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Environmental Impact of Tropical Sea Cucumber Mariculture Practices

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Abstract In recent years, with the increase in market demand and the emergence of economic benefits, the tropical sea cucumber farming industry has developed rapidly. Sea cucumbers, as benthic animals, have the functions of biological disturbance and potential ecological purification. However, intensive and large-scale breeding have also brought about many environmental impact problems. This study aims to comprehensively assess the environmental impact of tropical sea cucumber farming practices, with a focus on analyzing the mechanisms and degrees of their effects on sediment conditions, water quality parameters, and ecosystem diversity. It also aims to summarize various farming models and management techniques, explore changes in biodiversity and ecological service functions, and present typical case studies of Indonesia, Papua New Guinea, and the South China Sea. Research has found that sea cucumber farming at moderate density helps improve sediment quality and promote nutrient cycling. However, under poor management conditions, it is prone to cause local water eutrophication, imbalance in microbial community structure and decline in ecosystem stability. Multi-nutrient-level integrated aquaculture (IMTA) demonstrates a strong environmental adaptability. This research helps to deepen the understanding of the environmental impact of tropical sea cucumber farming and provides theoretical basis and practical reference for eco-friendly aquaculture policies and technologies.

Keywords Tropical sea cucumber farming; Environmental impact assessment; Sediment ecology; Multi-nutrient-level integrated aquaculture (IMTA); Sustainable aquaculture

1 Introduction

Sea cucumbers, these seemingly unremarkable mollusks, play a significant ecological role in tropical seas. Especially tropical sea cucumbers, which are classified in the class Holothuroidea and belong to benthic invertebrates, are not only numerous and widely distributed, but also involved in a whole set of ecological cycles, such as sediment migration, nutrient redistribution and organic matter degradation, etc. (Purcell et al., 2016). There are currently over 1,700 known tropical species. Among them, the most "viral" ones have to be the "star varieties" like Holothuria scabra and Stichopus monotuberculatus - not only because of their taste and nutrition, but also because they are very popular in the medicinal and health supplement markets, especially in Asia. It is regarded as a high-end ingredient and functional component (al-yaqout et al., 2021). However, the high market heat has also brought about side effects. The demand for dried sea cucumbers is on the rise. Coastal communities have indeed earned a decent income from fishing, but at the same time, wild resources are also running low. Overfishing has pushed many species to the brink of depletion. To relieve this pressure, tropical sea cucumber farming emerged, especially developing rapidly in the Indo-Pacific and coastal areas of Asia. Among them, China not only started early but is also very active in breeding technology. From hatching, seedling raising to adult cultivation, a relatively mature industrial chain has been formed.

But things are not that simple. Integrated multi-trophic aquaculture (IMTA) has been highly regarded in recent years. To put it simply, it involves raising sea cucumbers together with other species. This approach can indeed make more full use of resources and has a relatively smaller environmental burden (Zamora et al., 2018; Ciriminna et al., 2024). The problem is that there have been no shortage of controversies surrounding this kind of intensive breeding, such as how to deal with the spread of diseases? How to control genetic pollution? Will the original habitat be changed. Once the scale becomes too large, are there any other ecological consequences that we haven't anticipated. These are all actual concerns (Chary et al., 2020). It's true that the economy can bring benefits, but the ecological aspect cannot be underestimated. At present, how to achieve profits while maintaining the ecological bottom line has become an unavoidable topic in tropical sea cucumber farming.

This research focuses precisely on this issue. We want to sort out the ecological impacts of tropical sea cucumber farming from different perspectives, including the possible changes it may bring in sediment restoration, water quality improvement and biodiversity. At the same time, we will also start from the breeding model and management techniques, and combine real cases to clearly understand the current development trends and controversial points of the industry. It is hoped that this work can provide some references for future policy-making and eco-friendly breeding practices, and also help everyone more clearly recognize that in the matter of breeding, the environment and the economy have never been mutually exclusive oppositances.

2 Tropical Sea Cucumber Farming Models and Management Practices

2.1 Major farming models: pond culture, sea ranching, and integrated multi-trophic aquaculture (IMTA)

The cultivation methods of tropical sea cucumbers are not monotonous. Each model has its own suitable scenarios and management focuses. Pond farming is currently the most common method, especially suitable for species like the rough sea cucumber (Holothuria scabra) that have clear requirements for their growth environment. The pond environment is easy to control, and seedling raising and cultivation are convenient. However, problems are also prone to occur - such as the potential risks of nutrient overflow caused by artificial feed and deterioration of water quality (Zamora et al., 2018; Guo et al., 2025). Let's take a look at the "sea release" method. In fact, it is to release young ginseng into natural or semi-natural environments. This method relies more on the management of local communities and has relatively low costs. However, the area needs to be large enough. If the management is not in place, problems such as illegal fishing and excessive harvesting may occur (Fabinyi et al., 2022). Another model that is increasingly valued is IMTA, which involves raising sea cucumbers together with other species such as fish, shellfish, and seaweed. Its principle is simple: sea cucumbers are used to "treat" the residues of other species, reducing the accumulation of organic waste in the system. It sounds good, but it is not a "universal solution". The effect depends on whether the species combination is reasonable and whether the production scale is balanced (Kunzmann et al., 2018; Ciriminna et al., 2024).

2.2 Farming management techniques: feed supply, water quality control, and stocking density regulation

No matter which mode is adopted, whether the care is good or not often depends on three key points: what is eaten, whether the water quality is good or not, and whether the density is placed correctly. In ponds or IMTA systems, the feed strategy should follow the species. Some sea cucumbers consume natural sediment debris, while others need to be fed with formula feed. However, overfeeding or inappropriate feed can easily lead to excessive nutrients in water bodies and aggravated pollution (Purcell et al., 2012). Especially for closed systems, water quality changes rapidly, making control even more crucial. Issues such as ammonia nitrogen accumulation and unstable pH all need to be addressed. The introduction of circulating water systems, biological filters or "natural scavengers" such as seaweed and halophytes can alleviate the pollution problem to a certain extent (Senff et al., 2020; Huo et al., 2024). The issue of density is rather subtle - if too much is placed, individuals will grow slowly and diseases are more likely to break out. If too little is placed, the system utilization rate may be too low and it is not cost-effective (Namukose et al., 2016). How much is just appropriate? It depends on what kind of plant it is, where it is raised and what the goal is.

2.3 Regional differences and the role of farming scale in modulating environmental impact

The farming methods of tropical sea cucumbers in different regions are greatly influenced by local natural conditions and social backgrounds. In the Indo-Pacific region, small-scale aquaculture is relatively common, such as pond and community stocking methods. Many of them rely on small fishermen for a living (Juinio-menez et al., 2017; Kunzmann et al., 2023). In East Africa and along the coast of the western Indian Ocean, it is more inclined to co-culture with seaweed. The IMTA system has also begun to be gradually promoted, mainly to alleviate ecological pressure and enhance the sustainability of aquaculture (Senff et al., 2020). But when it comes to environmental impact, the size of the scale is really an issue that cannot be avoided. Small-scale and community-based breeding has a small impact and high acceptance. Conversely, if large-scale and intensive systems are not managed properly, pollution, diseases and even habitat destruction may follow one after another (Zamora et al., 2018; Chary et al., 2020; Magondu et al., 2021). To expand the scale of IMTA without any problems, the key still lies in flexible management measures to act as a "balance beam".

3 Impact on Benthic Environments

3.1 Effects of sea cucumber feeding behavior on sediment structure and nutrient release

Don't be fooled by the slow appearance of sea cucumbers. They are not idle during the process of turning over silt at the bottom of the sea. What they consume is not clean sand but "nutrient mud" rich in organic matter, which is exactly what they like. Sea cucumbers digest the easily decomposing parts and then discharge the treated sediment, which to some extent can be regarded as giving the sediment a "makeover". Such processes often change the structure of sediment and also bring out some stored nutrients. For instance, the release of ammonium increases significantly, which is beneficial to benthic algae - it can promote their growth (MacTavish et al., 2012; Purcell et al., 2016). However, the undigested proteins and lipids in feces are actually quite sought-after. Many other benthic animals will take over and continue to break them down and utilize them. In high-density aquaculture environments, the "scavenger" eating method of sea cucumbers is particularly crucial. They can break down excess organic matter and reduce the burden on sediment in the aquaculture system - especially when the feed input is excessive, the effect is more obvious (Pasquini et al., 2023).

3.2 Benthic eutrophication and organic matter accumulation issues

Once the organic matter in the sediment accumulates too much, the system begins to malfunction. Intensive farming can easily exacerbate this eutrophication, especially when it accumulates at the bottom. Can sea cucumbers alleviate this problem? The answer is - it depends. They can indeed accelerate the rate of debris decomposition and reduce the concentrations of organic carbon and nutrients, especially at appropriate densities (Ennas et al., 2023). However, if the density is too high or the system management is unreasonable, the situation may be reversed. Not only will the problem not be alleviated, but local organic matter may also accumulate more (Namukose et al., 2016; Hou et al., 2017; Zamora et al., 2018). Therefore, "how much to put" and "how to raise" remain the key factors determining whether sea cucumbers can play a purifying role.

3.3 Bioturbation and microbial community restructuring in sediments

Sediment is not dead, especially when sea cucumbers are churning inside. Their activities stir up sedimentary layers, causing changes in the REDOX environment of the sediments and also affecting the microbial composition within them (Figure 1). Some studies have found that after sea cucumbers are active, the bacterial abundance increases and the number of primary producers at the bottom decreases. Instead, those bacteria that are good at decomposing organic matter gain the upper hand (Namukose et al., 2016; Yamazaki et al., 2019). Oxygen production decreases, the number of active microorganisms in anaerobic or hypoxic environments increases, and certain functional genes also increase accordingly (MacTavish et al., 2012; Maritan et al., 2025). Such changes not only concern the microorganisms themselves, but also affect the stability and functional performance of the entire benthic system (Robinson et al., 2016; Wang et al., 2023). It is worth noting that the feeding and excretion of sea cucumbers are not "one-off". They repeatedly process the sediment in the same area, thereby selectively enriching certain microbial groups and causing a shift in the microbial composition of the sediment. This may also be a manifestation of ecosystem self-regulation (Wang et al., 2023).

4 Impact on Water Quality and Planktonic Systems

4.1 Suspended particulate matter (SPM) and water transparency variations

In tropical regions, whether sea cucumbers are farmed alone or placed in a mixed system like IMTA, people have found that the water becomes clearer. This is not surprising - sea cucumbers themselves like to "eat" the organic particles that sink to the bottom, and as a result, they also carry away the suspended solids (SPM) in the water. In contrast, in ponds or systems without sea cucumber farming, the concentrations of colored dissolved organic matter

(CDOM) and suspended solids in the water are much higher, and the water clarity is also lower (Meirinawati et al., 2020). This is actually related to the feeding characteristics of sea cucumbers. They can process a large amount of POM and some gelatinous particles, reducing the absorption and scattering of light in water. However, it also depends on the density and the underlying environmental conditions. It's not the case that placing sea cucumbers will definitely be good.

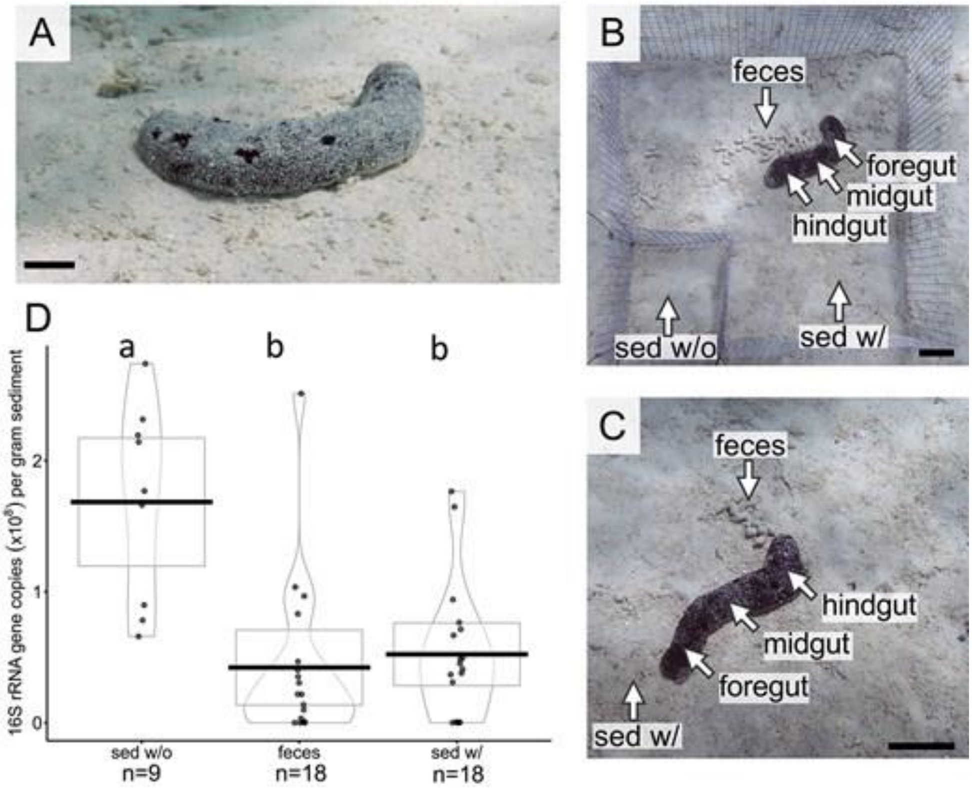

Figure 1 Sediment microbial load decreases in the presence of the sea cucumber *Holothuria atra* (Adopted from Maritan et al., 2025)

4.2 Nitrogen and phosphorus cycling and responses in primary productivity

Sea cucumber farming not only helps to "clear the bottom", but also plays a significant role in the circulation of nutrients. They will absorb some inorganic nitrogen and phosphorus and also discharge them. This process promotes nutrient reuse to a certain extent and is also helpful for the primary production of the entire water body (Purcell et al., 2016). Especially in the IMTA system, "troublesome" indicators such as ammonia, nitrate and total phosphorus often decline significantly (Huo et al., 2024). Some farmers also add sodium bicarbonate as a carbon source to build a biofc system. As a result, the pH stabilizes, ammonia nitrogen decreases, and sea cucumbers grow well (Xiao et al., 2024). However, to improve these indicators, it really cannot rely solely on the sea cucumber species. Studies have found that when sea cucumbers are co-cultured with shrimp or even jellyfish, the removal rates of nitrogen and phosphorus are higher, but the prerequisite is that the quantities of each species are properly matched; otherwise, the effect will be reduced (Li et al., 2014; Chary et al., 2020).

4.3 Comparison of physicochemical parameters between cultured and non-cultured areas

The same sea water can make a big difference whether sea cucumbers are raised or not. Many comparative studies in various places have shown that key indicators such as pH, dissolved oxygen, ammonia nitrogen and nitrate in aquaculture areas are more stable and closer to the ideal range. In waters without sea cucumbers, these data tend to fluctuate greatly, especially in the context of intensive aquaculture (Sadeghi-Nassaj et al., 2018; Zamora et al., 2018). In addition, sea cucumbers can also help reduce the number of bacteria in water bodies and improve water transparency, which is beneficial to the habitats of plankton and benthic animals. However, these effects are not equally significant everywhere (Liu and Han, 2025). It also depends on how the system structure is designed, what species are raised, and whether the daily management methods are in place.

5 Changes in Biodiversity and Ecosystem Services

5.1 Positive and negative impacts on benthic faunal diversity

Not all sea cucumber farming can bring ecological benefits. In some systems, the activities of sea cucumbers can indeed have positive effects. For example, during the process of feeding and turning the sediment, they can promote nutrient cycling, reduce the accumulation of organic matter, and provide more "breathing space" for benthic animals (MacTavish et al., 2012). In such environments, not only benthic small animals, but also the diversity and number of some symbiotic species and upper-middle consumers may increase. Even some studies suggest that sea cucumbers have indirectly helped seagrass, promoting the growth of primary producers and driving greater ecosystem vitality (Arnull et al., 2021). However, to be fair, if the density is too high or management is inadequate, the situation will change. Sediments may become more compact, oxygen deficiency may intensify, and diseases may also breed easily. In such environments, some sensitive benthic species may be suppressed instead. Whether it is good or bad depends on the local environmental conditions, the stocking density and the specific type of sea cucumber (Namukose et al., 2016).

5.2 Shifts in ecosystem services: bio-cleaning vs. ecological disturbance

It is often said that sea cucumbers are natural "scavengers". Indeed, they perform well in cleaning up sediment and stabilizing water quality. Especially in multitrophic systems such as IMTA, the addition of sea cucumbers can significantly slow down the trend of eutrophication and help nutrients re-flow in the system (Purcell et al., 2016; Zamora et al., 2018). However, this "cleaning effect" is not without conditions. Once the system becomes closed, overly dense or has management problems, the original ecological services may turn into sources of interference. For instance, excessive disturbance of the sediment, rapid release of nutrients, and even the accelerated spread of certain diseases within the system. That is to say, the ecological services brought by sea cucumbers cannot be simply regarded as a "universal tool". Appropriate design and early warning mechanisms are still necessary.

5.3 Estimation methods for ecological thresholds and environmental carrying capacity

How many sea cucumbers can a system actually raise? It is unlikely that there will be a uniform answer to this question. The differences can be quite significant in different places and under different conditions. But there had to be an explanation, so the researchers tried every possible way to "calculate". Some use models, such as the individual energy flow model, or ecosystem tools like Ecopath with Ecosim; Some people simply conducted on-site tests to see how the environment reacted and whether the number of species changed after placing a certain amount (Chary et al., 2020; Wang et al., 2022; Grosso et al., 2023). There is also life Cycle assessment (LCA), which is more comprehensive. It measures whether the system is on the verge of collapse from aspects such as energy and water usage, and nutrient flow. Ultimately, calculating all this is not to arrive at a fixed figure, but to figure out at which point the benefits of bioremediation will be offset by potential risks. Some environmental factors cannot be ignored either, such as the speed of water flow, the abundance of food, and those ecological changes that gradually accumulate. All these may cause the so-called "optimal density" to fluctuate. Therefore, carrying capacity is not a matter of making a guess based on formulas, but rather depends on whether it aligns with the actual situation.

6 Case Studies

6.1 Sediment impact assessment of pond-based sea cucumber farming in Indonesia

In Indonesia, when it comes to pond sea cucumber farming, many people's first reaction is that it is quite helpful for the bottom sediment, especially for those farms with low farming density and sufficient daily maintenance. Indeed, the substrate can become cleaner and organic matter is less likely to accumulate. But things don't always go so smoothly. Once the breeding density exceeds that "appropriate range", especially after artificial feed is started to be used, the mess at the bottom begins to become troublesome. Organic matter begins to accumulate, the water quality becomes cloudy, and the sedimentary layers outside the aquaculture area may also encounter problems. However, these changes may not be immediately apparent; sometimes they occur quietly.

However, there is another point that is often overlooked, which is that the structure of the pond itself is also "affected". Once the facilities are set up, the direction of water flow and the location of sediment deposition will change. Fortunately, such changes are often reversible. As long as the aquaculture facilities are dismantled, the hydrodynamic system can gradually return to its original state (Zamora et al., 2018). So, don't expect that just one test can tell whether the sediment condition is good or not. This thing needs to be closely watched, monitored according to the time nodes, and then the management methods should be slightly adjusted in combination with the current breeding conditions. Only in this way can it truly be both stable and environmentally friendly.

6.2 Ecological restoration effects of sea ranching practices in Papua New Guinea

Releasing the larvae of Holothuria scabra into seagrass beds is not always as smooth as expected. In the experiments in Papua New Guinea, the survival rate and growth performance of some locations were good, but in some areas, there was almost no harvest and all the individuals were wiped out (Figure 2). There are also many influencing factors, including the quality of seagrass beds, local hydrological conditions and even human disturbances (Hair et al., 2016). This makes the importance of site selection stand out all at once, and the participation and management of the community also become particularly crucial. The technology itself is not a problem. However, in actual operation, situations such as illegal fishing, inadequate monitoring and weak governance occur from time to time, which directly limits the long-term benefits of the project (Hair et al., 2020). However, if good locations are selected and local management is implemented, the release of sea cucumbers can in turn promote the growth of seagrass and facilitate ecological restoration (Arnull et al., 2021). Nevertheless, this effect is not a one-time solution but requires continuous maintenance.

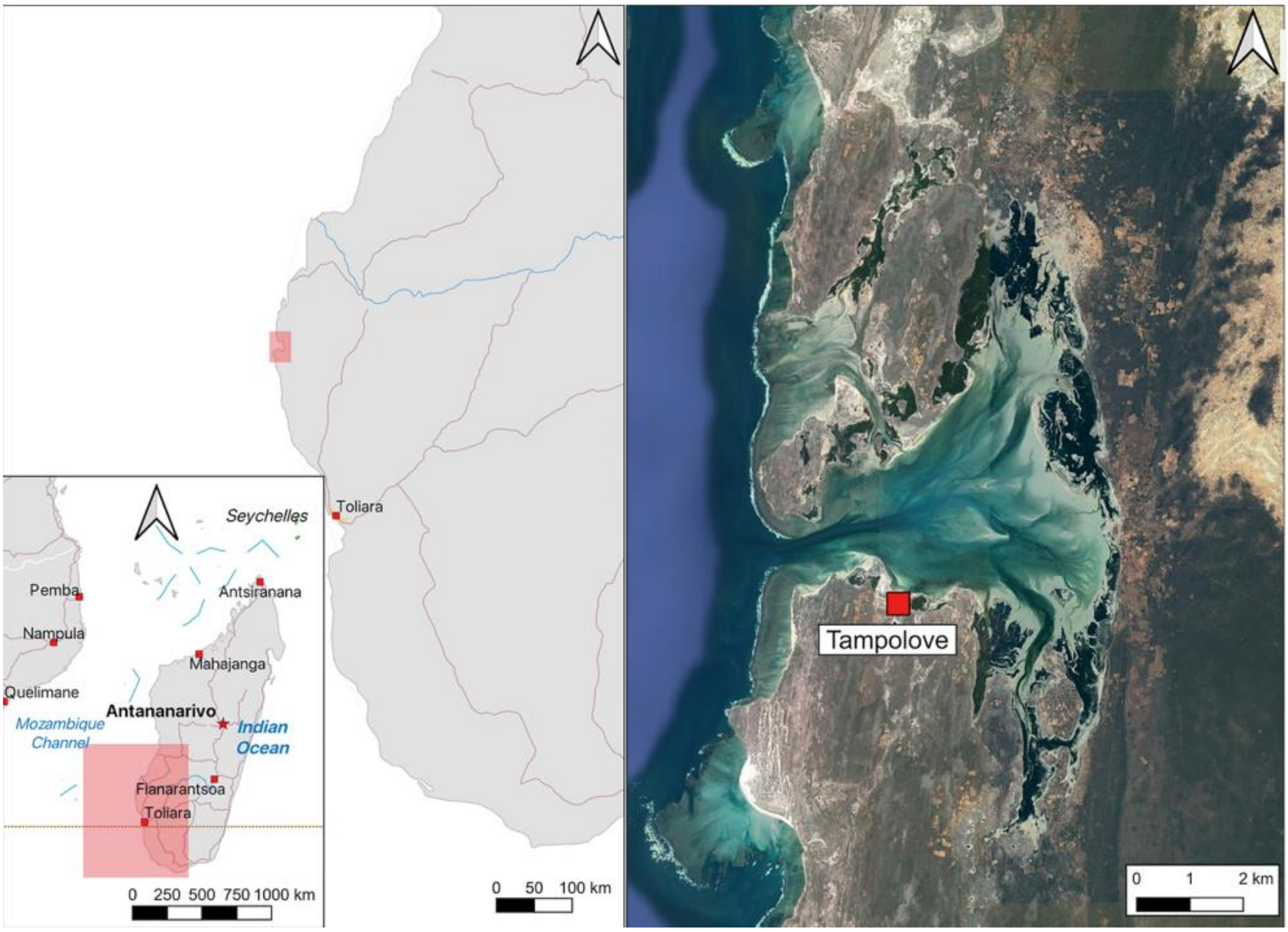

Figure 2 Location of Tampolove within the Bay of Assassins in southwest Madagascar (Adopted from Arnull et al., 2021)

6.3 Environmental monitoring data from IMTA practices in the South China Sea

The integrated aquaculture (IMTA) model in the South China Sea was actually once highly regarded by many people, especially the type where fish and shellfish are raised together in the sea. Judging from the monitoring data, it is indeed effective, mainly in reducing suspended particles and improving the quality of sediment (Zamora et al., 2018).

But ultimately, the extent to which the effect can be exerted depends on whether the quantity of sea cucumbers is sufficient. If their "proportion" in the system is too low, the task of cleaning up aquaculture waste cannot be done either (Chary et al., 2020). A more detailed life cycle assessment also indicates that although IMTA does have advantages in controlling eutrophication and improving system efficiency, it is not without cost - it uses more energy and may also increase the pressure on the climate. So, to achieve a win-win situation for the economy and the ecosystem through IMTA, not only should the design be reasonable, but also the environmental changes must be closely monitored in the later stage and adjustments made in a timely manner. This matter is far more complicated than initially imagined.

7 Conclusion and Sustainable Development Recommendations

The potential of tropical sea cucumber farming in terms of environmental restoration and economic output is no longer a novel topic, especially when combined with multi-trophic level aquaculture (IMTA) systems, the advantages become even more obvious. They are regarded as natural "scavengers", capable of consuming organic waste left over from the eutrophication process, and may also promote the growth of seagrass and drive the nutrient cycle of benthic systems. However, not all farming can bring about these effects. In actual operation, if the stocking density is too high or the system design is inadequate, it may not only fail to achieve the expected restoration goals, but also increase the burden on the water body, and even induce the spread of diseases and the destruction of habitats. Such risks may be magnified if management is slightly loosened. The results of the life cycle assessment also remind us that the feeding and breeding stages are often the hardest-hit areas in terms of energy consumption and water resource consumption.

Is there a more reliable way. Actually, there are quite a few. For instance, when it comes to density, don't rush towards the idea that "more is better" right from the start. Only by maintaining good health can one have the ability to recover. Green aquaculture is not just a formality. Clean energy, micro-ecological preparations, and circulating water systems are not new tools, but they are indeed effective. At the governance level, policies are of course important, but their actual implementation still depends on whether the community actively participates. In the final analysis, illegal fishing and disease control are issues of "people". Also, don't underestimate environmental monitoring. Conducting a life cycle assessment is not about submitting a report, but about always knowing which part has problems and how to make improvements.

Regarding IMTA and mixed breeding, they are still in the exploration stage at present, and there is much room for optimization. How and to what extent sea cucumbers should cooperate with other species to achieve high efficiency still requires in-depth research. At the same time, resource conservation should also be given due attention, such as energy conservation and emission reduction, optimizing the feed structure, or introducing renewable energy to relieve pressure from the source. Furthermore, many key issues remain unclear at present, such as the long-term control of diseases, the potential risks of genetic pollution, and the long-term impact of large-scale aquaculture on Marine ecology. These are all the key directions for future scientific research. Finally, if environmental protection behaviors can be encouraged through green certification and market mechanisms, giving enterprises the motivation and benefit to take the sustainable path, it may be more effective than relying solely on administrative orders.

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Conflict of Interest Disclosure

The authors confirm that the study was conducted without any commercial or financial relationships and could be interpreted as a potential conflict of interest.

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