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Understanding Coral Bleaching: Mechanisms, Impacts, and Pathways to Reef Restoration

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ABSTRACT

Coral reefs, which provide critical coastal protection and support a large share of marine biodiversity, are declining rapidly worldwide. Today, global coral reef systems face the detrimental effects of bleaching. Although the reefs are bleaching due to a wide variety of reasons, most are due to anthropogenic climate change and acidification of the ocean. They either die or their ability to perform the essential functions that sustain life around them is significantly impaired. It not only leads to a major loss in biodiversity and human communities but can also potentially exacerbate global warming, which in turn may accelerate their bleaching.

Drawing from an extensive collection of research, this literature review employs a holistic approach to the analysis of the various methods being explored to combat coral bleaching. From solutions that are more established like coral gardening to solutions that are more preliminary techniques, like 3D modeling, this paper covers their advantages and disadvantages as well as their effectiveness. This study provides a wide overview of the reef bleaching problem, from the cause and effect of coral bleaching to the cost-benefit considerations of techniques used to combat this problem. It underscores the need for a dual approach that combines short-term restoration efforts with long-term strategies to combat climate change and human-induced pressures. Only through coordinated, multidisciplinary action can we strengthen reef resilience and secure their survival for generations to come.

INTRODUCTION

Coral reefs are often called the rainforests of the sea, thriving biodiversity hubspots shaped by intricate relationships between corals, algae, and countless other organisms (Liao et al., 2019). These dynamic relationships have helped coral reefs thrive for millions of years. The most important of these is the mutualistic relationship between algae and corals, which is one of the biggest factors for the reefs to thrive. This symbiotic relationship involves a mutually beneficial nutrient exchange. The corals provide shelter and nutrients that the algae need for photosynthesis and growth, such as carbon dioxide, water, and nitrogenous waste products like ammonium. Meanwhile, the algae use sunlight to photosynthesize and produce oxygen and organic compounds like sugars, lipids, and amino acids, which they transfer to the coral host (Muller-Parker et al., 2015). Algae have also been found to potentially be able to adapt to varying environmental conditions. Recent studies found that algae can secrete sugars by breaking down

their own cell walls under acidic environments similar to those inside coral cells. This newly discovered sugar secretion method does not require photosynthesis, suggesting that symbiotic algae have a variety of ways to produce and provide nutrients for the corals (Hambleton, 2023). Furthermore, symbiotic corals can deposit calcium carbonate to build their skeleton up to 10 times faster than non-symbiotic corals, enabling rapid reef growth (Zandonella, 2016). Thus, symbiotic corals have a much higher chance of surviving under difficult conditions.

The primary algae found in corals that take part in this relationship is the endosymbiotic dinoflagellate algae called the symbiodinium algae, colloquially known as zooxanthellae. The zooxanthellae algae provides up to 90% of the energy requirements of the host coral (Muscatine & Porter, 1977; Wooldridge, 2013). This allows corals to survive and thrive in nutrient-poor tropical waters; and is vital for coral survival, growth, and reef-building in nutrient-poor tropical oceans (McIlroy et al., 2022).

Coral reefs are crucial to biodiversity on Earth. They have a direct impact on reef fish, fish that live in or near coral reefs. There are many reef fishes in the ocean with over 25% of all marine fish species or around 4,000 species that inhabit and rely on coral reefs (*Coral Reef Ecosystems | National Oceanic and Atmospheric Administration*, n.d.). Without the shelter, food, and nursery areas that the coral reefs provide for the reef fishes, they will be endangered or even at risk of extinction. According to the study done by Coker et. al. 2014 with 320 species of coral-associated fish, 39% of the species showed marked declines in abundance following severe changes such as mass bleaching and tropical storms that caused a sizeable loss of live coral cover. This highlights the fish species' strong reliance on live coral (Coker et al., 2014). However, coral reefs affect the entire ecosystem structure and not just reef organisms. Many other species have less obvious associations with corals and the structural complexity of reefs and coral skeletons (Coker et al., 2014). Additionally, the interconnectedness of all marine and terrestrial life makes coral reefs a vital part of the ecosystem as a whole, as their health has a propagating effect throughout the whole ecosystem (Ricot et al., 2023).

Coral reefs greatly affect life on land as well. Specifically, they have a substantial effect on humans who live in coastal areas. Many coastal communities, made up of at least 500 million people, are highly dependent on coral reefs and the commodities that they provide (Hoegh-Guldberg et al., 2019). They are dependent on either the food provided by the coral reefs or their monetary value in the form of tourism revenue. In fact, around 30% of the world's coral reefs are believed to contribute to tourism generating 36 billion dollars annually (Spalding et al., 2017). They also have direct economic benefits to tourists who are willing to pay more for the reefs. The per person per vacation net economic benefit of coral reef tourism is around $600 or more USD (O'Mahoney, J. et al., n.d.). Furthermore, coral reefs benefit us in less obvious ways. They protect life on land from floods by acting as a natural barrier and reducing waves and currents. They can engineer the physical environment for entire ecosystems, making it possible for other coastal ecosystems such as seagrass beds and mangroves to develop, which in turn serve their own suite of services to humans (Barbier et al., 2011). Specifically, reefs are estimated to prevent around $4 billion USD in flood damages from storms per year. In fact, without reefs, annual damages would more than double (118%) and the flooding of land would increase by 69% affecting 81% more people annually (Beck et al., 2018).

Coral reefs also play a role in global oxygen and carbon cycling through their partnership with the symbiotic algae zooxanthellae. These algae perform photosynthesis, using sunlight to convert carbon dioxide and water into glucose and oxygen (Long et al., 2013). Reef organisms are estimated to fix approximately 70 to 90 million tonnes of carbon annually through photosynthesis (Allemand, 2016). However, this should not be interpreted as straightforward carbon removal. The precipitation of calcium carbonate during reef calcification releases CO_2 back into seawater, so the net climate effect of a reef depends on the balance between organic carbon fixation and carbonate production, and many reefs are considered close to carbon-neutral or even slight net sources of CO_2 over time (Allemand, 2016; Andersson & Gledhill, 2013). The climate relevance of reefs therefore lies more in the biodiversity, fisheries, and coastal protection services they sustain than in net carbon removal.

The purpose of this review is to outline what is causing the coral bleaching phenomenon and discuss the direct solutions that people around the world are working on while examining what has been the most effective ways of adapting coral. The Review Methodology section describes how sources were selected and compared. The following section covers the anthropogenic drivers of bleaching and their human, marine, and broader environmental impacts. The review then examines four direct restoration approaches, before discussing their limitations, potential improvements, and the wider picture, and closing with the paper's main conclusions.

This review is guided by a central question: which coral restoration strategies show the strongest potential for supporting reef resilience under climate-driven bleaching, and what limitations prevent these methods from functioning as long-term solutions? By evaluating coral gardening, Biorock technology, artificial reef structures, and coral in-vitro fertilization in terms of scalability, cost, genetic diversity, ecological resilience, and dependence on broader climate mitigation, this paper presents these approaches not as standalone interventions but as complementary components of an integrated resilience system.

REVIEW METHODOLOGY

This paper uses a critical literature review approach to summarize current research on coral bleaching mechanisms, ecological impacts, and reef restoration strategies. Sources were identified primarily through Google Scholar, supplemented by publisher databases (ScienceDirect, SpringerLink, Wiley Online Library, MDPI, and PLOS) and the websites of marine science institutions (NOAA, the Smithsonian Ocean Portal, and the Global Coral Reef Alliance). Search terms included “coral bleaching,” “zooxanthellae symbiosis,” “ocean acidification” and “coral,” “coral reef ecosystem services,” “coral restoration,” “coral gardening,” “Biorock,” “artificial reef,” and "coral IVF." The reference lists of key reviews were also evaluated to identify additional relevant studies. Searches were conducted between September and December 2024. The review prioritized sources published between 2009 and 2024, with a small number of older foundational studies kept for context on coral-algal symbiosis.

Sources were included if they (1) addressed coral bleaching mechanisms, the ecological or socio-economic consequences of reef degradation, or one of the four restoration approaches examined here; (2) were peer-reviewed articles, technical reports from research institutions, or reports from

recognized governmental organizations; and (3) were available in English. Sources were excluded if they were opinion pieces, if they focused on restoration approaches outside the scope of this review, or if they lacked sufficient methodological detail to assess the outcomes reported. A small number of non-peer-reviewed sources (e.g., organizational websites and one news article) were used only to source figures or provide descriptive context, not to support quantitative claims. When sources reported conflicting findings, such as differences in survival rates between asexual and sexual propagation, greater weight was given to peer-reviewed studies with larger sample sizes and longer monitoring periods, and the range of reported outcomes was presented rather than a single figure. As this paper is a critical literature review, it does not aim to provide comprehensive coverage of the literature but to critically compare major restoration strategies, their strengths and limitations, and their potential role in broader reef resilience.

THE CAUSES AND EFFECTS OF BLEACHING

Coral bleaching occurs when corals lose or expel their symbiotic algae, or when the algae lose their photosynthetic pigments. This leaves the white calcium carbonate skeleton visible through the coral's transparent tissue. However, the algae are not necessarily killed outright; bleaching is primarily a breakdown of the coral-algal symbiosis triggered by environmental stressors, and corals may regain their algae if conditions improve (van Woesik et al., 2022). While there are factors that are not human-related, such as natural disasters and natural fluctuations in ocean temperature, the bulk of the root causes lie in anthropogenic climate change.

Notably, the rise in sea temperature due to anthropogenic climate change is the biggest driving factor of coral bleaching. The small increases in sea temperature destabilize the symbiotic relationship between the coral and the algae, which sustains each other through their exchange of nutrients. Once the coral are deprived of their primary nutrition source, the algae, they may eventually die due to starvation (Veron et al., 2009). Additionally, under extreme temperature stress, coral tissues can deteriorate or detach from their skeleton (van Woesik et al., 2022).

When corals lose their symbiotic algae due to bleaching, their primary energy source is disrupted and in jeopardy (Shaver et al., 2020). However, corals can survive for a limited time after bleaching by relying on stored energy reserves or through heterotrophic compensation, which is a process where corals increase their reliance on heterotrophic feeding---capturing and consuming organic matter, plankton, or dissolved nutrients from the water---to compensate for the loss of photosynthetic energy. During this period, the coral's health is severely damaged. Their metabolic processes slow down, and their ability to grow, repair, and reproduce is significantly diminished. Nevertheless, without sufficient compensation or reserves, starvation may occur, leading to weakened coral health and possibly even death. If environmental conditions improve, some corals may regain their algae and recover their symbiosis (van Woesik et al., 2022).

According to a study done by Dao et al. (2021) in the coral reefs of Cu Lao Cham, a biosphere reserve in Vietnam, the combination of climate change and stronger El Niño events is expected to exacerbate

temperature increase. El Niño is a non-anthropogenic warming of tropical Pacific surface waters. This interaction of climate change and El Niño may result in prolonged periods of extreme temperatures, which the corals may not recover from. There has already been a reported decrease of coral in the area by 47% from 2004 to 2016, which may be attributed to various factors, including ones caused by humans like tourism and rising sea temperatures (Dao et al., 2021).

The rise in CO2 levels is also a significant driver of coral bleaching. Atmospheric CO2 has risen from a pre-industrial level of about 280 ppm to roughly 387 ppm, increasing at least 100 times faster than natural rates due to anthropogenic emissions. This concentration, which exceeds the ~350 ppm threshold, is associated with increased coral bleaching, mortality, disease, and reduced calcification (Veron et al., 2009; Sabine et al., 2004).

This results in the acidification of the oceans because carbonic acid is formed as CO2 dissolves, which alters the ratio of the pH-maintaining carbonate/bicarbonate buffers, decreasing pH (Veron et al., 2009). Ocean acidification harms coral health, affecting their skeleton, reproduction, and energy production. Acidification reduces the availability of calcium minerals, which are used by corals for skeleton building and repair. It can also erode the coral skeletons (*No Safe Haven for Coral from the Combined Impacts of Warming and Ocean Acidification | NOAA Climate.Gov*, 2018). Furthermore, since corals lose their symbiotic algae (zooxanthellae) under increased CO_2 conditions, their net photosynthesis is reduced by 60% per cell. This reduced photosynthesis results in decreased energy availability for coral polyps, which directly impacts their reproductive capabilities. Their energy allocations are also compromised since they must increase their internal cellular pH regulation, spend more energy on calcification, and attempt to maintain their symbiotic relationships with the zooxanthellae (Kaniewska et al., 2012). As the ocean becomes more acidic and the corals struggle to build and maintain their calcium carbonate structures, they start eroding faster than they can rebuild themselves. In addition, ocean acidification sets off a chain reaction in marine ecosystems. When pH levels drop, shell-building organisms like mussels and oysters struggle to survive, and zooplankton populations decline. Their decline significantly impacts the entire coral ecosystem (Ocean Portal Team, 2018).

Coral calcification is the process of forming calcium carbonate, providing structural support for organisms that use it to form their skeletons and shells. This process provides many benefits, including protection from predators, increased surface area, and the ability to stay elevated above the sediment-water interface. It also helps corals remain close to high light levels and adapt to rising sea levels, which is crucial for the persistence of coral reefs. However, ocean acidification leads to the rate of calcium calcification significantly decreasing and dissolution rates could increase. This change could cause reductions in coral reefs' resiliency. (Andersson & Gledhill, 2013)

Though their direct influence on coral is not as prominent, waste pollution from chemicals and plastics is another contributor to coral bleaching. A primary cause for pollutants entering the ocean is via terrestrial runoff, particularly from agricultural and urban areas. There are many types of contaminants, including pesticides, metals, and hydrocarbons, that can enter the ocean. For example, elevated metal concentrations have been associated with declines in coral health as copper has been found to be harmful to coral reproduction. Furthermore, oil spills in the ocean have been linked to coral health declines and studies

have associated it with decreased photosynthetic performance and reproductive impairment (Negri et al., 2011). Plastic pollution is another growing problem for coral health that is overlooked. As the plastic pollution problem in the world increases, its damage to the world's reefs increases. Ocean debris, like plastics, can have direct and indirect impacts. The direct impacts on the coral reefs include physical damage, substrate covering, and gut blockage for the animals living near the reefs if the items are ingested (Santodomingo et al., 2021). Marine debris can have devastating long-term impacts as well. Macroplastics can eventually decompose into microplastics, which can be unintentionally ingested by corals (Santodomingo et al., 2021). These plastics can then become a transmitter of bacteria and toxic chemicals (Allen et al., 2017).

The countless anthropogenic drivers of coral bleaching have devastating effects on the corals themselves, marine life, and even humans, as discussed in the introduction. However, coral reef health affects the entire environment: as reef fishes struggle, the effect propagates. In a study examining the widespread ecological impacts of coral bleaching and reef fish declines on the Great Barrier Reef, they found that as dead corals erode over time, structural complexity is lost, further diminishing habitat availability for reef fishes. Furthermore, the decline in key groups like herbivores that rely on coral reefs reduces the ecosystem's ability to recover from large-scale disturbances such as bleaching since these fishes play a critical role in maintaining the balance of reef ecosystems. For example, after a bleaching event, when coral mortality is high, algal cover often increases significantly, as observed in the 2016 bleaching event on the Great Barrier Reef. Without enough herbivores that feed on these algae and control this algal increase, the recovery of corals can be significantly hindered (Stuart-Smith et al., 2018).

Continuing, as a result of the loss of reef fish prey species, there is a disruption in predator-prey relationships. Declines in prey abundance can lead to a reduced population of fish-eating predators who depend on these prey species for survival. For instance, the sharp decline of small reef fishes such as Chaetodon trifascialis (a highly specialized butterflyfish) following a mass bleaching event can directly impact populations of piscivorous predators, such as groupers (Plectropomus maculatus and Cephalopholis urodeta), which depend on these smaller fish as a food source. This disruption can propagate through the food web, weakening ecosystem stability and resilience (Pratchett et al., 2011).

According to surveys done by A'Bear et al. (2023), there was a 55-60% reduction in overall fish abundance on reefs between 2015 (pre-bleaching) and 2020 (post-bleaching) (A'Bear et al., 2023). The aftermath of these coral bleaching events has ripple effects throughout the whole ecosystem. In fact, most fishes declined in abundance following acute disturbances that caused >10% declines in local coral cover. In a separate study done by Pratchett et al. (2011), it is shown that extensive coral loss (over 60%) often leads to significant declines in fish diversity. Specialized or fish species that are highly dependent on live coral for food or habitat are especially vulnerable. For example, certain butterflyfishes, which are obligate coral-feeding species, often experience local extinctions following coral bleaching events. The loss of these species disrupts key ecological functions such as nutrient cycling and energy transfer within the reef ecosystem (Pratchett et al., 2011).

Given that the health of coral reefs is so vital to the overall health of the entire marine ecosystem and has significant impacts on human lives, there have been many efforts made to combat the increasing problem of coral bleaching. The leading approaches will be discussed in the following section.

DIRECT INTERVENTION SOLUTIONS (ENGINEERED SOLUTIONS)

Scientists and researchers worldwide have been developing countless methods to combat the effects of coral bleaching directly. Although many of these solutions are still in their preliminary stages, each shows promise and has the potential to address the issue of coral bleaching in unique ways.

Coral Gardening



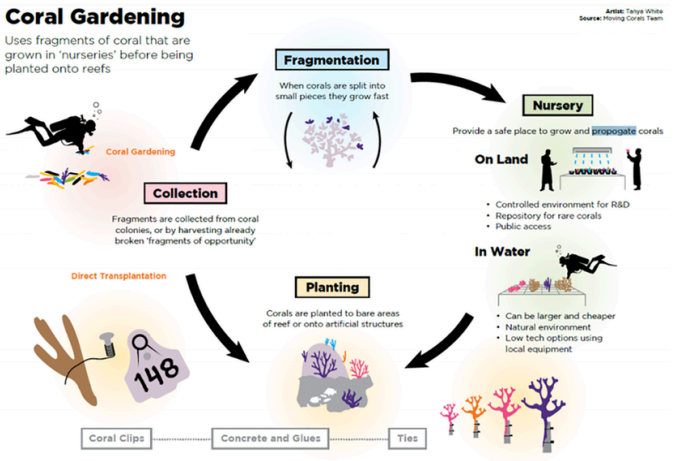


Figure 1. Coral Gardeners transplanting baby corals into their coral nurseries. This image was originally taken by and acquired from Coral Gardeners (Coral Gardeners, n.d.).

Figure 2. The Coral Gardening process is highlighted in this image. It involves the collection of coral fragments, fragmentation, a nursery phase, and the planting phase. This image was originally created by Tanya White with the Moving Corals Team and acquired from PLOS One (McLeod et al., 2022).

Coral gardening is one of the most widely used and operationally established approaches for restoring corals today (Rinkevich, 2021), although its success varies considerably with coral species, site conditions, storm exposure, and the level of maintenance and monitoring provided (Boström-Einarsson et al., 2020). This approach is a form of asexual restoration method (Meesters et al., 2015), involving the

transfer of coral fragments or whole colonies from a donor reef to a damaged one. First, coral fragments are extracted from naturally broken corals (e.g. from natural disasters) or from healthy donor colonies to minimize future harm (see Figure 2). Then, these harvested coral fragments are often placed in in-situ nurseries, a process of growing huge numbers of fragments of coral into substantial coral colonies under carefully monitored and ideal conditions (see Figure 1). Lastly, they are transplanted into depleted natural habitats (Mohale et al., 2023). Direct transplantation, which involves transplanting coral fragments directly from healthy donor colonies to depleted habitats (see Figure 2, counterclockwise arrow), contrasts with full coral gardening, where corals are first cultivated in nurseries. This streamlined method skips the nursery phase, prioritizing speed over the extensive cultivation of corals.

Coral gardening supports the transplantation process by cultivating coral fragments through asexual propagation, which are later transplanted to restore degraded reefs. It provides an opportunity to further fragment and culture corals for the storage of species and genotypes (Ferse et al., 2021). Thus, transplantation makes up a vital step in the overall coral gardening method of coral restoration. Once the fragments reach a certain size, they can be broken into smaller pieces. Through the nursing process, these pieces can multiply in the number of fragments available to transplant (Boström-Einarsson et al., 2020). The main advantages of coral gardening are that it bypasses the early larval stages of coral fragments where mortality is high and that new colonies can be started anywhere in the field. This method also requires less advanced expertise, leading to a higher level of public outreach since volunteers can easily be integrated into the program (Meesters et al., 2015). Regardless of the goal of the coral gardening project, the economic viability of coral nursery operations is an important consideration. For coral propagation to be economically viable, there must be a balance of achieving maximum survivorship and limited operational costs (Barton et al., 2017).

In a study done at two reef sites in the rock islands of Palau, the effectiveness of asexual propagation was tested. In particular, survival rates and growth rates for the asexual propagation method were examined. At the Lighthouse Reefs in Palau, the asexual propagation survival rate of the reefs was around 73.3%. Meanwhile, the growth was around 120.6g ± 21.8g for asexual propagation reefs. These numbers were both higher than those of sexually propagated reefs, proving its effectiveness at an early stage compared to that of sexual propagation, which was also tested in the same conditions (Boch & Morse, 2012). Since coral gardening involves the use of asexual propagation, it can be a highly effective method for coral restoration under suitable conditions. However, because coral gardening, in many cases, involves an intermediate step of nursing, there is an additional improvement in the growth and survivorship rates of fragments, compared to just direct transplantation through asexual propagation (Boström-Einarsson et al., 2020).

Coral gardening has relatively low costs compared to the other methods mentioned in this section because it employs the method of fragment gathering. The stage that would require the most cost is the nursery stage since it requires a lot of planning and attention to ensure successful growth settings for the nursery corals (Mohale et al., 2023). Despite it being the most costly step of the Coral Gardening method, the costs for the nursery phase can be as low as $6,000 USD. Comparing this to the cost of artificial reefs, which is another coral restoration method discussed below that can cost up to $4,000,000 USD, Coral Gardening is a much more cost-effective method.

This method does still come with its risks, however. Particularly, there is a risk of creating populations of corals with little genetic variability, which can be combatted with selective breeding, but only to a certain extent, and this method also only works for branching coral species. In addition, there is a relatively high maintenance associated with Coral Gardening as a result of the time and attention required to maintain the nurseries (Meesters et al., 2015).

Overall, coral gardening is among the most practical and widely employed methods of coral restoration. It is well suited to producing large numbers of transplantable fragments that can be moved to a variety of sites. Although genetic variability must be considered when selecting corals to transplant, it currently has the largest body of operational experience and outcome data of the methods reviewed in this paper (Rinkevich, 2021).

Biorocks

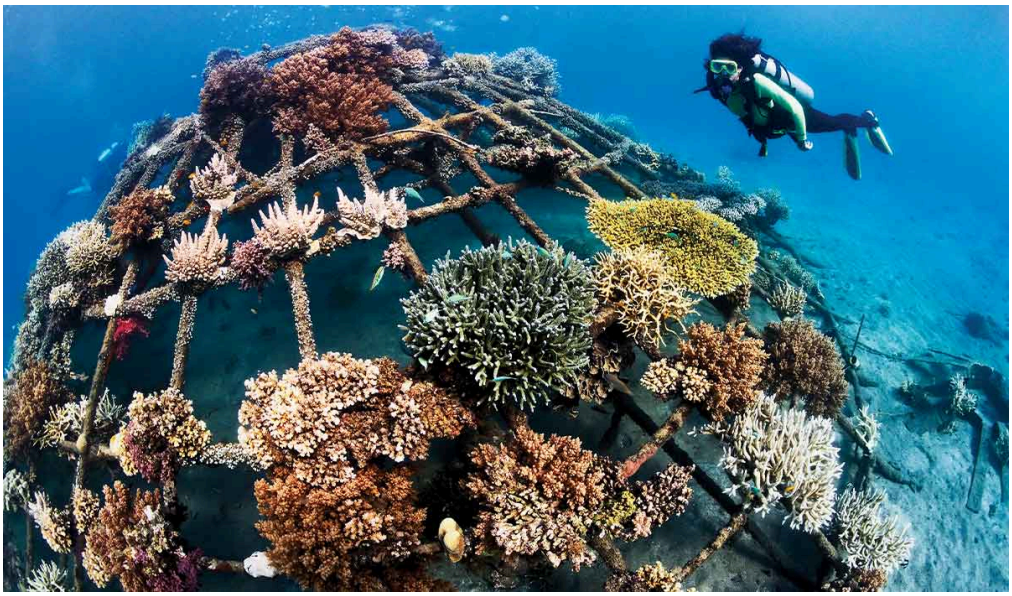


Figure 3. Coral reefs supported by Biorock Structures. This image was originally taken by Brandon Cole Marine Photography and acquired from alamy.com.

Biorock electric reef technology is an innovative method of shore and reef protection. Reefs that use Biorocks structures are grown by low voltage electrolysis of seawater. These Biorocks are limestone formations that become stronger over time and have the ability to self-repair (see Figure 3). They usually consist of two electrodes submerged in the water and a low-voltage electrical current supply system. This Biorock technology operates through an electrochemical mechanism. When electric current passes through seawater, it triggers two reactions. An oxidation reaction occurs at the anode and a reduction reaction takes place at the cathode. These electrochemical processes facilitate mineral development. First, natural seawater minerals begin to crystallize at the electrodes. Then, calcium carbonate and magnesium hydroxide form through the chemical reactions. These minerals collect around the cathode, which creates a mineral-rich environment. This process also enhances calcium absorption by the corals, which is crucial for their skeletal development, resulting in significantly faster growth rates compared to natural

conditions (Nugroho et al., 2023). Hence, this technology is used to increase coral growth and restoration and coastal protection (T. Goreau & Prong, 2017). However, Biorocks are used as more of a support mechanism for other restoration projects and coral are unlikely to grow on them without human intervention through processes like coral gardening. The electricity required for the electrolysis is called safe extremely low voltage (SELV), which is provided by transformers, chargers, batteries, solar panels, windmills, ocean current generators, or wave energy generators. The source depends on whichever is most cost-effective and easy to install. Maintaining electrical supply is critical to guarantee a positive outcome for the Biorocks and historically, electricity failure has been a major issue for Biorock projects not living up to their expectations (T. J. Goreau, 2014).

The countless benefits of electric Biorocks include physical, cost, and stimulatory effects. These structures have been shown to significantly increase corals' settlement, healing, growth, survival, and resistance to stresses such as extremely high temperatures, sedimentation, and eutrophication. Since Biorocks reefs can grow back eroded beaches faster than the rate of sea level rise, it is the premier method for shore protection and adaptation to global sea level rise for low-lying islands and coasts (T. Goreau & Prong, 2017). Biorocks are also much cheaper and more effective than alternative methods of shore protection, such as sea walls. According to a study done on the effects of hurricanes on Biorock Coral Reefs in Turks and Caicos, Biorock reef restoration can be effective even in storm-impacted areas. Specifically, the project lost around 30 to 40 percent of corals due to hurricanes, but most of them were only recently wired and had not been attached firmly. The overall high coral survival and low structural damage despite the effects of the hurricanes display the effectiveness of Biorock reef restoration (T. Goreau & Prong, 2017; Wells et al., 2010). Furthermore, the effectiveness of Biorock usage for reef growth is highlighted in a study done with corals grown in the Maldives, where the survival of Biorock corals was 16 to 50 times greater than surrounding natural coral reefs following the 1998 coral bleaching event (T. J. Goreau & Hilbertz, n.d.; T. Goreau & Prong, 2017). Biorock projects have been initiated in over 20 countries and with the widespread involvement of the local population, the usage of Biorocks has become an established example of coral reef restoration. The largest of these is the site in Permuteran Bay, Bali, Indonesia, where Biorock technology has helped restore coral and allowed fishermen to catch more fish, allowing local businesses to thrive (T. J. Goreau, 2014). Nevertheless, there are also potential drawbacks to the Biorock technology. If the Biorock structures become too solid with filled pores or if the rock fill is too impermeable to transit wave pressure through spaces, they may cause sand-eroding scour around the structures. However, this is more of a consideration for proper design rather than an inherent flaw in the technology itself (T. J. Goreau, 2014). This method of reef restoration is not as much of a direct solution as the other methods mentioned in this section as it is used as a means to stimulate growth, but there is still a need to implant the coral onto the Biorock structures for anything to grow since it does not germinate coral on its own. There needs to be further human intervention for Biorock structures to be useful. However, since it can greatly augment the restoration process and does not have any inherent flaws, this method is a viable method overall.

Three-Dimensional Reef Technology



Figure 4. Archireef's 3D-printed reef tiles in terracotta, which is environmentally friendly. Their design resembles a custom-designed artificial reef (CDAR), offering complete customizability and promoting coral inclusivity. It facilitates the natural recruitment of juvenile corals and enhances the establishment of outplanted corals, as illustrated in the image. This image was originally taken by Vriko Yu and acquired from Archireef Limited (Wong, n.d.).

Three-dimensional reef technology, also known as artificial reef (AR) technology, is a newer but highly promising method, with potential to be customizable, scalable, and effective (Komyakova et al., 2021; Levy et al., 2022). Artificial reefs are structures that help recover environmentally degraded coastal areas and complement existing natural reefs by creating favorable habitats for marine life development (see Figure 4). They replace the bleached corals and try to emulate natural reefs' capacity to support marine ecosystems. While they do not develop the same ecological functions and diversity as natural reefs unless their structure closely mimics natural reefs, Artificial Reefs can still provide hard surfaces where algae and invertebrates like barnacles, oysters, and corals can attach. This way, although they do not artificially create corals, ARs create favorable environments for corals to attach to. It is important to note that ARs address the loss of physical habitat structure, but they do not directly counteract the heat stress or ocean acidification that cause bleaching in the first place. Hence, corals settling on artificial structures remain exposed to the same thermal and chemical stressors as those on natural reefs. Some of the main design considerations for ARs include their stability against ocean currents/waves and resistance to sliding and overturning (Yoris-Nobile et al., 2023). There are two main design types of ARs: Reef Balls (RBs), which are prefabricated hollow, dome shaped concrete modules, and custom-designed artificial reefs (CDARs), which are purpose-built for a specific site. RBs have a cave-like appearance and they are less structurally complex compared to CDARs. On the other hand, CDARs have more structurally complex habitats with good vertical relief. The CDAR showed overall better performance with higher survival rates (Komyakova et al., 2021).

There are many applications of this technology, such as protecting coastlines, promoting recovery, and supporting ecotourism. It is most commonly used today for fishery enhancement; however, this overemphasis on enhancing fish production may be preventing the growth of the AR technology because they are only looking for one target objective and are not exploring the full parameter space of its capabilities. The loss of corals increasingly leads to diminished architectural complexity, which many reef fishes depend on for hunting, mating, and hiding. By focusing more on designs that increase complexity and durability with various rugosity, ARs can play a crucial role in species richness, habitat complexity, biodiversity, and the rate of recovery in a degraded area. AR production with a higher focus on using data collected from each coral ecosystem and combining that with an improved AR design can help maximize their ability to achieve goals (Levy et al., 2022).

The need for an innovative technology that allows for the replication of structurally complex reefs is still strong given the increased loss of corals. However, most ARs today rarely replicate the 3D shape of marine ecosystems, are not focused on complexity and durability, and fail to use sustainable materials (Levy et al., 2022). There are many challenges to the success of ARs, for example, they run the risk of becoming an ecological trap, which is where it attracts marine organisms but fails to provide the necessary resources for their long-term survival. Furthermore, other challenges such as high costs, high failure rates, and some design flaws underscore the need for innovation and improvement in this technology and emphasize its nascency. At least half of artificial reef deployments fail to achieve their goals due to inappropriate size, and despite millions of dollars being spent worldwide on AR deployments, many of them fail to provide the intended benefits. According to a study conducted in Port Phillip Bay, Australia, RB reefs acted as an ecological trap for the fish Trachinops caudimaculatus, with roughly nine times higher juvenile mortality than on natural or custom-designed reefs. These custom-designed ARs are more effective because it creates specifically designed models that can potentially optimize their shapes and textures to create as optimal of an environment for marine animals as possible (Yoris-Nobile et al., 2023). Additionally, poorly designed or placed artificial reefs can lead to insufficient positive outcomes and even negative impacts on marine communities (Levy et al., 2022). In fact, a reduced social acceptance of new placements of ARs, could act as an impediment to future management and conservation efforts (Komyakova et al., 2021). Solutions addressing some of these critical issues lie in the design of ARs and a novel customizable 3D interface (Levy et al., 2022; Yoris-Nobile et al., 2023). According to a study done in four locations Dinard Bay, Poole Bay, Poro, and Santander, CDARS, which have more complex artificial reefs, were generally more likely to positively affect fish populations. However, a singular artificial reef design may be insufficient due to the high habitat specialization of many marine fish species, therefore using AR designs combining multiple types is recommended to maximize effectiveness. Sustainable material usage in ARs has also been implemented. Unfortunately, the potential of ARs for coral reef restoration is seen as limited due to a low level of natural recruitment (Meesters et al., 2015).

All in all, despite the current issues with AR technology, it remains one of the most promising restoration methods, given its potential for customization and contribution to marine biodiversity. With future improvements, ARs could become a significant contributor to reef restoration worldwide (Levy et al., 2022).

Coral In-vitro Fertilization



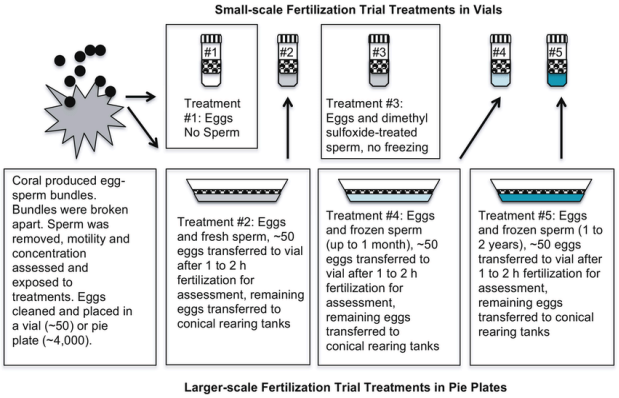


Figure 5. A member of the research team planting baby corals fertilized via IVF near Puerto Morelos in Mexico. These baby corals were bred over five years using a version of IVF developed by Secore. Divers gathered coral spawn and used it in a laboratory to fertilize eggs. The resulting juvenile corals were later transplanted onto the reefs shown in the image. This image was originally taken by Paul A Selvaggio and acquired from Secore International (Gardiner, 2024).

Figure 6. A flow diagram representing large-scale and small-scale coral IVF. The small-scale trials tested four treatments: eggs without sperm, eggs with fresh sperm, eggs with frozen sperm, and eggs with dimethyl sulfoxide-treated sperm. Successful fertilization was evaluated after 1-2 hours, and remaining fertilized eggs were transferred to rearing tanks for further assessment, with larger-scale trials conducted in pie plates under similar conditions (Hagedorn et al., 2017). This diagram was originally created by Hagedorn et al., 2017 with Scientific Reports available as a Scientific Figure on ResearchGate (Hagedorn et al., 2017).

Coral In-vitro Fertilization (IVF), also known as larval seeding or enhancement, is a type of coral sexual reproduction (Meesters et al., 2015). Coral IVF involves collecting coral gametes, fertilizing them in a controlled environment, and settling the resulting larvae onto degraded reefs (see Figure 5). This allows for the production of large numbers of genetically diverse coral larvae, which can enhance the resilience of restored coral populations (see Figure 6) (Boström-Einarsson et al., 2020). Through IVF, the power of corals to reproduce millions can be harnessed by reducing the coral's high early life mortality rate, scaling up restoration from the more small-scale solutions that are being implemented today (Boström-Einarsson et al., 2020).

The processes in IVF are much harder and more complex than asexual propagation, a method used for its speed rather than a higher genetic diversity since it starts at the larva stage, which has a higher mortality rate. In the same study mentioned in the Coral Gardening section, at two reef sites in the rock islands of Palau, the survival rate of sexual propagation was tested as well. At the Lighthouse Reef, the sexual propagation survival rate of the reefs was around 24.6%, which is a lot lower than that of asexual propagation (73.3%). Meanwhile, the growth was around 13.4mm ± 0.9mm for sexual propagation reefs (Boch & Morse, 2012). Compared to the asexual propagation method used in coral gardening, sexual propagation has a much lower initial success rate since larval rearing and settlement are delicate processes

(dela Cruz & Harrison, 2022). However, IVF has advantages that make this difficult initial process worth it.

Unlike asexual restoration methods, IVF, a sexual restoration method, is not limited in scale and effectiveness, does not require maintenance of coral nurseries, and does not limit genetic diversity, increasing adaptive capacity and resilience in transplanted populations (dela Cruz & Harrison, 2022). A study done in Lyudao, Taiwan, and Kochi, Japan conducted experiments on the effectiveness of IVF and how corals from different latitudes respond to climate change conditions and found that IVF generally had a high rate of success. Under ambient conditions, the fertilization success rate was generally high (>80%) for most species when using optimal sperm concentrations, which is 10^5 sperm/mL. However, the climate change conditions, particularly with increased temperature, significantly decreased its effectiveness (Schutter et al., 2015).

Unfortunately, relatively few studies have used IVF, and a lot of the initial studies were done on healthy reefs with naturally high larval supply and recruitment. Moreover, many of these studies monitoring the settlers' survival, growth, and recruitment were performed in periods of six weeks, six months, and approximately 13-month periods; Thus, the underlying longer-term restoration outcomes of this approach were not determined (Harrison et al., 2021). Conversely, in a study done in Northern Luzon, Philippines, the effectiveness of longer-term mass IVF was studied. In a period of three years, the coral colonies grew rapidly, reaching a mean diameter of 16.1 ± 0.7 cm. By 35 months, 53 colonies that were larger than 12.5 cm in mean diameter became sexually reproductive. The IVF also resulted in 70 times greater recruitment compared to natural acroporid recruitment, highlighting the success of the IVF method in the long term (dela Cruz & Harrison, 2017).

Despite this, IVF does still have its drawbacks. The current methods of IVF are highly sensitive to the environment and weather. Its success depends on suitable environmental conditions during the critical settlement and early post-settlement periods. Poor water quality, sedimentation, and temperature stress are all major threats to larvae and recently arrived recruits. Strong winds and waves are examples of weather conditions that can harm contaminated constructions that were utilized during the colonization times. The success of larval dispersion and spawn collection can be significantly impacted by these factors (Harrison et al., 2021).

In conclusion, Coral In-vitro Fertilization is one of the most promising restoration methods with the potential to address the problems that asexual coral restoration holds. However, since it is a relatively new technique, it lacks the necessary research and implementation. Despite the drawbacks, studies like the one at Northwestern Philippines highlight the potential long-term success of IVF, therefore, there are many encouraging signs of its future success.

OVERVIEW OF FLAWS, PROGRESS, AND POTENTIAL INNOVATIONS

Table 1. Comparative Evaluation of Coral Reef Restoration Strategies

Method	Main Strength	Main Limitation	Scalability	Genetic Diversity	Evidence Strength / Maturity	Best Use Case
Coral Gardening	Practical, established, cost-effective	Limits genetic diversity; requires maintenance	Medium	Low–Medium	High – well established; largest body of monitored outcomes	Short-term local reef recovery
Biorock Technology	Enhances coral growth and stress resistance	Requires electrical supply and transplant stock	Low–Medium	Depends on source	Moderate – established at several sites, but highly site-dependent and reliant on continuous power	Support system for transplantation programs
Artificial / 3D Reefs	Customizable habitat structure	Expensive; ecological-trap risk if poorly designed	Medium	Low (unless paired with seeding)	Low–Moderate – emerging; site-dependent, limited long-term coral-recovery data	Rebuilding structural habitat in degraded reefs
Coral IVF	Promotes genetic diversity and adaptive capacity	Technically complex; low early larval survival	High potential	High	Low–Moderate – high potential, but few studies and limited long-term monitoring	Long-term resilience and large-scale restoration

Table 1 compares the four restoration methods across their main strengths, limitations, scalability, contribution to genetic diversity, current evidence strength and maturity, and best use cases. The table shows that the methods that are easiest and most commonly deployed today, such as coral gardening, tend to generate little genetic diversity, whereas the methods with the greatest long-term potential, such as coral IVF, remain technically demanding and less established despite their ability to produce large numbers of genetically diverse larvae. The evidence-strength column makes this trade-off clear. Coral gardening is supported by the largest body of monitored outcomes, while Biorocks and 3D reefs have produced strong results at particular sites but remain highly site-dependent. On the other hand, IVF has high potential but still rests on relatively few studies with limited long-term monitoring.

Limitations

Coral restoration efforts still have their limitations as well. The obvious limitations include insufficient funding, a lack of trained personnel, managerial issues, and limited long-term monitoring of restoration outcomes. The main problem with funding is due to limited government support for restoration projects. This limits the number of people who can be involved due to funding constraints, affecting the ability to

do restoration work properly at the required scale to make a positive impact. Insufficiently trained personnel is a difficult issue since there is a trade-off between having more hands to scale up restoration and maintaining the quality of planting. This is due to the fact that there may be potential damage inflicted as a result of untrained volunteers such as during coral transplantation. Furthermore, scientists show reluctance to trust public involvement due to quality concerns, limiting future restoration efforts. Managerial issues are also a problem since they lead to a disconnection between restoration projects and local communities, poor time management of workers, and limited community awareness. Long-term and large-scale monitoring is one of the biggest issues in coral restoration. It is difficult to understand, measure, and adapt to the success of a given restoration project without proper long-term monitoring (Hein et al., 2019).

However, a more subtle limitation of Coral restoration exists that poses a bigger threat to future restoration efforts and should be regarded as a crucial consideration moving forward. Coral restoration attempts don't address the overarching global issues around climate change, pollution, and ocean acidification. Therefore even though these efforts may be effective in the short term, improving local reef health and providing socio-cultural benefits, it is only delaying the damage to corals due to climate change, which is the driving force of coral bleaching. A study done in Koh Tao, Thailand highlights that even with localized coral restoration efforts, large-scale environmental stressors will still cause continuous degradation of coral ecosystems. In that study, they found that mass bleaching events are most directly linked to abnormally high sea surface temperatures. No amount of coral restoration efforts can counteract this completely and it doesn't address the root of the issue (Hein et al., 2019).

Potential Improvements

Looking forward, improving these innovative solutions can greatly help mitigate the effects of coral bleaching not only in the short term but also in the long term. Using a combination of these solutions will help maximize the effect. For example, using biorocks and coral gardening can augment the process of restoration greatly. Using biorocks during the transplantation stage of the coral gardening method greatly speeds up the recovery and growth process. In a coral reef restoration project done in Turks and Caicos, naturally broken, but still live corals were transplanted onto Biorock structures, greatly increasing growth, healing from physical damage, settlement, and resilience to high temperature and sedimentation stresses (Wells et al., 2010). Since coral gardening is already a well-established solution with the most operational experience behind it, it is currently the most practical approach for local, short-term restoration. However, further research is still needed on in-vitro fertilization, as it is probably the most promising solution today, as it is able to increase coral genetic diversity and resilience (Meesters et al., 2015). Since current coral restoration practices are heavily focused on short-term ecological gains rather than long-term resilience, restoration methods such as IVF, that prioritize the enhancement of reef resilience are crucial. This involves not only the restoration of coral but also the addressing of overarching environmental stressors such as poor water quality and rising sea temperatures that accelerate coral bleaching (Hein et al., 2019). Most research today only focuses on the short-term benefits of IVF but lacks research on its long-term effects. As more research supporting the long-term benefits of IVF emerges, it may help to direct more efforts into this solution as it allows for more widescale coral restoration efforts without much expertise. Paired with other solutions like Biorocks, IVF may prove to be the best approach moving forward.

Similarly, enhancing long-term monitoring of restoration outcomes is an essential improvement to help measure the success of restoration efforts and assess broader ecological impacts over time.

The Big Picture

In retrospect, humans have made significant strides in addressing the coral bleaching problem, developing groundbreaking technologies and solutions that tackle this problem in unique ways. However, despite all of the efforts put into coral restoration, the best solution to global issues like coral bleaching is to address the overall problem of climate change and focus on achieving better climate (reducing CO2 in the atmosphere) and marine care (less pollution in water) (Hein et al., 2019). Since the rise in CO2 levels is a major contributing factor to the increasing acidity of the ocean---which, along with temperature increases, leads to more frequent coral bleaching---addressing the root cause is crucial.

Recent studies have found that the best way to save impacted reefs is by engaging in urgent action to reduce global CO2 emissions. However, taking steps aimed at tackling climate change on an international scale face many challenges such as the large time requirement and major international cooperation. Thus, to achieve the most favorable outcomes for coral, their restoration should occur concurrently while combatting the climate stressors (Boström-Einarsson et al., 2020; Levy et al., 2022). To align with the goals of the UN Decade on Ecosystem Restoration, the exploration and integration of innovative technologies are crucial for scaling up restoration efforts and supporting marine biodiversity (Anthony et al., 2017). There is room for more development and using this framework provides a guiding vision for harnessing technology to restore and protect the coral ecosystems of this planet effectively.

Therefore, it is essential to avoid the mistake of viewing coral restoration as a substitute for addressing the root causes of reef degradation, particularly climate change and other anthropogenic stressors. While coral restoration efforts are a pivotal step to solving the coral bleaching problem in the short term, without solving the overarching issue of climate change and marine pollution, it will continue to be a problem that threatens us. Efforts must be paired with broader management efforts to reduce threats and build reef resilience. In summary, the coral bleaching problem is complex, thus it requires a holistic approach that integrates ecological, social, and economic considerations (Hein et al., 2019).

CONCLUSION

This review has examined the mechanisms driving coral bleaching, its ecological and human consequences, and four direct restoration approaches. The consequences of bleaching extend from reef fish assemblages to the coastal communities that depend on reefs for food, income, and storm protection (Beck et al., 2018).

Of the four restoration methods reviewed, coral gardening is the most operationally mature and is well suited to local, short-term recovery, but it leads to little genetic diversity. Biorocks and three-dimensional artificial reefs can accelerate growth and rebuild habitat structure, but their outcomes are site-dependent, and they do not address the thermal and chemical stressors that cause bleaching. Coral IVF offers the greatest long-term potential for producing genetically diverse, resilient populations, yet it remains

technically demanding and requires more long-term monitoring before it can be scaled with confidence (Boström-Einarsson et al., 2020; dela Cruz & Harrison, 2022). None of these approaches, alone or in combination, can substitute for addressing the root causes of reef decline.

Therefore, the main takeaway of this review is that restoration must be paired with action on the drivers of bleaching themselves: emissions reduction, pollution control, and long-term reef monitoring. Although restoration can buy time and rebuild local reef function, the persistence of coral reefs over the coming decades will depend on whether these drivers, such as rising sea temperatures, ocean acidification, and declining water quality, are brought under control (Hein et al., 2019).

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