aquaculture by utilizing the waste products of one species as inputs for another, thereby reducing environmental impacts and improving resource efficiency.

IMTA has shown promise in various settings. For instance, the Regional Integrated Multi-Trophic Aquaculture (RIMTA) model proposes spatially separated but ecologically linked cultures of low and high trophic level species within the same water body. This approach can sequester dissolved waste and support primary production, fostering a circular economy and enhancing ecosystem services (Sanz-Lázaro and Sanchez-Jerez, 2020). Offshore IMTA is another innovative application, which can reduce pressure on nearshore ecosystems and provide alternative income options for coastal communities by transforming waste products into valuable co-products (Buck et al., 2018).

Laboratory-scale studies have demonstrated the feasibility of co-culturing species such as sea urchins and sea cucumbers, which can significantly reduce organic waste and provide added value in the form of biomass (Grosso et al., 2020). Additionally, the functional response of filter feeders like mussels to varying food sources can inform the optimal placement of shellfish cultures, further enhancing the efficiency of IMTA systems (Montalto et al., 2017).

In brackish water ponds, IMTA has been shown to outperform conventional polyculture in terms of environmental remediation, productivity, and economic return. The integration of species such as mullets, shrimp, and oysters can improve water quality and nutrient cycling, leading to more sustainable aquaculture practices (Biswas et al., 2020). The large-scale implementation of IMTA in regions like Sanggou Bay, China, has also provided valuable insights into the interactions between biogeochemical cycles and ecosystem functions, highlighting the potential of IMTA to support large-scale seafood production (Fang et al., 2016).

7.2 Synergies with fisheries and marine conservation

The integration of shellfish aquaculture with fisheries and marine conservation efforts can create synergies that enhance both food production and ecosystem health. IMTA systems can support the sustainable exploitation of marine resources by reducing the environmental impacts of aquaculture and promoting biodiversity.

For example, the strategic model for sustainable mariculture in Samanco Bay, Peru, emphasizes the need for IMTA to mitigate the negative impacts of monospecific aquaculture, such as benthic degradation and eutrophication. By adopting IMTA, private companies can achieve greater efficiency and environmental balance, which can be adapted to other regions (Loayza-Aguilar et al., 2023). In the Mediterranean Sea, IMTA and mariculture practices are being explored for their potential to support environmental restoration and conservation. These practices can be coupled with artificial reefs and offshore mussel farming to create controlled environments that enhance marine biodiversity and ecosystem services (Giangrande et al., 2021).

Moreover, the use of biofloc technology in conjunction with IMTA can further improve the sustainability of aquaculture systems. Although some studies have shown that certain species, like the oyster Crassostrea gasar, may not effectively reduce suspended solids, they can still benefit from the microbial communities present in biofloc systems, contributing to the overall health and productivity of the aquaculture environment (Costa et al., 2021).

The applications of shellfish aquaculture extend beyond habitat restoration to include innovative practices like IMTA and synergies with fisheries and marine conservation. These approaches can enhance the sustainability and resilience of coastal and marine ecosystems, supporting both ecological and economic goals.

8 Concluding Remarks

Shellfish aquaculture has demonstrated significant ecological and economic benefits in habitat restoration and the provision of ecosystem services. Ecologically, bivalve shellfish and seaweed aquaculture can increase the abundance and species diversity of wild, mobile macrofauna, providing structured habitats and food resources that support coastal faunal communities. These ecological benefits contribute not only to habitat restoration and recovery but also offer additional advantages such as bioremediation, climate change mitigation, and coastal defense. Moreover, shellfish aquaculture plays a crucial role in the recovery of endangered species by providing a controlled environment for their growth and reintroduction into the wild.

Economically, shellfish aquaculture contributes significantly to local economies by creating jobs and providing a sustainable source of seafood. Global studies indicate that strategic investments in regions with high potential for shellfish aquaculture can yield substantial economic benefits. Additionally, integrating aquaculture with habitat enhancement practices can improve fisheries productivity and deliver socioeconomic benefits to a broad range of stakeholders. The ecosystem services provided by shellfish, such as nutrient removal and habitat modification, also hold significant economic value, supporting the overall sustainability of coastal communities.

Looking ahead, the development of shellfish aquaculture and coastal restoration should focus on maximizing ecological benefits while ensuring economic viability. Restorative Shellfish Mariculture (RSM) presents a promising approach by addressing socio-ecological issues through targeted interventions during the species life cycle. Future development should incorporate social, environmental, and economic factors into marine planning, supported by innovative policies, financing, and certification schemes to promote the provision of ecosystem services. This includes establishing clear and measurable indicators of success to evaluate the ecological benefits of aquaculture activities and prevent "greenwashing." Additionally, expanding hatchery capacity in key areas and incorporating local knowledge and stakeholder goals can further enhance the recovery of endangered species and support community restoration efforts. Continued research and development, particularly in the fields of aquaculture techniques, genetics, and quantitative modeling, will help refine strategies and outcomes, enabling shellfish aquaculture to play a pivotal role in coastal habitat restoration, promoting both ecological sustainability and economic prosperity.

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