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Optimization of Sea Ranching Techniques for Sustainable Tropical Sea Cucumber Aquaculture

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Abstract Sustainable tropical sea cucumber aquaculture is a crucial issue in current marine resource management. Tropical sea cucumbers are widely used in the global aquaculture industry due to their high economic value and ecological contribution. With increasing demand, optimizing sea ranching techniques to achieve sustainable farming becomes essential. This study systematically evaluates traditional and modern sea ranching methods, providing a comprehensive analysis of habitat selection, environmental monitoring, feeding strategies, disease management, breeding and restocking programs. The research highlights that proper habitat selection and management, scientific supplemental feeding formulations, effective disease prevention, and health monitoring protocols are key to improving the efficiency and health of sea cucumber farming. Additionally, advancements in breeding techniques and larval rearing practices, along with considerations of ecological and economic feasibility, contribute to enhancing the sustainability of farming systems. This study aims to provide optimized solutions for tropical sea cucumber aquaculture, promoting the protection of marine ecosystems and the long-term development of the aquaculture industry.

Keywords Tropical sea cucumber; Aquaculture; Sea ranching techniques; Sustainability; Ecological management

1 Introduction

Tropical sea cucumber aquaculture has become a significant field due to the high demand for sea cucumbers in global markets, particularly in Asia where they are considered a delicacy and possess various medicinal properties (Al-Yaqout et al., 2021). The overexploitation of wild sea cucumber populations has led to a decline in their numbers, prompting the need for sustainable aquaculture practices (Sahu et al., 2022). *Various* species, such as *Holothuria scabra* and *Stichopus monotuberculatus*, have been the focus of aquaculture and sea ranching efforts due to their commercial value and ecological importance (Hair et al., 2016; Xu et al., 2022).

Sustainable sea cucumber aquaculture is crucial for several reasons. It helps conserve wild populations by reducing the pressure on natural stocks (Han et al., 2016). It supports the livelihoods of coastal communities by providing an alternative source of income through mariculture activities (Dvoretsky and Dvoretsky, 2021; Fabinyi et al., 2022). Additionally, sustainable practices ensure the long-term viability of sea cucumber farming by maintaining ecological balance and preventing habitat degradation (Hair et al., 2020; Hartati et al., 2021). Effective sea ranching techniques, such as the use of sea pens and acclimation operations, have shown promise in improving the survival and growth rates of cultured juveniles (Hair et al., 2016; Taylor et al., 2016; Xu et al., 2022).

This study evaluates and optimizes sea ranching techniques for tropical sea cucumber aquaculture by assessing the effectiveness of different release and protection methods for juvenile sea cucumbers in various marine environments, identifying the biophysical and human factors that influence the success of sea ranching operations, and exploring the socio-economic challenges and governance structures impacting community-based sea cucumber mariculture. The study aims to provide recommendations for best practices and future research directions to enhance the sustainability and productivity of tropical sea cucumber aquaculture. By synthesizing findings from multiple studies, this study contributes to the development of more efficient and sustainable sea ranching techniques, ultimately supporting the conservation of sea cucumber populations and the economic well-being of coastal communities.

2 Overview of Sea Ranching Techniques

2.1 Traditional sea ranching methods

Traditional sea ranching methods for sea cucumbers have primarily involved the use of sea pens and other containment systems to protect juveniles from predators and environmental stressors. For instance, in Papua New Guinea, hatchery-cultured juveniles of *Holothuria scabra* were released into sea pens within seagrass meadows. These pens were managed by local wardens, and various levels of protection were tested to improve survival rates. However, short-term cage protection did not significantly enhance survival, indicating the need for further research to identify optimal conditions for sea ranching (Hair et al., 2016). Similarly, in Indonesia, sea pens were used to ranch *Holothuria atra*, showing promising results with high survival rates and good adaptation to the new environment (Hartati et al., 2021).

2.2 Modern innovations

Modern innovations in sea ranching techniques have focused on improving the efficiency and effectiveness of juvenile release methods and integrating sea cucumber aquaculture with other marine farming practices. In northern Australia, researchers developed a chute release method for *Holothuria scabra* juveniles, which proved superior to traditional cage methods in terms of recovery rates and cost-effectiveness (Taylor et al., 2016). Additionally, integrated multi-trophic aquaculture (IMTA) systems have been explored, where sea cucumbers are co-cultured with other species like red drum to utilize waste products and improve overall farm sustainability. Although current stocking densities limit the full potential of IMTA, it shows promise for reducing environmental impacts and enhancing bioremediation (Chary et al., 2020).

2.3 Comparative analysis

Comparing traditional and modern sea ranching techniques reveals several key insights. Traditional methods, such as the use of sea pens, have been effective in certain contexts but often require significant management and may not always yield high survival rates (Hair et al., 2016; Hartati et al., 2021). Modern innovations, like the chute release method, offer improved efficiency and cost-effectiveness, making them more suitable for high-energy environments (Taylor et al., 2016). Furthermore, the integration of sea cucumbers into IMTA systems represents a forward-thinking approach to sustainable aquaculture, although it requires further optimization to maximize benefits (Chary et al., 2020).

The evolution from traditional to modern sea ranching techniques highlights the importance of continuous innovation and adaptation to local environmental conditions. By leveraging both traditional knowledge and modern technological advancements, sustainable sea cucumber aquaculture can be achieved, contributing to the conservation of natural stocks and the economic development of coastal communities (Xu et al., 2022).

3 Habitat Selection and Management

3.1 Criteria for habitat selection

Selecting an appropriate habitat is crucial for the success of sea cucumber ranching. The habitat must support the growth and survival of sea cucumbers while minimizing environmental impacts. Key criteria for habitat selection include biophysical parameters, environmental stability, and ecosystem compatibility. For biophysical parameters, the habitat should have suitable water quality, substrate type, and availability of natural food sources. For example, a study in Papua New Guinea found that despite meeting all considered criteria for suitable release habitat, one site experienced total loss of juveniles, indicating the complexity of habitat suitability (Hair et al., 2016).

For environmental stability, the habitat should be stable and free from extreme environmental conditions. High-energy environments, such as those in northern Australia, pose challenges for sea cucumber ranching, necessitating the development of specialized release techniques to ensure survival (Taylor et al., 2016). Regarding ecosystem compatibility, the habitat should meet the ecological requirements of the sea cucumber species. For instance, sea ranching of *Stichopus monotuberculatus* in a tropical coral reef island area in China demonstrated the importance of acclimating juveniles to the new environment to improve survival rates (Xu et al., 2022).

3.2 Environmental monitoring

Continuous environmental monitoring is crucial to ensure the habitat remains suitable for sea cucumber growth and to promptly detect any adverse changes. Key aspects of environmental monitoring include water quality, substrate conditions, and predator presence. For water quality, regular monitoring of parameters such as temperature, salinity, pH, and dissolved oxygen is essential. Poor water quality can lead to high mortality rates, as observed in various studies (Hair et al., 2016; Xu et al., 2022). During the study by Xu et al. (2022), the growth performance, nutritional composition, and food sources of sea cucumbers were monitored (Figure 1). Results showed that sea cucumbers grew well during the experimental period, with a survival rate of 27.5%, and significant accumulation in nutritional composition, validating the feasibility of sea ranching in that area.

For substrate conditions, monitoring changes in composition and quality is also important, as sea cucumbers rely on the substrate for food and shelter. In China, the use of dedicated ponds with controlled substrate conditions has been successful in sea cucumber aquaculture (Han et al., 2016). Regarding predator presence, monitoring for predators and implementing measures to exclude them can significantly improve survival rates. Although short-term predator exclusion methods are not always effective, they are among the strategies tested in different habitats (Hair et al., 2016).

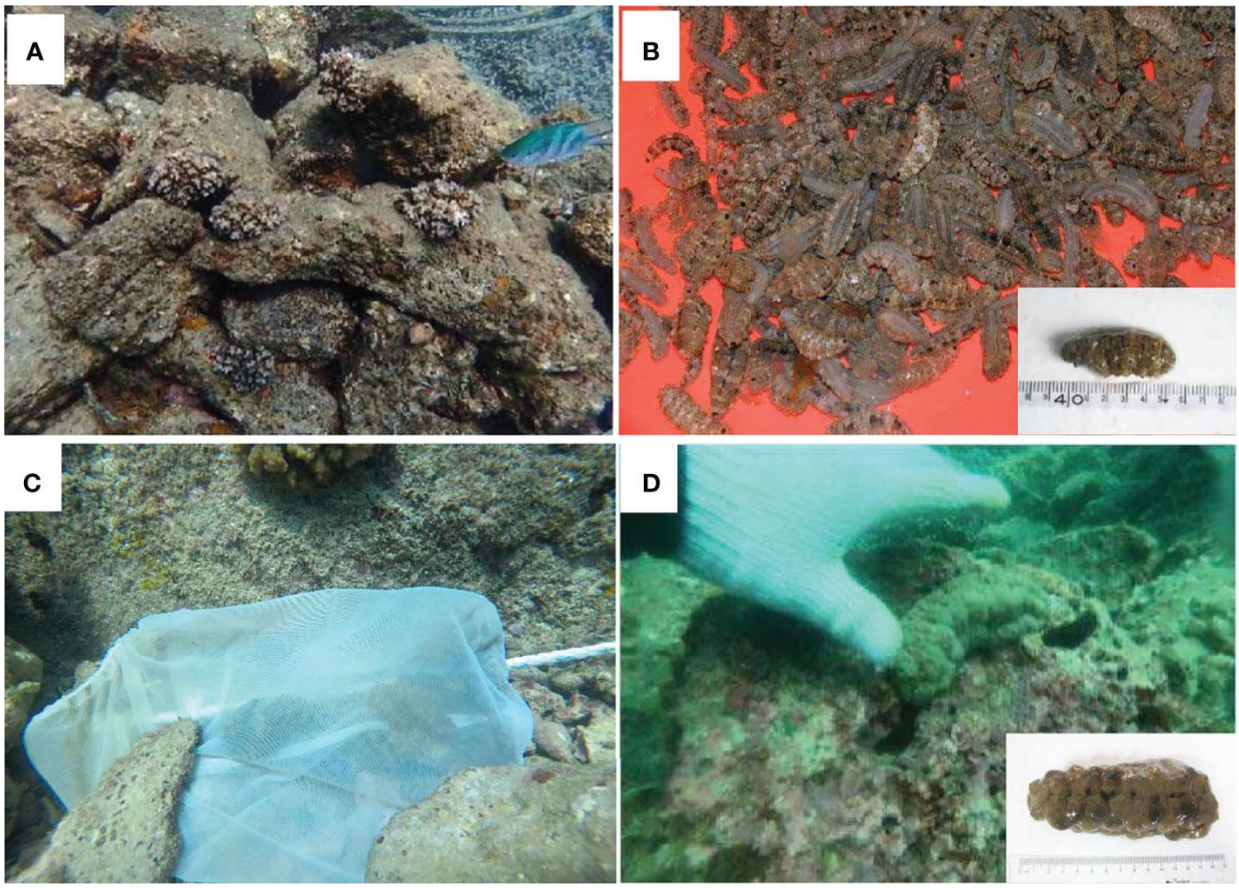

Figure 1 The deployed volcano rocky artificial reefs with settled corals (A); Sea cucumber *Stichopus monotuberculatus* juveniles in the hatchery (B); The self-release mesh bag with juveniles in it (C); A sea-ranched individual 8 months after release (D) (Adopted from Xu et al., 2022).

The figure from Xu et al. (2022) illustrates the cultivation process of the tropical sea cucumber *Stichopus monotuberculatus*, including the transition and acclimation stages from the hatchery to the wild environment. The figure emphasizes the importance of acclimation procedures before release to enhance the survival rates of sea cucumbers. Continuous environmental monitoring is crucial to ensure the habitat remains suitable for sea cucumber growth and to promptly detect any adverse changes. The data and methods presented in the figure provide valuable references for optimizing tropical sea cucumber aquaculture techniques.

3.3 Management practices

Effective management practices are vital for the sustainability and productivity of sea cucumber ranching. These practices include release techniques, acclimation procedures, integrated multi-trophic aquaculture (IMTA), and community involvement. For release techniques, the method of releasing juveniles into the habitat can impact their survival and dispersal. In northern Australia, the chute release method proved superior to cage release due to higher recovery rates and lower costs (Taylor et al., 2016; Juinio-Meñez et al., 2017; Zhou et al., 2019).

For acclimation procedures, acclimating juveniles to the new environment before release can improve survival rates. This was highlighted in the study of *Stichopus monotuberculatus*, where appropriate acclimation operations were recommended (Xu et al., 2022). For integrated multi-trophic aquaculture (IMTA), combining sea cucumbers with other species in an IMTA system can enhance environmental sustainability by utilizing waste products as food for sea cucumbers. This approach has shown promise in reducing waste and improving overall farm efficiency (Chary et al., 2020; Grosso et al., 2020).

Regarding community involvement, engaging local communities in the management of sea ranching operations can enhance sustainability and economic benefits. In the Philippines, evolving governance structures in community-based mariculture have shown that integrating community involvement with effective management practices can lead to better livelihood outcomes (Fabinyi et al., 2022). By adhering to these criteria and management practices, sea cucumber ranching can be optimized for sustainability and productivity, contributing to the conservation of natural stocks and the economic development of coastal communities.

4 Feeding Strategies and Nutritional Requirements

4.1 Natural diets and foraging behavior

4.1.1 Assessing natural food availability

Natural food availability is a critical factor in the successful sea ranching of tropical sea cucumbers. Studies have shown that sea cucumbers primarily feed on organic matter derived from various sources such as water deposits, seaweed debris, phytoplankton, and coral mucus-derived organics. For instance, in a study conducted on the sea cucumber *Stichopus monotuberculatus* in the South China Sea, stable isotope and lipid biomarkers revealed that these food sources were crucial for their growth and survival (Xu et al., 2022). Additionally, the northern sea cucumber *Cucumaria frondosa* in the Barents Sea primarily consumes detritus, pellets, phytoplankton, and small planktonic crustaceans, indicating a diverse natural diet (Dvoretsky and Dvoretsky, 2021).

4.1.2 Formulating supplemental diets

Formulating effective supplemental diets is essential to enhance the growth and health of sea cucumbers in aquaculture settings. Research on integrated multi-trophic aquaculture (IMTA) systems has demonstrated the benefits of using diets with varying fish meal concentrations. For example, a study on the co-culture of sea urchins and sea cucumbers found that a diet containing 20% fish meal (D-20) was most effective in promoting growth for both species (Grosso et al., 2020). This suggests that incorporating a balanced mix of vegetable and animal-based nutrients can optimize the nutritional intake of sea cucumbers.

4.1.3 Impact on growth and health

The impact of diet on the growth and health of sea cucumbers is significant. In the study of *Stichopus monotuberculatus*, the sea cucumbers exhibited a growth rate of 0.35-0.78 mm per day and a weight gain of 491.13% over an 8-month period, reaching commercial size within the first year of sea ranching (Xu et al., 2022). However, a notable decrease in nutritional indexes such as amino acids, total lipid, and crude protein was observed, particularly in the first month after release, likely due to environmental adaptation challenges. This highlights the importance of acclimation and appropriate diet formulation to support the health and growth of sea cucumbers in aquaculture (Hartati et al., 2021).

4.2 Supplemental feeding techniques

Supplemental feeding techniques play a crucial role in the success of sea cucumber aquaculture. The use of IMTA systems, where sea cucumbers are co-cultured with other species such as sea urchins, has shown promise in

reducing waste and enhancing growth. In such systems, sea cucumbers can effectively utilize organic matter from the feces of other species, thereby improving nutrient recycling and reducing environmental impact (Zamora et al., 2018; Grosso et al., 2020). This approach not only supports the growth of sea cucumbers but also contributes to the overall sustainability of the aquaculture system.

4.3 Nutritional composition and requirements

Understanding the nutritional composition and requirements of sea cucumbers is essential for optimizing their growth and health in aquaculture. Sea cucumbers require a diet rich in organic matter, including detritus, phytoplankton, and other marine-derived nutrients. The nutritional needs can vary based on species and environmental conditions. For example,Cucumaria frondosain the Barents Sea thrives on a diet that includes detritus and small planktonic crustaceans, while *Stichopus monotuberculatus* benefits from a diet supplemented with fish meal and other organic materials (Figure 2) (Dvoretsky and Dvoretsky, 2021; Xu et al., 2022). Ensuring that these nutritional requirements are met through natural foraging and supplemental feeding is key to the sustainable aquaculture of sea cucumbers.

Optimizing feeding strategies and understanding the nutritional requirements of sea cucumbers are vital for the success of sea ranching and aquaculture. By assessing natural food availability, formulating effective supplemental diets, and employing sustainable feeding techniques, it is possible to enhance the growth, health, and overall sustainability of tropical sea cucumber aquaculture. The cultivation process of the sea cucumber *Cucumaria frondosa* in the Russian waters of the Bering Sea includes fertilization under laboratory conditions, larval rearing, transfer to the seabed, and the stages of ranching and harvesting. Figure 2 emphasizes the importance of nutritional composition and requirements for the growth and health of sea cucumbers. By controlling the nutritional supply to larvae, survival rates and growth speeds can be significantly improved, optimizing farming efficiency. This detailed process provides valuable reference cases for sea cucumber farming in other regions.

5 Disease Management and Health Monitoring

5.1 Common diseases in sea cucumbers

Sea cucumbers, particularly those in aquaculture, are susceptible to various diseases, primarily due to weakened immunity or the prevalence of pathogenic bacteria. *Apostichopus japonicus*, a commercially important species, often faces bacterial infections that can significantly impact its health and survival rates (Zhang et al., 2021). These infections are exacerbated by the intensive farming conditions and the high density of individuals, which facilitate the spread of pathogens.

5.2 Disease prevention strategies

To mitigate the impact of diseases in sea cucumber aquaculture, several eco-friendly alternatives to antibiotics have been explored. The use of immunostimulants to enhance the immune responses of sea cucumbers and antagonists to inhibit bacterial pathogens has shown promise. These methods aim to prevent bacterial infections without the drawbacks associated with antibiotics, such as the development of antibiotic-resistant bacteria and environmental degradation (Zhang et al., 2021). Additionally, proper acclimation procedures before releasing hatchery-reared juveniles into the wild can improve their survival rates by reducing stress and enhancing their ability to adapt to new environments (Xu et al., 2022).

5.3 Health monitoring protocols

Effective health monitoring protocols are crucial for the sustainable management of sea cucumber aquaculture. Regular monitoring of growth performance indexes, nutritional components, and survival rates can provide valuable insights into the health status of sea cucumbers. For instance, in a study on *Stichopus monotuberculatus*, growth rates, weight gain, and survival rates were closely monitored to assess the feasibility of sea ranching in a tropical coral reef area (Xu et al., 2022). Implementing a tiered harvest strategy that includes pre-agreed, transparent rules for monitoring and data collection can also support sustainable management practices. This approach encourages the collection of both fishery-dependent and fishery-independent data to inform decision-making and regulate the fishery effectively (Plagányi et al., 2020).

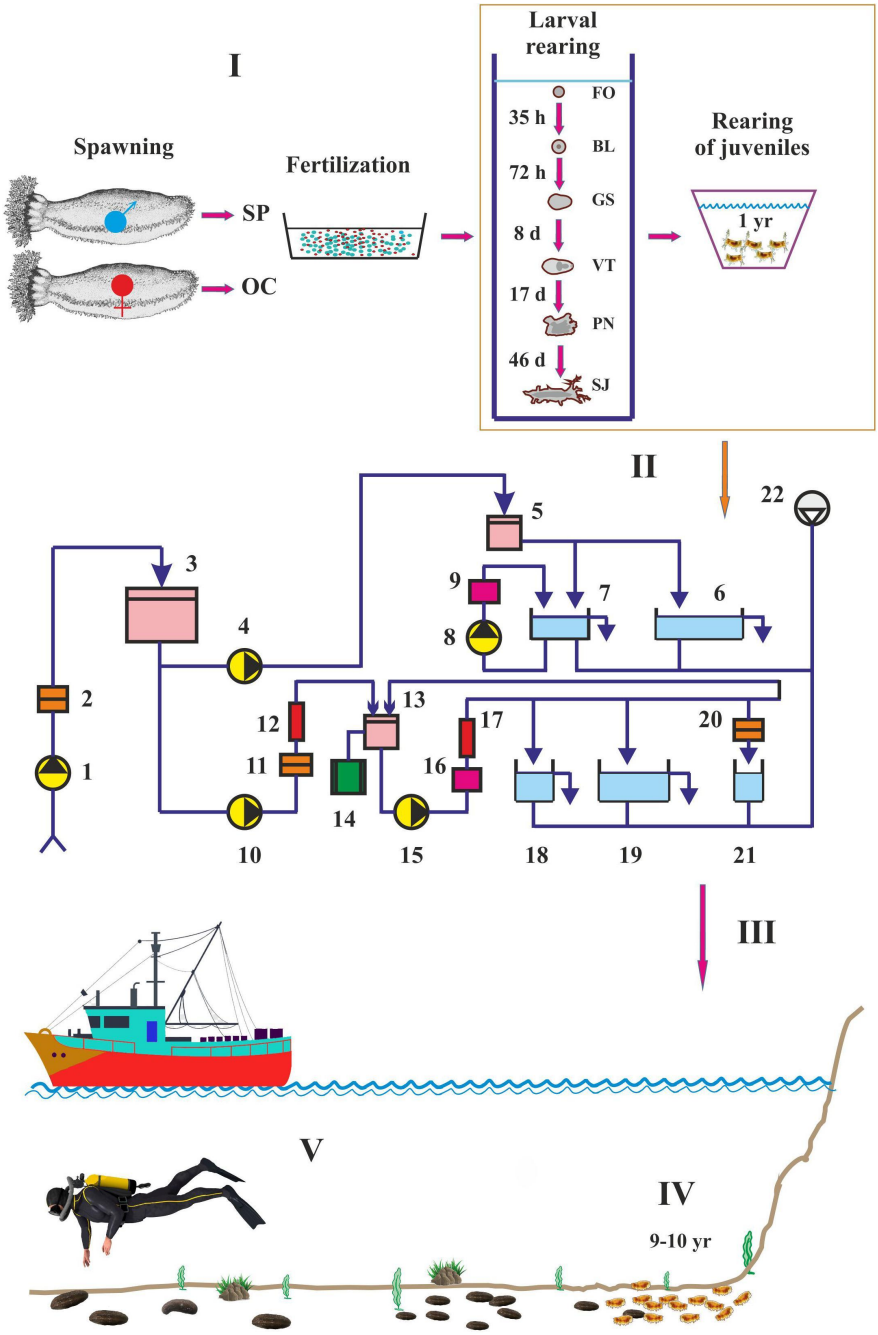

Figure 2 Cultivation of Cucumaria frondosa (Adopted from Dvoretsky and Dvoretsky, 2021)

Image caption: I – fertilization under laboratory conditions, II – schematic diagram of the TINRO commercial rearing system, III – transfer of juveniles on the seafloor, IV – sea ranching, V – harvesting (adopted from Hamel and Mercier, 1996; Gavrilova et al., 2006). SP, sperm, OC, oocytes. FO, fertilized oocytes, BL, blastula, GS, gastrula, VT, vitellaria, PN, pentactula, SJ, settled juvenile. 1, 4, 8, 10, 15 – pump for seawater; 2 – filter (pore diameter 150–200 μm); 3 – septic tank; 5, 13 – water can; 6 – holding tank for juveniles; 7 – broodstock tank; 9, 16 – chiller, 11 – micro-filter (pore diameter 20–40 μm); 12, 17 – UV-sterilizer with ozonation; 14 – heater with thermoregulation; 18 – tank for spawning and fertilization; 19 – rearing tank for larvae; 20 – ultra-filter (pore diameter 0.1–0.2 μm); 21 – tank for food items; 22 – aerator (Adopted from Dvoretsky and Dvoretsky, 2021)

6 Breeding and Restocking Programs

6.1 Breeding techniques

Breeding techniques for sea cucumbers have been explored for various species to support aquaculture and restocking efforts. For instance, *Holothuria arguinensis* was successfully induced to spawn using thermal stimulation, with larval development reaching the juvenile stage after 18 days post-spawning, although high mortality rates were observed at the doliolaria and juvenile stages (Domínguez-Godino et al., 2015). Similarly,

Holothuria polii was induced to spawn using thermal shock, which proved effective in obtaining healthy gametes, with larvae reaching the pentactula stage in 10 days (Rakaj et al., 2019). *Holothuria tubulosa* also responded well to thermal stimulation plus thermal shock, with larvae reaching the juvenile stage in 27 days (Rakaj et al., 2018). For the tropical species *Stichopus monotuberculatus*, a modified low-temperature stimulation method was more suitable for inducing spawning, resulting in a detailed record of gonadal and embryonic development (Cheng et al., 2021). These methods highlight the importance of optimizing spawning induction techniques to improve breeding success across different sea cucumber species (Wang et al., 2022).

6.2 Larval rearing practices

Larval rearing practices are crucial for the successful aquaculture of sea cucumbers. For Holothuria polii, three different microalgal feeding regimens were tested, with the highest concentration (20,000~40,000 cells/mL) proving most effective, resulting in 14% of larvae metamorphosing into settled juveniles (Rakaj et al., 2019). In the case of Holothuria leucospilota, a combined diet of microalgae (*Chaetoceros muelleri*) and yeast (*Saccharomyces cerevisiae*) at a 3:1 ratio was found to be optimal, significantly improving larval survival, growth, and development (Yu et al., 2022). For *Stichopus monotuberculatus*, diets supplemented with digestive enzymes such as α-amylase, cellulase, and trehalase improved larval survival rates and settlement rates significantly compared to control groups (Cheng et al., 2021). These findings underscore the importance of diet optimization in larval rearing to enhance survival and growth rates.

6.3 Restocking strategies

Restocking strategies involve the release of hatchery-reared juveniles into natural habitats to replenish depleted populations. For *Holothuria scabra*, experimental releases of juveniles into seagrass meadows in Papua New Guinea showed varying levels of success depending on the site and protection measures, with significant differences in juvenile growth observed between sites (Hair et al., 2016). Similarly, an 8-month sea ranching study for *Stichopus monotuberculatus* in a tropical coral reef island area in China demonstrated the feasibility of this approach, with juveniles reaching commercial size within the first year, although high mortality was observed in the first month post-release (Xu et al., 2022). These studies highlight the potential of sea ranching and restocking as viable strategies for sustainable sea cucumber aquaculture, while also emphasizing the need for site-specific assessments and acclimation procedures to improve survival rates.

By integrating optimized breeding techniques, effective larval rearing practices, and strategic restocking approaches, sustainable tropical sea cucumber aquaculture can be achieved, contributing to the conservation of natural populations and meeting market demands. Further research and refinement of these methods are essential to address the challenges and improve the overall success of sea cucumber aquaculture programs.

7 Environmental and Socio-Economic Impacts

7.1 Ecological considerations

7.1.1 Assessing ecosystem health

The health of ecosystems where sea cucumber ranching is implemented is a critical factor for the success and sustainability of these operations. Studies have shown that sea cucumber ranching can contribute positively to ecosystem health by alleviating overfishing pressures on natural populations and enhancing the ecological balance. For instance, the sea ranching of *Stichopus monotuberculatus* in the South China Sea demonstrated that sea cucumbers could grow to commercial size within a year, suggesting that ranching can help relieve stress on natural populations and protect coral reef ecosystems (Xu et al., 2022). Additionally, the integration of sea cucumbers in multi-trophic aquaculture systems has been shown to have bioremediation potential, reducing particulate waste and benthic impacts, although the scale of sea cucumber production needs to be significantly increased to achieve substantial environmental benefits (Chary et al., 2020).

7.1.2 Evaluating economic benefits

The economic benefits of sea cucumber ranching are multifaceted, encompassing direct financial gains from harvests and broader socio-economic impacts. In the Philippines, communal sea ranching projects have generated various livelihood benefits, although substantial economic returns from harvests were not always realized, leading

to a shift from communal to more exclusive household models to improve operational efficiency (Fabinyi et al., 2022). In northern Australia, improved release techniques for cultured sea cucumbers have shown promise in enhancing recovery rates and operational efficiency, which could translate into better economic outcomes for ranchers (Taylor et al., 2016). Furthermore, the successful growth and survival rates of *Holothuria atra* in Indonesia indicate that sea ranching can be a viable economic activity, contributing to local livelihoods and food security (Hartati et al., 2021).

7.1.3 Strategies for community involvement

Community involvement is crucial for the success of sea cucumber ranching projects. Effective governance structures and community engagement can significantly influence the outcomes of these projects. In Papua New Guinea, community-based mariculture projects faced challenges such as poaching and weak local leadership, which hindered their success. However, involving local communities as 'wardens' to oversee sea pens and protect juvenile sea cucumbers has shown potential in improving survival rates and fostering a sense of ownership and responsibility among community members (Hair et al., 2016). Additionally, integrating community-based management with broader fisheries management and government support can enhance the sustainability and benefits of sea ranching projects (Fabinyi et al., 2022).

7.2 Economic viability

The economic viability of sea cucumber ranching depends on several factors, including the species being cultured, the methods used, and the local environmental conditions. In China, the development of sea cucumber aquaculture has been highly successful due to advances in culture methods and the establishment of dedicated ponds and ocean ranching systems (Han et al., 2016). However, the economic viability of these operations can be threatened by environmental challenges and diseases, necessitating ongoing research and adaptation of practices. In northern China, assessing the ecological carrying capacity for stock enhancement is essential to ensure that ranching activities do not negatively impact ecosystem function and resilience, thereby supporting long-term economic viability (Wang et al., 2022).

7.3 Community engagement

Community engagement is a cornerstone of successful sea cucumber ranching projects. Ensuring that local communities are actively involved in the planning, implementation, and management of these projects can lead to better outcomes and more sustainable practices. In the Philippines, the evolution of governance structures in community-based mariculture projects highlights the importance of adapting institutional arrangements to local contexts and challenges (Fabinyi et al., 2022). In Papua New Guinea, despite the initial failure of a community sea ranch due to poaching and governance issues, the widespread community approval and respect for the project indicate a strong potential for future success with improved management and support (Hair et al., 2016). Engaging communities through education, capacity building, and participatory governance can enhance the sustainability and socio-economic benefits of sea cucumber ranching.

8 Concluding Remarks

Various studies have optimized sea ranching techniques for tropical sea cucumber aquaculture, revealing critical insights. Research indicates that the survival and growth of hatchery-reared sea cucumbers are significantly influenced by release methods and environmental conditions. For example, short-term predator exclusion did not consistently improve survival rates, indicating the need for site-specific strategies. In high-energy environments, chute release methods showed higher recovery rates compared to cage methods, highlighting the importance of choosing the appropriate release technique for success. Additionally, acclimation operations before release are recommended to improve survival rates, as sudden environmental changes can lead to high mortality. The development of community governance structures has also improved operational efficiency and livelihood outcomes, emphasizing the importance of institutional arrangements in sea ranching projects.

Optimizing sea ranching techniques is vital for the sustainable development of tropical sea cucumber aquaculture. Effective sea ranching can alleviate pressure on wild stocks, contributing to the conservation of natural resources and the protection of marine ecosystems. Improved techniques can enhance the economic viability of sea

cucumber farming, providing significant livelihood benefits to coastal communities. Developing practical and economically sound release methods, such as chute release techniques, can lead to higher recovery rates and better growth performance, making sea ranching a more reliable and profitable venture. Understanding the biophysical and human factors influencing site suitability can guide the establishment of successful sea ranching operations, ensuring long-term sustainability.

Future research should focus on several key areas to further optimize sea ranching techniques for tropical sea cucumber aquaculture. More comprehensive studies are needed to identify the biophysical and human factors determining the suitability of potential sea ranching sites, including understanding the interactions between environmental conditions and sea cucumber survival and growth. Investigating best practices for acclimating hatchery-reared juveniles to natural environments before release can help reduce initial mortality rates and improve overall survival. Continued exploration of different release methods, including refining chute and cage techniques, can provide insights into the most effective strategies for various environmental conditions. Researching the evolution of governance structures in community-based sea ranching projects can offer valuable lessons on balancing operational efficiency with equitable livelihood outcomes. Finally, studying the ecological impacts of sea cucumber aquaculture and ranching is essential to ensure these practices do not adversely affect marine ecosystems, including monitoring interactions between aquaculture farms and wild organisms. Addressing these research areas can advance the optimization of sea ranching techniques, promoting sustainable and profitable sea cucumber aquaculture in tropical regions.

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Conflict of Interest Disclosure

The authors affirm that this research was conducted without any commercial or financial relationships that could be construed as a potential conflict of interest.

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