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Integrated Approaches to Restore Ecosystem Functions in Degraded Coral Reefs

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Abstract Coral reefs provide habitats for a vast array of marine life and play a crucial role in coastal protection, tourism, and fisheries. However, they are facing severe degradation due to multiple stressors such as climate change, overfishing, ocean acidification, and pollution. This study reviews the research progress on biological and technological interventions, including coral gardening, assisted evolution, 3D-printed artificial reefs, and genetic editing. It further explores the synergistic effects of these approaches across ecological, social, and governance dimensions. By analyzing successful cases and lessons from failures, the study proposes strategies integrating marine protected areas, habitat connectivity restoration, and community participation to enhance the resilience and recovery potential of coral reefs. The aim is to provide theoretical foundations and practical strategies for the conservation and restoration of coral reef ecosystems, contributing to global sustainable marine ecology.

Keywords Coral reef restoration; Climate change; Marine biodiversity; Biological interventions; Sustainable marine ecology

1 Introduction

Coral reef ecosystems are one of the richest and most important ecosystems on the planet. They provide habitat for many marine life, protect the coast, and bring benefits from tourism and fisheries (Lirman and Schophmeyer, 2016). Although coral reefs account for less than 1% of the ocean area, about 25% of marine life rely on them to survive (Rinkevich, 2021). The complex structure of coral reefs gives them a high level of biodiversity, which in turn supports the livelihoods of millions of people around the world. The role of coral reefs in the ocean, such as nutrient circulation and providing habitat, is very important for maintaining ocean health and productivity.

Despite the importance of coral reefs, they are rapidly degrading due to various local and global pressures. Artificial activities such as overfishing, coastal development and pollution, coupled with climate change, have led to a decline in coral coverage and poor health of coral reefs (Sapkota et al., 2018). The global coral bleaching incident from 2014 to 2016 was caused by rising sea water temperatures, which also allowed us to see the vulnerability of coral reefs to climate change and reminded us that we urgently need effective recovery methods. Existing management measures, such as setting up marine protected areas and catchment management, are helpful, but not enough to prevent the degradation of coral reefs, so we need to explore new means of restoration (Boström et al., 2020; Gouezo et al., 2021).

This study summarizes a variety of recovery techniques, such as coral horticulture, assisted evolution and increasing the number of herbivorous carp, hoping to find ways to improve the resilience of coral reefs. We also evaluate the ecological, social and management conditions required for successful recovery and explore the possibility of these integrated approaches to be widely used in different coral reef environments. Through these analyses, we want to provide policy makers, hands-on operators and researchers with some practical advice to help them better protect and repair coral reef ecosystems.

2 Driminant Factors of Coral Reef Degradation

2.1 Climate change and coral bleation

Climate change is the biggest cause of coral reef degradation, mainly due to coral bleaching. Global temperatures rise, and seawater temperatures rise. Corals will expel symbiotic algae (zooxanthellae) that live in their bodies.

After losing these algae, corals not only lose their color, but also lose their important energy sources. This situation has become increasingly common around the world in recent years, such as the global coral bleaching incident from 2014 to 2016. As sea water continues to warm, coral bleaching occurs more and more frequently and the impact becomes more and more serious (Rinkevich, 2021; Shaver et al., 2022). Once corals bleach, they are prone to death, and the structure and function of coral reefs are damaged (Steneck et al., 2019).

2.2 Marine acidification

The increase in carbon dioxide in the atmosphere also makes seawater more and more sour. This ocean acidification is another important reason for the degradation of coral reefs. After seawater absorbs more carbon dioxide, the pH drops, and the number of carbonate ions used by corals to build bones becomes less. In this way, corals grow more slowly, and bones become fragile and easily eroded or injured (Albright and Cooley, 2019). If this continues, not only will the area of coral cover be reduced, but it will be difficult for coral reefs to recover after bleaching events.

2.3 Overfishing and destructive fishing behaviors

Overfishing, as well as destructive behaviors such as fried fish and cyanide fishing, are very harmful to coral reefs. These practices not only reduce fish populations, but also directly damage the structure of coral reefs. Especially overfishing and eating grass carp will cause algae to grow wildly. Algae and corals grab space and sunlight, further affecting coral growth and recovery (Weijerman et al., 2018). Research shows that banning these harmful fishing methods, while increasing the number of herbivorous carp, can help coral reefs become healthier and ecosystems can slowly recover.

2.4 Pollution (such as nutrient loss, plastic pollution and sediment deposition)

Pollution from land, such as nutrient loss, plastic waste and silt caused by agriculture, also poses a great threat to coral reefs. Too much fertilizer is used in agriculture, which will allow nutrients to flow into the sea, leading to eutrophication of water and a large number of algae growth. These algae suffocate the coral and the water quality becomes worse. Plastics and other marine litters not only directly damage corals, but may also bring harmful chemicals (Boström-Einarsson et al., 2020). In addition, coastal development and deforestation have increased the inflow of silt, seawater becomes turbid, affecting photosynthesis, and corals are easily covered with silt. To protect coral reefs, we must improve land use and waste disposal methods (Weijerman et al., 2018).

3 Understanding of Coral Reef Ecosystem Functions

3.1 Key ecological roles of coral reefs

Coral reefs are one of the most biologically diverse and most productive ecosystems on the planet. They provide many important services, such as supplying protein, protecting the coast, and bringing tourism revenue (Shaver and Silliman, 2017). Coral reefs provide home and food for many marine animals, maintain complex food chains, and are very helpful for overall ocean health (Seraphim et al., 2020). In addition, the complex structure of coral reefs also plays an important role in maintaining high biodiversity and ecological functions.

3.2 Loss of biodiversity and its impact on ecosystem services

Anthropogenic activities and climate change degrade coral reefs, resulting in huge losses in biodiversity. This change has affected many ecosystem services. For example, as coral cover decreases and structures become simpler, fish and invertebrates have fewer habitats, and fishery resources and food sources have also decreased (Tebbett et al., 2021). Once biodiversity declines, coral reefs can become weaker and are more susceptible to new damage (Williams et al., 2017). If ecological functions like nutrient circulation and primary production are destroyed, the decline of the entire ecosystem will become more severe.

3.3 Resilience mechanism of coral reef ecosystems

3.3.1 Adaptation strategies for coral species to environmental stress

In order to cope with environmental pressure, corals have developed many adaptation methods. This includes selecting varieties with strong tolerance, introducing new genes, and enhancing stress resistance through regulatory and epigenetic changes. These practices can enhance the viability of coral populations in the face of climate change and other stresses, helping coral reefs stay healthy and resilient (Wang, 2024).

3.3.2 The role of symbiotic relationships (such as corals and algae symbiosis) in maintaining resilience

The symbiotic relationship between corals and algae is very important in maintaining resilience in coral reefs. Algae can help corals acquire nutrients and energy and also have a great effect on the nutrient circulation of the ecosystem (Vanwonterghem and Webster, 2020). In addition, microorganisms that live with corals can also help capture, retain and recycle nutrients. These symbiotic relationships make corals more resistant to stress and more likely to recover after damage.

3.3.3 Coral reef recovery mode after interference and factors affecting repair

Whether coral reefs can recover after being damaged depends on many factors, such as whether there are key species, whether the habitat is complex enough, and whether there are good management measures. The study found that if species diversity is paid attention to during recovery, the survival rate and growth rate of corals can be improved, laying a good foundation for ecological restoration. Reducing local pressures such as fishing pressures and land pollution can also enhance the resilience of coral reefs (Weijerman et al., 2018). In addition, good interactions among species, such as mutually beneficial cooperation and nutrient promotion, also play a great role in coral recovery (Jiang and Xu, 2024).

4 Biological Methods for Coral Reef Restoration

4.1 Coral reproduction and transplantation technology

Coral reproduction and transplantation are the most basic ways to repair coral reefs. The very common "coral gardening" technique now is to first cultivate corals in underwater nurseries, and then transplant them on degraded coral reefs when they grow up. This approach has achieved good results in increasing coral coverage and making reef structure more complex and is very helpful for ecological restoration (Lirman and Schophmeyer, 2016). Generally speaking, the practice is to first choose corals with strong adaptability and raise them in a controlled environment, and then plant them in places that need to be repaired. This not only allows the number of corals to rise, but also provides habitat, prevents other organisms from seizing space and helps the entire fauna recover (Schmidt-Roach et al., 2020; DeFilippo et al., 2022).

4.2 Evolutionary assistance and selective breeding of stress-resistant coral varieties

Assisted evolution and selective breeding are new approaches recently developed, with the goal of making corals more resistant to environmental stress, especially in addressing climate change. These methods include selecting adaptive varieties, introducing new genes, and adjusting the microbiota in corals to cultivate more heat-resistant and stress-resistant corals (DeFilippo et al., 2022). Scientists are particularly concerned with coral genotypes that have shown stress resistance in natural environments. By observing their performance under high temperatures and other pressures in the wild, useful survival characteristics can be found. These corals are then taken to the laboratory for testing under controlled environments, such as high temperature, low pH and symbiotic ability tests. This can screen out the most tolerated coral genotypes, which is equivalent to accelerating the process of natural selection. Research shows that adding heat-resistant corals to coral reefs can improve coral coverage and resilience, but the final effect depends on the degree of practical efforts (Figure 1) (Caruso et al., 2021). These approaches focus on selecting corals that can better cope with future changes.

4.3 The role of reef-related organisms (such as fish and microorganisms) in ecosystem recovery

In addition to the coral itself, other organisms living on reefs, such as fish and microorganisms, are also important for recovery. Herbivorous carp can control the algae population. Without them, algae will seize the space and light of the corals, affecting coral growth. The study found that in places with large numbers of herbivorous carp, coral survival rates are also high. Microorganisms, especially the microbiomes on the body of corals, are equally important for coral health and stress resistance (Figure 2) (Hein et al., 2020). Scientists are studying how to make corals more adaptable to the environment and recover better by adjusting these microbiomes (Rinkevich et al., 2021). It can be said that fish and microorganisms together support the function and resilience of the entire coral reef ecosystem, so protecting and managing them in recovery efforts is very critical.

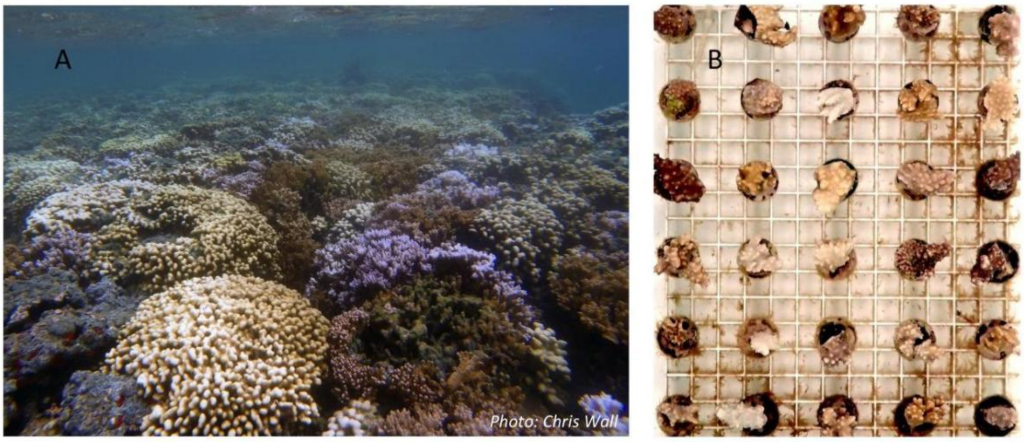

Figure 1 Changes in coral response to heat stress. (A) Communities of several species on coral reefs during bleaching events (B) Coral fragments of individual species are undergoing heat stress testing based on artificial aquariums (Adopted from Caruso et al., 2021)

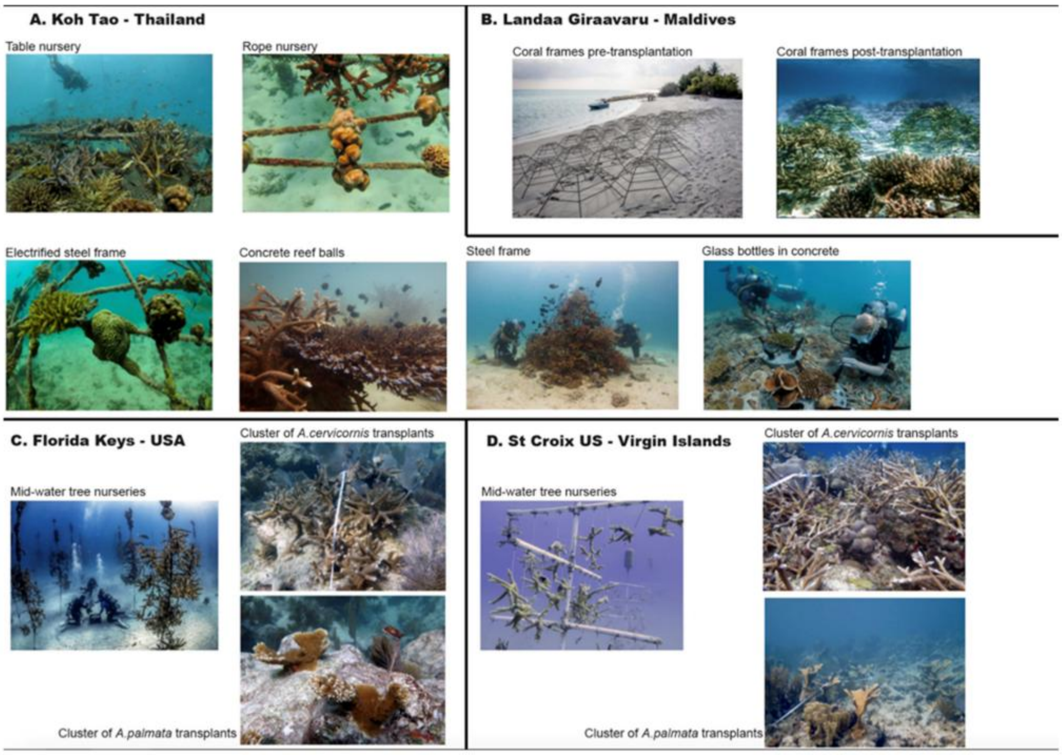

Figure 2 Photo montage illustrating coral restoration strategies at the four coral restoration programs surveyed (Adopted from Hein et al., 2020)

5 Technology Innovation in Coral Reef Restoration

5.1 Artificial reefs using 3D printing

3D printed artificial coral reefs have now become a promising method of restoration. These structures are specially designed to mimic the complex appearance of natural coral reefs, providing habitat for marine life while promoting coral growth. During the production process, environmentally friendly materials are used, which can ensure that the artificial reef is both sustainable and does not harm the marine environment. The study found that the number and species of fish that these artificial reefs can feed are similar to natural reefs (Angelini et al., 2020). We can place them in a planned manner in the right place to help corals reproduce, and also attract coral larvae and repair degraded coral reefs (Schmidt-Roach et al., 2023).

5.2 Marine robots and automated monitoring systems

Marine robots and automated monitoring devices are changing the way corals are repairing. They can improve work efficiency and reduce labor costs. These devices include underwater drones and autonomous vehicles with sensors and cameras. They can be used to monitor the health of coral reefs, observe the growth of corals, and detect environmental changes in a timely manner. For example, remote sensing technology can collect data on distribution, composition and status of coral reefs around the world, which is particularly important for the development of conservation and restoration plans (Foo and Asner, 2019). Applying these technologies to repair projects can achieve real-time data collection and analysis, making management more flexible and improving the chances of repair success (Schmidt-Roach et al., 2023).

5.3 Application of genetic engineering and CRISPR technology in coral protection

Genetic engineering, especially CRISPR technology, has brought new ways to improve corals' ability to resist environmental stress. Assisted evolution, such as breeding selection, gene flow help, and adjusting the microbiome in corals, are all to make corals more adaptable to changing environments. CRISPR can directly edit coral genes, which may help them better deal with high temperatures and seawater acidification. These genetic improvement techniques are part of a larger-scale strategy with the goal of enhancing coral resilience to climate change and protecting long-term health and survival of coral reefs (Weijerman et al., 2018).

6 Comprehensive Ecosystem-Based Methods

6.1 Combining marine protected areas (MPAs) with restoration work

Marine protected areas (MPA) are a widely recognized approach to protect marine biodiversity and also enhance resilience of coral reefs. MPA can help them recover faster from natural hits such as bleaching, disease and storms by stabilizing the structure of reef communities (Mellin et al., 2016). However, most traditional MPAs only protect healthy coral reefs. But now, many coral reefs around the world have degenerated, and traditional practices alone may not be enough. Incorporating degraded coral reefs into protected areas (called DR-MPA) can help select places with great recovery potential and can resist future threats, and further restore biodiversity and ecological service functions (Abelson et al., 2016). Adding active repairs to MPA, such as coral transplantation and the arrangement of artificial reefs, can also accelerate the recovery of degraded areas (Montseny et al., 2021). This combination method not only takes advantage of the protection of MPA, but also actively repairs ecological functions.

6.2 Restore connectivity between habitats of split coral reefs

Maintaining connectivity between reefs is important to protect genetic diversity, enhance resilience and help coral population recovery. A good conservation plan requires considering the needs of different species in their spread and habitats. Scientists will use biophysical models and tools like Marxan to help design MPA layouts to find out which places are the "sources" of larvae, which reefs can maintain themselves, and which places can serve as "springboards" for larvae diffusion. At the same time, combining the genetic information and quantitative data of the population can better understand the connections between different coral populations (Gazulla et al., 2021). By smartly arranging MPA and ecological corridors, connectivity between coral reefs can be restored, resilience across the ecosystem can be enhanced, and they can be more easily recovered from the strike.

6.3 Adaptive co-management, combining local communities and stakeholders

Adaptive co-management means bringing local communities and stakeholders into the protection and restoration efforts. This approach is particularly important for success. Involving local communities in MPA design and management can increase people's sense of identity with the reserve and their willingness to comply with management regulations. Good management and community participation can also allow everyone to see practical benefits, such as the improvement of fishery resources, thereby enhancing the support of protected areas. Incorporating local knowledge and traditional practices into restoration work can also make the project more effective and sustainable. For example, coral horticulture can do better if combined with local ecological experience and flexible management (Rinkevich et al., 2021). This collaboration model can also cultivate a sense of responsibility and belonging among locals, helping coral reef ecosystems become more resilient and sustainable.

7 Case Study on Coral Reef Repair

7.1 Success stories from the Pacific and Indian Oceans

Coral reef restoration has achieved good results in many parts of the world, especially in the Pacific and Indian Ocean regions. A well-known example is the "coral gardening" method, which is widely used in the Caribbean and the Western Atlantic Ocean. The practice is to first cultivate corals in the nursery and then transplant them onto damaged coral reefs to help restore coral reefs and marine life. Another good example is the Marias Islands in the eastern tropical Pacific. The repair there uses the method of directly explanting microfragments of coral. Despite natural challenges such as hurricanes, transplanted small corals showed good growth rates and survival rates. This suggests that this approach also has great potential in remote areas (Tortolero-Langarica et al., 2020).

7.2 Lessons learned from failed fix attempts

Although there are many successful cases, coral reef restoration has encountered many difficulties, and some projects have even failed. A summary of existing projects has found several common problems, such as unclear goals, poor monitoring and recording, or defective project design from the outset (Boström-Einarsson et al., 2020). These problems often lead to poor repair results, so better planning and execution are particularly important. In addition, many projects are inconsistent in setting goals and evaluation criteria, which also affects the results. Many times, only short-term monitoring is done, and the long-term ecological benefits required for restoration are not paid attention to (Hein et al., 2020).

7.3 Comparative analysis of regional repair strategies

The repair strategies and effects adopted in different regions vary greatly. In the Caribbean and the Western Atlantic Ocean, coral horticulture methods are very effective, not only promoting ecological restoration, but also bringing socio-economic benefits. In the Eastern Tropical Pacific, direct explantation of coral microfragments is more suitable because the infrastructure there is relatively limited. This micro-fragment transplant method is to cut the coral into small pieces and then plant it directly onto the degraded reef. The study used photos to record the growth and colonization of small corals over time, and also marked the damaged or recovered places with red arrows. This detailed observation reminds us that it is important to select strong coral fragments during transplantation and to continuously monitor their structural integrity (Figure 3) (Tortolero-Langarica et al., 2020).

In the Pacific, resilience-based management methods have also been introduced. Prioritization of restoration is determined based on the social value and recovery potential of coral reefs (Gouezo et al., 2021). These different methods show that the repair strategies in each region need to be tailor-made according to local specific conditions and cannot be one-size-fits-all.

8 Future Directions and Innovation

8.1 Multidisciplinary approach to promoting restoration

To better restore coral reefs, a multidisciplinary approach must be used. Recent efforts have also emphasized this. Combining ecological, social and technological perspectives can make the restoration effect better. For example, Australia's Coral Reef Recovery and Adaptation Program (RRAP) is an example. This project combines marine planning, socio-economic research and various interventions in the hope of enhancing coral resilience under climate change (McLeod et al., 2022). In the Caribbean Sea and the Western Atlantic Ocean, people have also achieved good results using ecological methods such as coral horticulture, which not only restores the ecology, but also brings economic benefits. These cases all illustrate one truth: In order to deal with the various complex problems faced by coral reefs, people from different industries and fields must work together to develop comprehensive restoration strategies.

8.2 Expand the scale of restoration projects worldwide

In order to deal with the problem of large-scale degradation of coral reefs, restoration work needs to be expanded globally. At present, the scale and duration of most restoration projects are relatively limited, and many projects lack long-term monitoring (Boström-Einarsson et al., 2020). To truly make an impact, future restoration projects must be bigger and longer-lasting. Remote sensing technology can help, which can provide data on the distribution, structure and health of coral reefs around the world. This will make large-scale monitoring and planning more efficient. In addition, developing unified terms and indicators can also make restoration projects easier to compare and evaluate in different places (Vardi et al., 2021). With the standards, restoration work around the world can be connected faster and cooperation will be smoother.

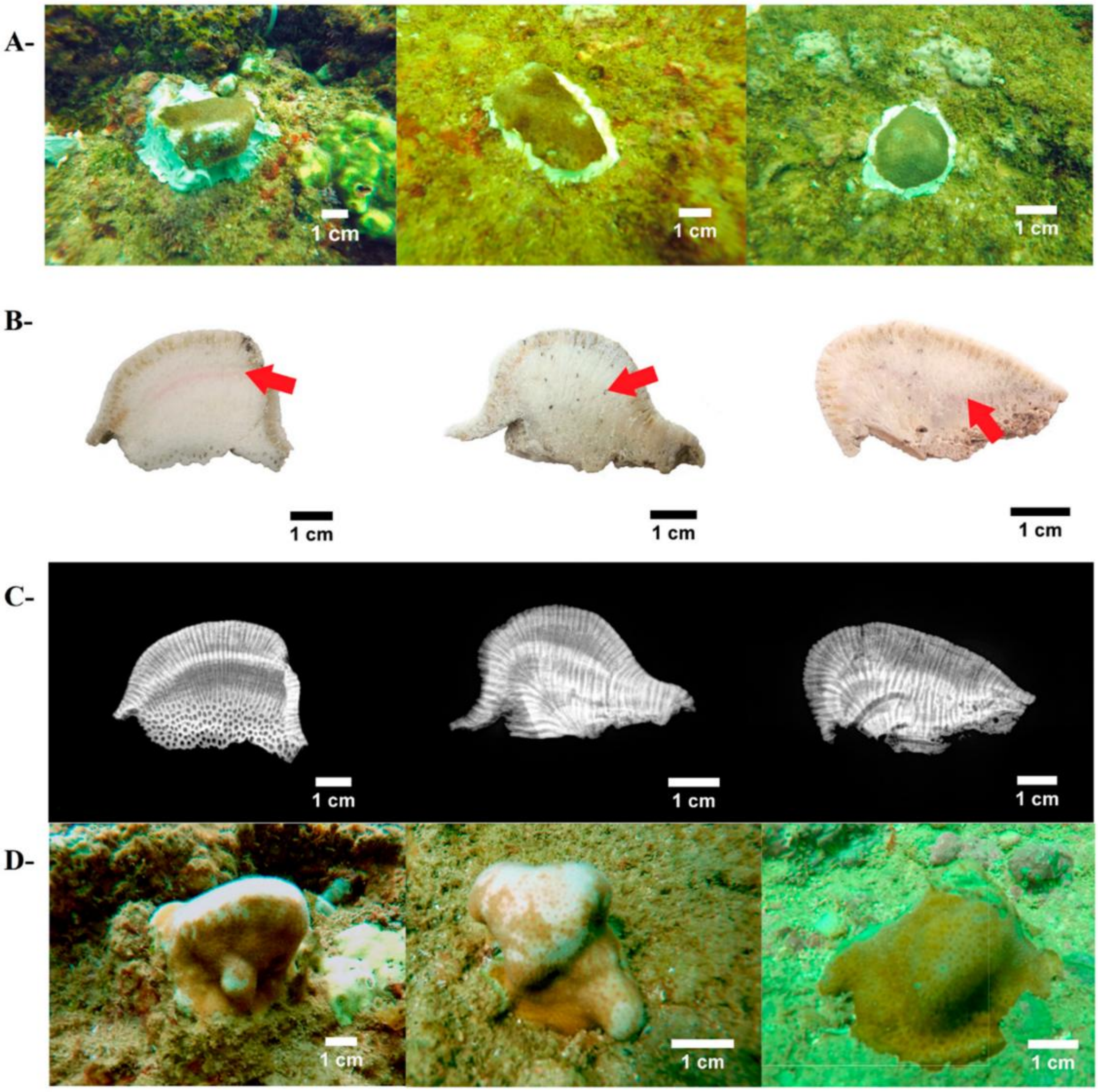

Figure 3 The use of micro-fragments of *Pavona clavus* from Islas Marías Cleofas for coral reef restoration (Adopted from Tortolero-Langarica et al., 2020)

8.3 Priorities for long-term coral reef toughness research

If you want to make coral reefs healthy for a long time, future research should focus on how to enhance coral adaptability and resilience. Incorporating the "resilience principle" into restoration design and practice is the key to helping coral reefs cope with climate change (Shaver et al., 2022). Research should focus more on new methods, such as assisted evolution. This includes selective breeding, introduction of new genes, and tuning coral microbiota to make them more adaptable to environmental stress.

Also, it is also important to establish a unified evaluation framework. This allows for a clearer judgment of the effectiveness of repair work and determine which management measures are most worthy of priority promotion (Gouezo et al., 2021). By focusing on these key areas, future restoration efforts will better support the health and resilience of coral reefs and help them face changing environments.

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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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