

# A Review of Coral Reef Restoration Methods

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## ABSTRACT

Due to global warming and human activity, the coral population has decreased by 50% since the 1950s. (Wetzel, 2021). Many policies have been placed on conserving the coral reefs, but more is needed to stop the rapid decline. All around the world, different researchers performed multiple types of restoration methods to try and reverse the damage and destruction the coral reef ecosystem has sustained. This paper reviews the other restoration methods researchers have tried and are currently trying to review their effectiveness in reversing the damage to coral reefs. Restoration methods can be divided into active and passive restoration methods. The methods reviewed are removing invasive algae, coral gardening, substrate manipulation, and stabilization, larval propagation, direct transplantation, substratum enhancement with electricity, and cryopreservation. All in all, all of these methods have their respective strengths and weaknesses. The method that can move forward to be more mass-produced would be direct transplantation, as additions such as nurseries are unnecessary. The restoration method that has shown the most promise has been substratum enhancement with electricity, but since the method is still relatively new, further research is needed. A possible recommendation for future coral reef restoration endeavors is to combine restoration methods to make up for the flaws of each method and incorporate long-term monitoring.

## **Introduction**

Corals are critical for maintaining biodiversity as they serve as shelter, protection, and breeding grounds for 25% of all marine species despite corals themselves only making up 0.1% of the entire sea. Outside of seas, corals are a major source of culture, identity, and economy. The total economic value of coral reef services is 3.4 billion dollars annually due to fisheries, tourism, and coastal protection, and 1 billion people are impacted directly or indirectly by coral reefs. Additionally, since corals can absorb wave shock, U.S. coral reefs provide flood benefits of \$1.8 billion dollars in averted damages to property. (NOAA, Tables 1-3).

Corals comprise tiny polyps that secrete a layer of calcium carbonate to create a rocky exterior. As coral larvae or fragmented parts of the coral attach themselves to hard surfaces nearby the coral, the singular coral develops into a reef. Corals have a mutual relationship with Zooxanthellae algae, which is a type of algae that lives within the tissues of the corals that provide oxygen which helps corals remove waste. The zooxanthellae also provide corals with glucose, glycerol, and amino acids, which the corals use to make protein, fat, carbohydrates, and calcium carbonate. (NOAA, paras. 1-2).

However, when stressed, coral polyps expel the zooxanthellae within them, giving the corals a white appearance which this widespread phenomenon is dubbed as ‘coral bleaching.’ When zooxanthellae are spent away from the corals for a long period of time, it can cause the corals to die from the lack of nutrients. A report done by the Global Coral Reef Monitoring Network (GCRMN), a network within the International Coral Reef Initiative (ICRI), showed that from 2009 and 2018 there has been nearly a 14% global decrease in corals due to coral bleaching. (NOAA). According to Dunne (2018), “...bleaching events have become five times more frequent, with the average reef being affected once every 25 to 30 years in the 1980s and once every six years in 2016.” (para. 7).

Dynamite fishing and overfishing have also been major contributors to the state of corals. Dynamite fishing, also known as blast fishing, is an act where dynamites or explosives are used to kill massive amounts of fish with one blow. The explosion causes a series of vibrations throughout the sea which ruptures the organs of fish. Contrary to what many people believe, corals are not rock; they are made up of soft polyps. Therefore, consistent blast fishing weakens corals to the point where they cannot recover pre-blast. Overfishing causes a depletion of diversity which harms the corals that depend on the waste excreted by these species.

According to Good and Bahr (2021), “Over the last 3 decades, living coral cover has declined roughly 53% in the Western Atlantic, 40% in the Indo-Pacific, and 50% on the Great Barrier Reef (GBR)...While it is estimated that 6% of reefs across the globe will not be affected by either local or global stressors, 11% of reefs will be threatened solely by global factors alone, 22% solely from local factors, and 61% from the combined effects of local and global drivers of environmental change.” (paras. 3-4). Drastic restoration methods are necessary to make sure the coral population does not decrease any further.

In efforts to stop the decline of coral reefs in the world, researchers have developed restoration methods to recover the ecosystem that has been damaged and destroyed. Restoration efforts have been distinguished into two by researchers: active and passive. Active restoration deals with directly dealing with the corals themselves while passive restoration is where a factor indirectly related to corals is changed, and its impact eventually reaches the coral naturally.

**Table 1.** Restoration Method Definitions

<b>Restoration Method</b>	<b>Definition</b>
Removing Invasive Algae	Removing invasive algae is a restoration method in which macroalgae is eradicated or controlled from the corals.
Coral Gardening	Coral gardening is a restoration method in which corals are grown in nurseries through asexual reproduction until they are mature enough to be planted back on the reef.
Substrate Manipulation	Substrate manipulation is a method where artificial structures with planted corals are planted among the reef.
Substrate Stabilization	Substrate stabilization is a method where substrate such as concrete to minimize fracture or movement.
Larval Propagation	Larval propagation is a method where larvae are reared until they are ready to be attached to an artificial structure or on top of a reef.
Direct Transplantation	Direct transplantation is a method where grown corals are transported and replanted from one place to another.
Substratum Enhancement with Electricity	Substratum enhancement is where electrical currents are used to mimic the chemical composition of a coral skeleton.
Cryopreservation	Cryopreservation is a method where coral larvae or adult colonies are frozen in liquid nitrogen.

## Removing Invasive Algae

A central problem that corals go through is that they are becoming dominated by invasive algae, otherwise known as macroalgae. Although some algae, like zooxanthellae, are beneficial for corals, macroalgae act almost as a pesticide. Macroalgae have some perks: it protects coral reefs from excessive UV rays, provides food for herbivores, and absorbs excess carbon dioxide. However, too much algae can smother the corals and cause a depletion of vital resources such as sunlight and nutrients excreted from fish. Biofouling, ballast water, aquarium trade, and seaweed mariculture are amongst the main reasons for macroalgae introduction in the first place. (Neilson et al., 2018).

Typically, divers physically remove macroalgae and coral reef populations to restore the balance of macroalgae and coral reef populations. According to the NOAA, “On average, it would take a diver two strenuous hours to remove one square meter (roughly 10.5 square feet) of the exotic red algae carpeting coral reefs in Kaneohe Bay, Hawaii.” Because approximately 20.9% of benthic communities are dominated by fleshy macroalgae, the manual process is inconvenient to tackle the entire issue. (Pratchett and Cvitanovic, 2011, para. 1). Additionally, this method needs constant monitoring and a lot of workers.

For instance, a study done in India where *Kappaphycus alvarezii*, an invasive macroalgae species, was manually plucked off was unsuccessful for two reasons. For one, according to the divers, the small fragments of the macroalgae were firmly attached to the corals. Thus, the researchers hypothesized that there could have been a possibility that there were still algal fragments within the coral tissue, allowing the algae to regrow and smother the corals as it was before the eradication. The second reason is the method employed for this algae removal was unscientific and not well planned. To this date, local island managers are collecting washed-up fragments with *K. alvarezii* but then dumping them into the seashore. Thus, the macroalgae continue to settle on corals, causing the never-ending cycle of algae infestation. When the researchers last visited in 2013, there had been a significant spread of infestation in the locality therefore efforts to physically remove the algae were proven to be futile. The number of *K. alvarezii* colonies was found to be 8.5 and 11.2 (per m<sup>2</sup>; n = 10 quadrats) within the two sites of the invaded ecosystem respectively. It was significantly higher than the average number of *K. alvarezii* colonies observed within the same invaded ecosystem during pre-removal, in 2009. (Kamalakkan et al., 2010)

However, an invention called The Super Sucker, a vacuum system that sucks macroalgae, has shown promising results compared to manually handpicking invasive species. This system has proved helpful to divers as a case study in Kāne‘ohe Bay showed that nearly 80% of the macroalgae could have been picked up by the Super Sucker while only 20% were picked up by the divers themselves. (Pratchett and Cvitanovi, 2011).

Besides divers manually removing macroalgae by hand and via The Super Sucker, biocontrol methods such as utilizing urchins to consume algae have been used to limit the macroalgae from infesting too much of the reefs. In a case study done in Kāne‘ohe Bay, “...four discrete patch reefs with high invasive macroalgae cover (15–26%) were selected, and macroalgae removal plus urchin biocontrol (treatment reefs, n = 2), or no treatment (control reefs, n = 2), was applied at the patch reef-scale.” (Pratchett and Cvitanovi, 2011). Manual removal and biocontrol from the urchins throughout the experiment reduced invasive algae cover by 85%. Biocontrol methods have been seeing some promise as sea urchins and mollusks have been shown to control invasive macroalgae throughout the Mediterranean and the Atlantic. Biocontrol methods were discovered to be most effective within areas low in infestation or for emerging populations with invasive macroalgae.

However, the algae's toxicity may impact the biocontrol source's performance, and depending on its reproduction methods, the rate at which it can control an infestation varies. Manually removing algae or using biocontrol methods is not the long-term solution but a solution that benefits the corals temporarily because of algae's strong regeneration ability and ability to reproduce through vegetative fragmentation.

## Coral Gardening

Coral gardening is a form of coral restoration where corals are raised in nurseries, usually placed a few feet above the sea floor, then planted on reefs. Over the past decade, high survival with fast-growing rates from corals grown in nurseries has allowed practitioners to create healthy and genetically diverse corals. Thousands of corals are propagated and outplanted (taking one coral from a nursery and planting it in the natural ecosystem) onto degraded reefs every year (Schopmeyer et al., 2017, para 1).

The nursery stages of the coral gardening method have been very successful in the Caribbean and Western Atlantic region, with a large number of fragments (> 50,000 kept in Florida nurseries alone), and an increasing number of species now routinely propagated. However, the next step, outplanting nursery-grown corals onto wild reefs, has had mixed results since there are various factors to consider. After all, these nursery-grown coral fragments can be attached via epoxy, cement, rope, frames, and many different ways. Once the coral fragments settle onto the coral floor, they become natural components of the reef. (Lirman & Schopmeyer, 2016).

Nevertheless, coral gardening has been a quick and relatively cheap way for coral restoration. For instance, a group of researchers practiced coral gardening in Eilat, where they developed a floating mid-water nursery prototype and were able to yield colonies ready for transplantation within 144-200 nursery days. The scientists successfully cultivated corals using cheap materials in a short period. Similarly, in a study conducted in Bolinao, Pangasinan, nurseries were constructed within 3 months and could hold around 7000 coral fragments. (Shaish et al., 2008).

In a study done in Maldives, researchers monitored 78 *Pocillopora verrucosa* colonies over one year on Athuruga Resort Island in the Maldives. After a year, outplanting success was 78% for 60 of *Pocillopora verrucosa* colonies. The main obstacle for this study was detachment which affected 25% of the corals within the study. Regardless, the majority of the corals were able to recover afterward. Partial mortality affects the corals yearly due to predation or coral reef coverage. Outplanting success noticeably increased with depth. (Dehnert et al., 2022).

However, there are also possible downsides to these restoration methods as well. The nursery-grown corals, which are often grown a few feet above the ocean floor or at a laboratory, have adapted to drastically different ecosystems as those of natural corals. Higher macroalgal cover and lower herbivore densities can cause the newly attached corals to be vulnerable to predators and cause rapid mortality. For example, in Florida, territorial damselfishes caused significant mortality to staghorn outplants soon after planting (Schopmeyer and Lirman, 2015) and in the Dominican Republic where the corallivorous fireworm *Hermodice* concentrates on newly deployed staghorn outplants (V. Galvan, 2016, unpublished data). Outplanted corals also face potentially detrimental water chemistry conditions where ocean acidification has created reef environments with low aragonite saturation states (Lirman & Schopmeyer, 2016).

## Substrate Manipulation and Stabilization

Substrate manipulation is a restoration method that uses artificial substrates for multiple purposes. They stabilize and act as a temporary refuge for damaged corals, protect corals from currents and fish, provide hard substrate for invertebrate colonization, and attract fish to promote biodiversity. For substrate manipulation, color, texture, and material all play an important factor for the corals. Substrate manipulation gives much more flexibility to the researchers because of the versatility researchers can achieve with such a variety of substrates.

In a study done by Valérie F. Chamberland, Dirk Petersen, James R. Guest, Udo Petersen, Mike Brittsan, and Mark J. A. Vermeij, researchers tested two tetrapod-shaped concrete substrates, one thicker and

one thinner, that the coral larvae would attach onto and eventually deploy to the reefs underwater. The researchers deduced that substrate manipulation was much more cost-effective than restoration methods relating to sexual propagation. Utilizing this seeding approach allowed the corals to be deployed 1.5% to 7% of the time for traditional outplanting techniques. (Chamberland et al., 2017).

An average of 70% of larvae settled on either tetrapod design. After the first two weeks and the subsequent 5.5 months, 50% of the tetrapods never moved. After one year, 76% of the tetrapods could be recovered, of which 84% were either firmly lodged in crevices or cemented to the reef framework by encrusting benthic organisms. (Chamberland et al., 2017).

However, artificial substrates are not the most efficient restoration tool. For instance, researcher Schuhmacher who has monitored artificial reefs in Eilat, Red Sea that had been established 30 years prior, has shown no signs of developed coral communities. The artificial reefs were not covered with corals and had limited coral recruits compared to the natural habitats surrounding the fabricated reefs. (Shokry & Ammar, 2009).

Similarly, substrate stabilization is a restoration method in which rubble surrounding the coral is removed and stabilized with a substrate such as cement to reduce the effects of turbulence. In Indonesia, seventeen years after damage from dynamite fishing ceased, the rubble beds displayed significantly lower coral cover than rehabilitated and controlled (not blasted) reef sites, despite an adequate supply of coral larvae. Cement to stabilize the corals and mesh to prevent further movement are common ways substrate stabilization is used. Stabilization activities are most recommended on a small scale, and due to the lack of documentation on this particular method, it could suggest that logistics and materials are still under development. (Ceccarelli et al., 2020).

In Komodo Park, Indonesia, large rubble fields created by dynamite fishing and coral mining have shown no signs of recovery over six years after disturbances ceased in 1990. In 2002, quarried rocks were introduced to stabilize and structure the rubble fields. With the configuration treatment, hard coral treatment increased from 0% in 2002 to 44.5% in 2016. Meanwhile, non-rehabilitated rubble fields remained at approximately 3%. Furthermore, dynamite fishing in Negros Oriental, Philippines, resulted in large rubble fields. However, by pinning down rubble with 2 cm plastic mesh, by 2003, within the 2,400 m<sup>2</sup> rubble field, five 17.5 m<sup>2</sup> plots were rehabilitated. Furthermore, after three years, the rehabilitated plots and adjacent reefs had significantly higher fish biomass than the un-rehabilitated rubble area. (Ceccarelli et al., 2020).

However, these methods also bring along some downsides. Many of these artificial structures are made out of concrete or plastic. In the case of plastic, in a place of high UV and changing conditions which are inevitable under the sea, the plugs will deteriorate, causing another problem of microplastics, which are harmful to the nearby marine life.

## Larval Propagation

Larval propagation is another word for sexual propagation. There are two methods of sexual propagation. The first method improves corals' survival rate post-settlement by germinating them outside of their natural habitat and then letting them settle on artificial structures. This method prioritizes promoting the diversity of corals and improving the coral reefs' resilience. The second method of larval propagation is by releasing the embryo and germ cell on the reef. Researchers take advantage of the times when the coral population suddenly spikes. Although it may be difficult to find the correct timing and the appropriate environment for larval propagation, when done correctly, it will be the form of reproduction that will disrupt the environment the least.

In an experiment by researchers Chamberlain and others, they tested two tetrapod-shaped concrete substrates where the larvae settled. After one year, approximately 9.6% and 67% of tetrapods harbored at least one colony. (Boström-Einarsson et al., 2020). Additionally, in a study done in Curaçao, researchers observed *D. cylindrus* colonies over three years and five separate lunar cycles. The timing of the spawning was consistent from 2012-2014, and they were able to successfully rear *D. cylindrus* larvae to the primary polyp settler stage.

Once fertilized, the polyps showed rapid development and a short settling time. However, the study's researchers warn that this could have important consequences for larval dispersion and population connectivity. (Marhaver et al., 2015).

At the same time, researchers Dexter W. dela Cruz and Peter L. Harrison warn that asexual fragmentation can increase disease risk and limit the genetic pool of the coral themselves, which constrains their resistance to future stress disturbances. Sexual reproduction fixes these two issues as it is the most organic way a coral can reproduce and repopulate. (Cruz and Harrison, 2017). When comparing two types of propagation methods— asexual and sexual – researcher Heyward concluded that after four weeks, more than 6,500 acroporid coral recruits were growing on conditioned terracotta tiles dispersed with larva while the tiles with nothing on them were up to 100 folds lower.

## Direct Transplantation

Direct transplantation is where healthy coral fragments are physically relocated to an area that is degraded to develop a new reef community. Unlike coral gardening, these corals are planted without an intermediate nursery phase. Three main goals of direct transplantation of corals are accelerating reef recovery, replacing dead coral, and improving underwater aesthetics for tourism reasons. Overall, direct transplantation studies reported an average survival of 64%, with 20% reporting >90% survival of transplanted corals. (Boström-Einarsson et al., n.d.).

In a study by researchers Boch and Morse, propagation by fragmentation was relatively successful in terms of survival. It showed that high survivability of the fragments is possible via direct transplantation. The researchers propagated 134 coral recruits from 4 sections of *A. hyacinthus* donor colonies. The mean survivorship of the translocated corals within the first year was approximately 52%, with the highest mortality occurring in the first three months. At the end of the second year—i.e., between 563 and 685 days after transplantation—the overall mean survivorship was reduced to 23.9%. The researchers utilized zipties and concrete to transplant these corals. While all the corals that were held down by zipties died, using concrete resulted in 80-100% fragment survivorship in 1 year for *Corallium sp.*, *Lillipathes sp.*, and *Swiftia kofoidi*, 12-50% for the bamboo corals *Keratoisis sp.* and *Isidella tentaculum*, and 0-50% for the bubblegum corals *Paragorgia arborea* and *Sibogorgia cauliflora*. (Boch & Morse, 2012).

As described by the researchers, "...the methods described here for relatively small fragment propagation are conducive to the faster and more cost-effective permanent attachment to reef substrates because it does not require a nursery phase." (Boch & Morse, 2012). The researchers also suggest that increasing the density of larval settlement before outplanting could lead to the fusion of the polyps, which could enhance growth and survivorship. (Boch & Morse, 2012).

Although these goals sound promising, some say that direct transplantation should be utilized as a last resort because restorationists tend to use fast-growing coral. Thus, the corals die during the process or when they have to endure stress from global warming or changing factors. On top of that, direct transplantation requires careful planning and long-term monitoring. However, direct transplantation could be combined with larval propagation to enhance genetic diversity over time (Horoszowski-Fridman et al. 2020a)

## Substratum Enhancement with Electricity

Substratum enhancement with electricity is the use of electric currents to enhance the growth and survival of corals. Applying a low-voltage electrical current to the reef stimulates the growth of coral larvae, improving the survival and growth rate of coral colonies. The goal of the enhancement is to replicate the chemical structure

of a coral, such as calcium carbonate and magnesium hydroxide, in a similar way the molecules would work within a coral.

Rather than restoration, this method focuses on resilience by increasing calcification and resilience to stressors. For instance, low-voltage mineral deposition technology (LVMD), commonly known as Biorock, uses direct current to grow underwater limestone structures on a metal frame of any shape and size in the sea. These structures can repair themselves, making them cost-effective. LVMD can be speeded up by increasing the voltage and allowing the precipitation of Magnesium Hydroxide (Brucite). In addition, the process has shown effects on other marine life, such as reef-building corals, soft corals, oysters, and salt marsh grass as they have shown growth rates 3.17 times faster than controls. (Margheritini et al., 2021).

A study done by Goreau and Hilbetz showed that minerals deposited on a substrate could grow up to 20cm in two years, and the coral transplanted on them could grow even faster; for instance, *Acropora cervicornis* grew 5-8 cm in only 10 weeks. Generally, the corals grew 3-5 times faster than the controls, but in some cases, they were almost 6-20 times faster. Additionally, the transplanted corals were able to tolerate lower water quality. In the 1998 Maldives mass bleaching event, approximately 95-99% of the corals on the natural reef died in a few weeks, along with 100% of the thousands of previously transplanted corals. Still, most corals on Biorock survived the extremely high temperatures. (Goreau, 2022)

Because of the success of this restoration method, the author suggests that this research method should be utilized in human-dense areas such as places close to resorts, hotels, or tourism sites. (Innovative Methods of Marine Ecosystem Restoration, 2023)

However, being that this method is still new, the outcomes have been unpredictable. As Gagliardi puts it, "...results are inconsistent, with different outcomes that may vary even between congeneric coral species." (Gagliardi, 2021). With some results that described increased growth and attachment in *P. cylindrica*, researchers said that the fragments they have found are also expensive and difficult to deploy, with a need for a reliable power source for this to be a feasible restoration plan. (Boström-Einarsson et al., 2020)

## Cryopreservation

Cryopreservation is a last-resort restoration method where coral larvae and adult colonies are kept at low temperatures in liquid nitrogen. Cryopreservation aims to conserve the genetic diversity of corals and provide a source of corals for future restoration efforts and generations. This method would be useful when the corals are on the brink of existence after all other restoration methods have been used.

There has been some progress made in terms of cryopreserving coral larvae. It has been discovered by researchers Daly and others that coral larvae can survive low-temperature cryopreservation and resume swimming after warming. This is proof that cryopreservation *is* indeed possible with corals. Researchers have learned that lasers could warm up the coral larvae in cryopreservation. However, depending on the size of the coral such as the *F. scutariai* larvae, which are relatively smaller in diameter (~100–200 μm) compared to acroporid species (~400–600 μm), may require new cryoprotectant solutions and warming parameters. (Daly et al., 2018).

Cryopreservation is still new to the scientific community, but researchers are still experimenting to see what this could mean for the future. Cryopreservation is used extensively within agriculture to help preserve out-of-season samples and to secure genetic diversity. (What Is Coral Cryopreservation?, 2021). Furthermore, since 2011 the Taronga Conservation Society, the Great Barrier Reef Foundation, the Australian Institute of Marine Science (AIMS), and the Smithsonian Conservation Biology Institute have collaborated to collect and cryopreserve sperm and eggs during the once-a-year coral spawning event off the Queensland coast. (Cryopreservation, 2022).

## Conclusion

Although many restoration methods have been successful, coral reef restoration is not designed to reduce climate impacts but to support natural recovery after disturbances in key areas. (Mer, n.d., 2020). As McLeod puts it, coral reef restoration should be part of an integrated resilience-based management framework and within the strategies and social and ecological priorities (e.g. McLeod et al. 2019). The key to the successful restoration and recovery of degraded coral reef ecosystems is analyzing the causes of degradation and destruction and removing these causes with restoration and preservation methods. Although restoration methods have been successful, a lack of long-term monitoring has shown the regression of the progress these methods have made. For instance, there was a case in Indonesia where coral cover and diversity improved dramatically after using artificial substrates. However, 100% of the corals died in a bleaching event six months after the study (Boström-Einarsson et al., 2020). Despite the initial high hopes, "...mismatch between relatively short monitoring times and the temporal scale at which disturbances occur may artificially inflate the growth or survival rate" (Boström-Einarsson et al., 2020). Many of these studies have performed these restoration methods to show short-term success, but there is a lack of research on the long-term success of these restoration methods. Additionally, researchers must focus on the key reasons for degradation in the coral reefs and effective restoration methods for each coral reef. An example of this is a study in Fiji and Kiribati. Their researchers focused on the natural reef recovery process by removing coral predators and re-introducing fish and sea urchins to control macroalgae. Granted, it would take much longer to see results and increase the costs of execution, but naturally, improving the surroundings of the coral reefs will boost the corals' resilience in the long run. To sum up, to improve coral reef restoration, researchers must prioritize long-term monitoring and mix strategies for removing threats to the coral reefs as well as restoration methods to achieve the long-term and constant growth of coral reefs.

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