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ECOLOGICAL AND SOCIOECONOMIC CONSEQUENCES OF CORAL REEF DEGRADATION.

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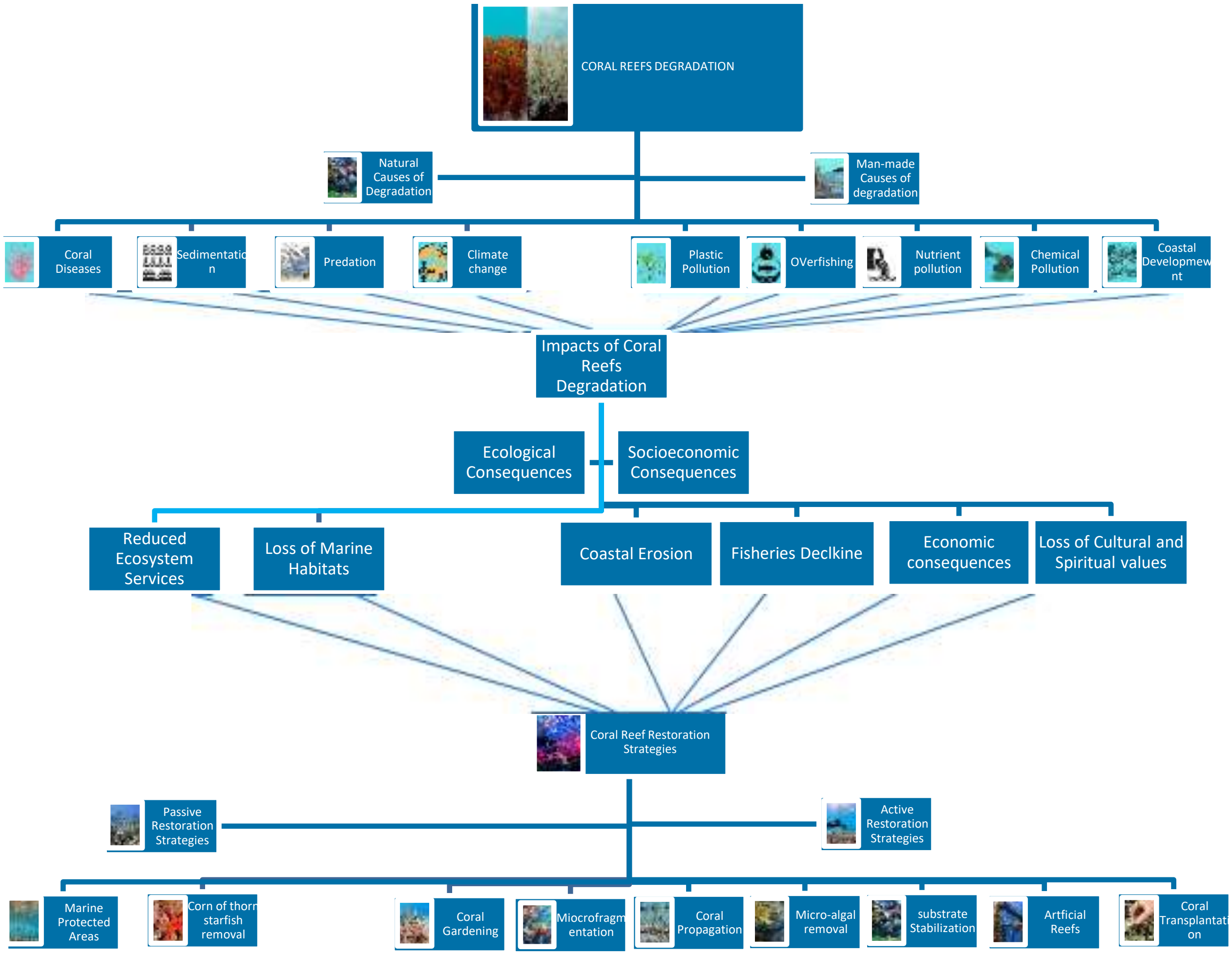
Article Info

Abstract

The coral reefs represent some of the planet's most significant ecological systems for marine biodiversity, along with environmental benefits. Still, they are rapidly vanishing due to a combination of various environmental and human-caused stressors. Global climatic changes, predation, coral diseases, sedimentation, marine development, and unsustainable fishing activities are major causes of reef degradation. Furthermore, declining water quality caused by eutrophication, plastic debris, and chemical pollutants, especially polycyclic aromatic hydrocarbons, UV filters, and hydrocarbons, worsens the situation by harming coral health and reproduction. The review examines the ecological and socioeconomic consequences of reef decline, including reduced ecosystem services, loss of marine habitats, declining fish populations, and diminished coastal protection and tourism revenue, particularly in regions that rely on reefs for their livelihoods. Several active restoration methods have been examined, including coral gardening, larval propagation, substrate stabilization, micro-algal removal, micro-fragmentation, artificial reefs, and coral transplantation, alongside passive approaches like establishing marine reserves and predator exclusion, highlighting the urgent need for comprehensive and multifaceted strategies. The paper offers several recommendations, including improving monitoring tools, expanding restoration efforts, enhancing stakeholder collaboration, and developing legislation to safeguard reefs for future generations. Through both national and global initiatives, it remains possible to prevent further deterioration and conserve the vital services they provide.

Keywords: *Reef degradation, Climate change, Chemical pollutants, Coral reproduction, Ecosystem services, Restoration methods, larval propagation, micro-algal removal, artificial reefs, marine reserves.*

GRAPHICAL ABSTRACT



1. INTRODUCTION

Coral reefs are some of the biologically unique ecosystems on earth because of their three-dimensional structure, which supports an enormous variety of marine species(Montano, 2020; Suan et al., 2025). They host more than 25% of the marine organisms, including fish, than rainforests(Corigliano et al., 2025; Van den Hoek & Bayoumi, 2017). For example, in Oman's reefs, a variety of marine species may be found (Al Ismaili et al., 2024). Coral generally forms colonies, consisting of thousands of individual organisms called polyps. Like all living things, corals have specific physiological and environmental needs to exist(Abrego et al., 2021). Corals' growth rate exhibits spatial and temporal variation, primarily influenced by light, water quality (turbidity), and temperature. Ongoing climate change-related conditions are expected to negatively affect scleractinian corals. Shifts in assemblage structure may further intensify these effects, favouring slower-growing coral species. (Pratchett et al., 2015). The Asia-Pacific region is home to 80% reefs area worldwide (Bartelet et al., 2024), and the Maldives' 21,500 km2 of coral reefs are iconic and plentiful worldwide(Galli et al., 2021). Reefs provide us with many benefits, including food supply, coastal protection, erosion control, ecological cycling, alongside tourist and leisure activities (Bayraktarov et al., 2016; Robles-Zavala & Reynoso, 2018; Wright et al., 2025; Younes et al., 2025). The fact that this estimate is higher than that of any other ecosystem on Earth emphasizes how crucial coral reefs are to ecosystem services and the related advantages they offer to human society(Vercelloni et al., 2018). Coral reefs serve as a crucial habitat across all kingdoms of life, providing shelter, breeding ground, and food sources. Furthermore, many reef organisms, including invertebrates, form essential mutualistic, commensalistic, and parasitic relationships that contribute to their survival and ecological balance. Reef-building corals host numerous microorganisms and macroorganisms, many of which play a key role in maintaining coral health and ecosystem stability. Coral-associated species help to recycle nutrients, mitigate sedimentation effects, and even slow disease progression, enhancing reefs' resilience. Some symbiotic organisms, such as Zanclea hydrozoans, protect corals from diseases and predators, improving their survival chances. Despite their significance, many species living within coral reef ecosystems remain undiscovered due to their small size, camouflage abilities, or deep-sea habitats(Montano, 2020). Coral reefs contribute to critical process such as nitrogen fixation and the regulation of CO2 and calcium carbonate levels in marine environments(Costa et al., 2016). The reefs of Sodwana Bay on South Africa's northeast coast offers essential environmental benefits, including sediment generation and sediment entrapment. Sediment generation and entrapment are valued at R74.4 million and R89.4 million (about \$5.6-\$6.7 million at R13.38/US\$1) annually. These services support the local economy(Laing et al., 2020). They support fisheries and other renewable marine resources, which are vital for food security and livelihoods. The physical structure of coral reefs helps to protect the shoreline by reducing and mitigating the impact of waves and storms. Because of the increase in sea level and tropical storms' intensity, coral reefs serve as natural barriers, helping to safeguard coastal communities(Costa et al., 2016). Mostly in tropical regions, coral reefs shelter over 500 million people. Reefs of shallow waters could weaken up to 98% of the incoming wave energy, making them ideal breakwaters(Carlot et al., 2023). Throughout over 100 countries and Islands, coral reefs offer revenue, including foreign exchange revenue, and draw tourists from domestic alongside international locations(Spalding et al., 2017). Coral reefs provide significant cultural services, particularly in regions where tourism and recreation flourish. These vibrant ecosystems attract millions of visitors annually, supporting industries that generate substantial economic revenue. Studies indicate economic value derived from coral reef tourism often supports other ecosystem services. Beyond their financial benefits, coral reefs hold policy relevance, as governments can leverage environmental taxes and conservation fees to support coral reef conservation and restoration. For example, countries like Fiji and Seychelles use money from tourism to protect their coral reefs and promote sustainable coastal development(Fezzi et al., 2023). These aesthetic components benefit human health and well-being in maritime environments by providing opportunities for outdoor recreation and the enjoyment of unique scenic attractions. Reef-building species such as calcareous algae, gorgonians, and scleractinian corals, as well as the amazing diversity of creatures that inhabit these ecosystems, make up the three-dimensional framework of coral reefs, which disperses the beautiful elements of these ecosystems. The framework of the reef is frequently visible from above, which enhances the reef's aesthetic value and scenic appeal(Waechter et al., 2024).

In the past few years, hard corals that provide habitat have been dramatically declining in reef environments. Reefs are subject to a variety of chronic and acute anthropogenic disturbances such as declining water quality, destructive fishing practices, over-harvesting of reef species, and outbreaks of coral predators and coral disease; however, over the last two decades, climate change has emerged as the primary threat to coral reef. This was highlighted during the recent 2016-17 global marine heat wave, which resulted in the most extensive coral bleaching event in history, including isolated and pristine reefs(Boström-Einarsson et al., 2020).

Coral reefs are under intense threat. According to one study, 27% are permanently lost, with an additional 30% in danger of loss within the coming 3 decades based on current trends(Roth et al., 2018). Over the past 40 years, there has been a significant reduction in coral cover on tropical reefs. In coral reef systems around the world, historical coral coverage was estimated to be between 58% and 70%. Between 1957 and 2000, the amount of coral reef cover worldwide decreased by almost 50%(Eddy et al., 2021).For example estimated that 3800 km2 of coral reefs were once present in the Gulf, with roughly 70% of them now effectively dead(Sheppard, 2016). According to some, coral reefs may completely disappear by 2070(Souter et al., 2021). Because corals are sedentary and have a limited range of environmental tolerance, reef ecosystems are extremely susceptible to acute stressors and can undergo fast structural and functional changes. Coral reefs, like many marine ecosystems, are predicted to be extremely sensitive to future climate change and are increasingly subject to a variety of chronic and/or episodic hazards(Adjeroud et al., 2017). Among the reasons behind this loss is sickness(Renzi et al., 2022).

Degradation of reefs is largely fueled by pollution, climate conditions, overfishing, and crown-of-thorn outbreaks. Over the past twenty years, reefs around the world have been significantly damaged by periods of coral bleaching and disease, along with increases in the regularity and intensity of storms. Corals lose their exterior tissue as they die, and algae may eventually take control(Chivers et al., 2016). Coral skeletons decompose over time, leaving behind an ecosystem that is dominated by rubble. The rate at which habitat change is happening is unprecedented, even if it is a natural tendency. According to estimates, 60% of reefs are in danger of going extinct and could disappear by 2030. There has been significant damage even in the Great Barrier Reef, which is frequently considered to be among the world's most pristine reefs(Chivers et al., 2016). Thermally induced coral bleaching events, cyclones, and outbreaks of keystone species are among the many large-scale disturbances that can drastically change the biological and ecological processes that sustain coral communities(Adjeroud et al., 2017). Reef fish populations in good health aid in the recovery from such occurrences(Gordon et al., 2018).

The tropical waters are warming along with the global climate system, which is bad for coral reefs. The coral-algal symbiosis can break down when relatively minor variations in sea surface temperature (SST) beyond the normal summer maximum occur, since tropical corals are near their upper thermal limit1. Modern coral reef ecosystems are built on the mutually beneficial association between photosynthetic microscopic plants (zooxanthellae, Symbiodinium) and coral animals. Because the coral host receives photosynthetic products from the algae, it can calcify more quickly than it would otherwise due to biological and physical erosion. The backbone of the reef is the calcium carbonate skeletons that are created throughout time. These skeletons serve as home for the myriad of creatures that are associated with the reef and collectively comprise the tropical coral reef ecosystem (Lough et al., 2018). Local stressors, such as excessive nutrient loading in coastal waters, further destabilize reef ecosystems by promoting algae overgrowth and accelerating bio-erosion. (Silbiger et al., 2018).

When corals die due to climate change, pollution, or human activities, the reefs often get taken over by seaweed and algae, which makes it harder for corals to grow back. Corals need space to grow, but algae and seaweed take up space and stop corals from growing, making it even more difficult for corals to recover. Some algae release chemicals that prevent coral reefs from growing. Furthermore, damaged reefs produce fewer young corals, slowing recovery(Roth et al., 2018). Coral destruction leads to an increase in algal turf and cyanobacteria, which can prevent coral from recovering and disturb reef ecosystems(Hernández-Delgado et al., 2024). Many sea creatures rely on reefs for shelter and food sources. When reefs degrade, these species struggle to survive. Particularly impacted are reefs in the western Atlantic region. The western Atlantic reefs' vital biological and geologic roles could be lost if the current rate of reef deterioration in this area continues(Kuffner & Toth, 2016). Many coastal areas, including parts of Africa, Southeast Asia, and the Bay of Bengal, rely on coral reef fish for food. Their decline affects people's nutrition and livelihoods. Countries with high fish consumption from coral reefs, such as Palau, Micronesia, and Kiribati, are facing food security challenges due to declining fish stocks(Eddy et al., 2021). Coral reefs' degradation severely impacts fishing communities by reducing fish availability, leading to lower protein consumption and nutritional concerns, especially for children. Economic struggles from reef degradation influence family planning, as seen after the 1998 bleaching in Indonesia. Malnutrition became a serious issue despite improved incomes by 2007, children from these families still faced educational difficulties(Chaijaroen, 2022). Hurricanes, like Irma and Maria in 2017, have caused massive destruction, including breaking corals, moving sediments and burying reefs under pressure(Hernández-Delgado et al., 2024). Ocean climate change has been seen to change many things that are important to corals, such as the surface salinity, the water column stratification, the supply of nutrients, ocean currents, oxygen levels, and the speed of winds and storms. In 2015 oceans became unusually warm, particularly in tropical areas(Hoegh-Guldberg et al., 2019). Coral reefs hold cultural significance for many indigenous and local communities. Their destruction can lead to loss of cultural heritage and identity, weakening community resilience and cohesion(Eddy et al., 2021). This cause coral bleaching in many northern hemisphere reefs, including Samoa and Hawaii. As global temperature continue to rise, heat reached to dangerous levels in southern hemispheres in early 2016. This lead to severe damaged to reefs specially in Indo pacific regions including western Indian regions , Maldives, Great barrier reef and the Western and central Pacific. More than 80% corals has been lost over past 30 years in Caribbean due to climatic variations(Hoegh-Guldberg et al., 2019).

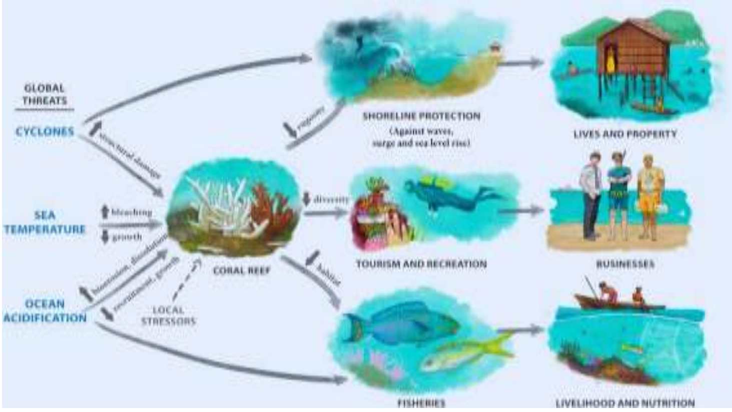


Figure 1: The consequences of global and local drivers on tropical coastal areas especially those including reefs and other ecosystems. https://doi.org/10.1016/j.rsma.2019.100699

Reef rehabilitation uses a variety of procedures, including recovering and transplanting corals and sponges, clearing debris, and restoring reef structures. These initiatives are frequently small-scale and target high-value places, such as tourism destinations, given to the high costs and labor intensity involved (Boström-Einarsson et al., 2020; Hughes et al., 2023). Coral nurseries and active rehabilitation activities are spreading worldwide as coral reef ecosystems disintegrate because of local and global challenges(Forsman et al., 2018). Prioritizing passive habitat protection above restoration was the norm in maritime conservation until recently. However, recent studies have shown that the most successful conservation efforts include habitat restoration and preservation (Boström-Einarsson et al., 2020). Reef rehabilitation is a reactive process that helps reef ecosystems recover after they have been deteriorated, ruptured, or demolished (Suggett et al., 2023). For coral reefs, the term' restoration' refers to both' restoration' and' rehabilitation'. The latter emphasizes "the reparation of ecosystem processes, productivity, and services…"(Boström-Einarsson et al., 2020). Coral reef restoration has emerged as a potential technique for ensuring the long-term conservation and viability of coral reef ecosystems. While there are several ways to coral restoration, the main element is purposeful intervention to encourage coral reef growth and recovery using techniques such as coral gardening, artificial reef structures(Cvitanovic et al., 2024), coral transplantation, and assisted larval production that helps corals to reproduce and settle in new areas. Additionally, strategies like manipulating coral microbiomes and accelerating calcium carbonate production aim to improve coral health and transplantation success. While these restoration methods offer hope, their large-scale effectiveness remains a challenge, requiring continued innovation and restoration efforts(Rinkevich, 2021). Recent advances in cryopreserved sperm technology allow for the long-term storage and controlled reproduction of coral species, supporting large-scale reef restoration efforts(Hagedorn et al., 2017).

Coral reef degradation is a global environmental challenge with serious environmental and economic consequences. These ecosystems provide a range a services including fisheries, coastal protection, and habitat support to wildlife. Understanding the science behind their degradation is essential for implementing the conservation measures. This review utilizes the current knowledge on reef challenges and restoring strategies, leading to the development of strategies and policies to ensure the long-term sustainability of these important ecosystems. This review aims to explore the major causes, effects, and restoration strategies linked with coral reef degradation. This review takes weeks to compile and analyze the existing research to provide a clear understanding of how coral reefs and being degraded and what restoration and conservation measures can be taken to prevent their degradation. The aim was to categorize and identify the ecological and artificial causes of reef degradation specially pollution, measure the environmental, economic, and social consequences of reef degradation, evaluate and review the existing conservation and restoration strategies, determine their effectiveness and limitations, develop policy recommendations and future research directions for sustainably managing the reef ecosystem.

2. MAJOR CAUSES OF CORAL REEF DEGRADATION

2.1 Natural Causes of Coral Reef Degradation

2.1.1 Coral Bleaching and Climate Change

Reefs are dealing with changing climate conditions, mainly because of rising ocean temperatures. Corals have a special relationship with tiny algae called zooxanthellae, which live inside them and provide food(Dutra et al., 2021; Van Woesik et al., 2022). These algae help the corals by providing up to 90% of their energy through photosynthesis(Heron et al., 2016). However, when the water gets too hot, this relationship is disturbed, leading to coral bleaching. Coral bleaching happens when corals are stressed by high temperatures and expel their algae. Since the algae give the corals their color and food, corals turn white when they leave(Montano, 2020; Van Woesik et al., 2022). When corals are stressed by heat, they become more prone to diseases, grow more slowly, and have fewer baby corals. Over time, this can lead to fewer corals, less variety of species, and weaker reef structures if the damage continues for many years; some coral species might even disappear from certain areas(Heron et al., 2016; Kang et al., 2021)

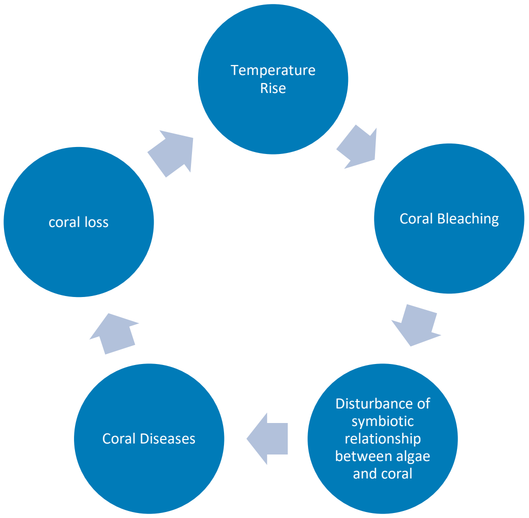


Figure 2: This cycle highlights the relationship between increasing temperature and coral reef degradation.

A most recent coral bleaching incident began in 2023 in the Caribbean and later spread to the southern hemisphere in 2024. Similar bleaching events have happened in 1998,2010, 2014-2017, and 2023, showing an increasing trend because of weather changes(Reimer et al., 2024).

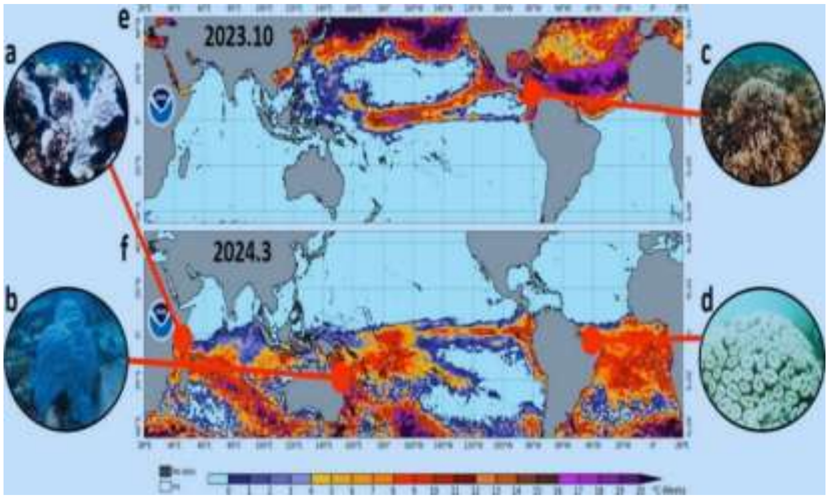


Figure 3: Worldwide coral whitening instances recorded in 2023-2024, highlighting affected regions such as Kenya, Australia, Panama, and Brazil. The map also shows degree Heating Week (DHW)data from NOVAA, indicating areas experiencing severe thermal stress, DOI: http://dx.doi.org/10.1007/s00338-024-02504-w

2.1.2 Coral Diseases

Coral diseases are the main reasons for reef deterioration, causing large-scale coral death in a short time. These diseases damage coral tissues, making them weak (Alvarez-Filip et al., 2022) against microbial infections and increased pathogen virulence(Subhan et al., 2020), and more likely to die from other environmental stressors like pollution and rising ocean temperature.(Alvarez-Filip et al., 2022). Diseased corals show changes in color, shape, size, and texture(Mohamed & Sweet, 2019).

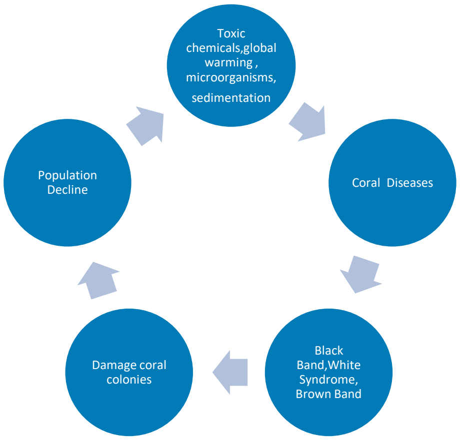


Figure 4: This cycle represents how environmental stressors lead to coral diseases, resulting in damage to colonies and population decline.

Factors like global warming, toxic chemicals, and increased sedimentation promote bacterial infections and algae growth, leading to diseases like black band disease(El-Naggar, 2020), Brown band disease, and White syndrome, which have been observed in protected marine zones like the Great Barrier reefs(Sisney et al., 2018). Destructive diseases cause significant changes in the growth and reproduction of coral reefs that ultimately alter the community structure, density of reef-related organisms, and the diversity of other organisms(Mulya et al., 2023). Several studies suggest that many types of microorganisms, like bacteria, fungi, and protozoa, are mainly responsible for coral diseases(Mohamed & Sweet, 2019). Coral colonies get damaged, forming scars and patches(Sharma & Ravindran, 2020). In the late 1970s, a disease called white band disease led to a major decline in coral population, wiping out around 80% of reef organisms in the Caribbean (Alvarez-Filip et al., 2022). Black band disease BBD is the most problematic disease worldwide, significantly affecting coral reef health (Séré et al., 2016; Sisney et al., 2018) due to its ability to spread rapidly and cause significant tissue loss(Morais et al., 2022). This disease has been observed in many regions, that involves the Caribbean, Indo-Pacific, India, South Africa, the Red Sea, the Philippines, the Maldives, and Hawaii. The condition is triggered through multiple microorganisms, including Cyanobacteria, sulfate-reducing bacteria, and other microbes, which work together to destroy coral tissues. Environmental stressors rising temperature, sedimentation, and pollution, further exacerbate the situation(Morais et al., 2022).

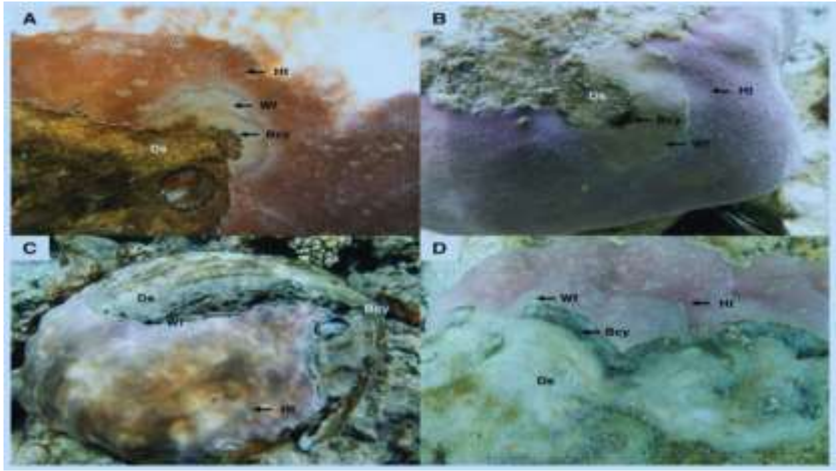


Figure 5: This image shows lutea corals affected by black band disease in Reunion Island at different locations , including Ravine des poux , La corne, and Trou d'Eau DOI: 10.7717/peerj.2073

Yellow Band Disease YBD is a serious and widespread disease first identified in the Florida keys in 1994(Randall et al., 2018; Susmaa et al., 2024). It appears as yellow or brown blotches that expand in a circular band, typically 1-5 cm wide, spreading at a rate of 0.6 cm per month and growing up to 15 cm in size. This disease is linked to Vibrio bacteria, which destroy coral algae symbionts, leading to death of coral tissues. Its impacts are worsened by pollution, overfishing, and climate change, making affected corals more vulnerable to degradation(Susmaa et al., 2024).

2.1.2 Sedimentation

Sedimentation is the major threat to the survival and recovery of coral species and their habitats(Najeeb et al., 2025). Sedimentation are a major source of stress for coral and coral reefs. Research dating back to 1975 highlights that silt and brackish water from floods harm the reefs. Sedimentation come from natural sources like rivers can be stirred up by waves. They include carbonate sediments that help to build and support reef structures through natural processes(Rogers & Ramos-Scharrón, 2022). Land-derived sediments,often carried by rainfall, landslides, and surface runoff, are commonly introduced into marine environments. Sediments can harm the corals in many different ways such as smothering (covering corals), stopping new corals from growing(Najeeb et al., 2025) and blocking sunlight(Adeniran-Obey et al., 2024b; Rogers & Ramos-Scharrón, 2022). Deposition on seafloors affecting coral reefs and seagrass beds(Rogers & Ramos-Scharrón, 2022). Sedimentation can harm the coral at all stages of their life. High sedimentation levels can block sunlight which can disturb their feeding process. Sediments can slow down the coral growth, weaken them, and make more likely to sick and damaged. If sediments level keep rising , corals can face serious harm , including death , which could change entire coral reef community and reduce its benefits to the ecosystem. Sedimentation can disturb the fertilization of coral eggs and sperm in water. Even a thin layer of sediments don't harm adult corals can stop baby corals larvae from setting on good surfaces. In areas with high to moderate sediments, there can be high mortality rates in young corals(Tuttle & Donahue, 2022). According to one study sediments increase energy demand on the corals because they need to produce mucus to clear the sediment away. Sediment buildup hinders the zooxanthellae's ability to photosynthesize, which may lead to coral bleaching and further decline in coral health(Ahmad et al., 2024).

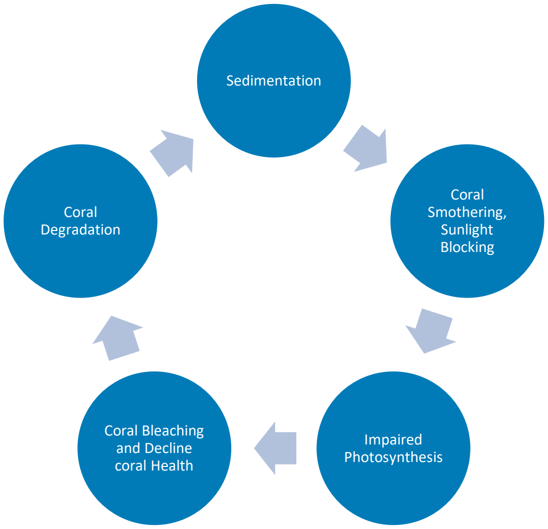


Figure 6: This cycle represents how sedimentation causes reef degradation through a cycle of impacts, including coral smothering, impaired photosynthesis, and decline in overall reef health.

2.1.4 Predation

Predation contributes to coral reef degradation both directly and indirectly(Bauman et al., 2019).
Coral predators, also known as corallivores, are animals that feed on the mucus, tissue, or skeletons of living soft and hard corals. When these predators eat corals, they damage the protective layers, which makes the corals more likely to get infections(Renzi et al., 2022). Coral reefs rely on a balanced food web. Apex predators like sharks and large groupers help to keep this balance by controlling the behavior of herbivores (plant fish). When predators are removed or reduced (due to overfishing or human activity), herbivores may overgraze, leading to imbalances. On the other hand, when predators are present, they

can scare herbivores into eating less or avoiding certain areas. This behavior change led to more algae (seaweed) growing on reefs, which can outcompete or smother corals. So, even though predators aren't directly harming the reefs, their indirect effect through changing prey behavior can contribute to coral reef degradation (Mihalitsis et al., 2022; Rani & Roy, 2025; Rizzari et al., 2014; Silveira et al., 2023).

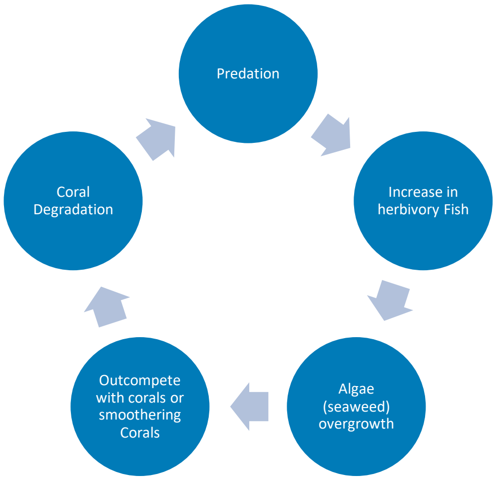


Figure 7: This cycle represents how predatory species contribute to reef degradation.

2.2: Man-Made Causes of Coral Reef Degradation

Reef ecosystems are becoming more and more dangerous by a wide range of man-made activities, both locally and globally. Over the last two centuries, human interaction has significantly altered coastlines, depleted fish populations through overexploitation, and contaminated coastal waters, which causes reef environments to rapidly deteriorate (Hoegh-Guldberg et al., 2017).

2.2.1 Nutrient Pollution

Nutrient pollution from agriculture runoff, sewage discharge, and coastal development is one of the major causes of coral reefs degradation, also called eutrophication. This introduces excessive nitrogen and phosphorus in reef ecosystems, leading to altered coral growth rate (positive under slight enrichment, harmful under excess) and increased competition between symbiotic algae and corals. Furthermore, nutrient pollution accelerates bioerosion and sediment dissolution, both of which weaken the physical structure of coral reef ecosystems. It also promotes the growth of fleshy macroalgae, which can outcompete and smother corals. Additionally, excessive nutrients disturb the pH balance and aragonite saturation levels, which are critical for coral reefs' calcification. The combined goods oppressively compromise reefs' adaptability and contribute to rapid decline (Silbiger et al., 2018).

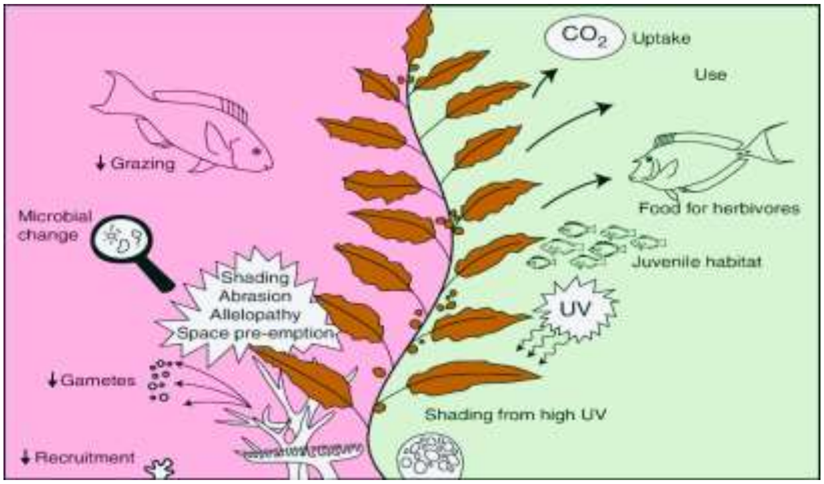


Figure 8: Conceptual graphic illustrating the detrimental (red) and beneficial (green) impacts of fleshy macro-algae on coral reefs DOI: 10.1111/rec.12852.

Nitrogen enrichment directly affects the coral physiology by lowering heat tolerance, prolonging bleaching and reducing classification. It also indirectly affects by promoting growth of competing organisms. These effect vary depending on coral genus, species , their symbionts(Zhao et al., 2021).

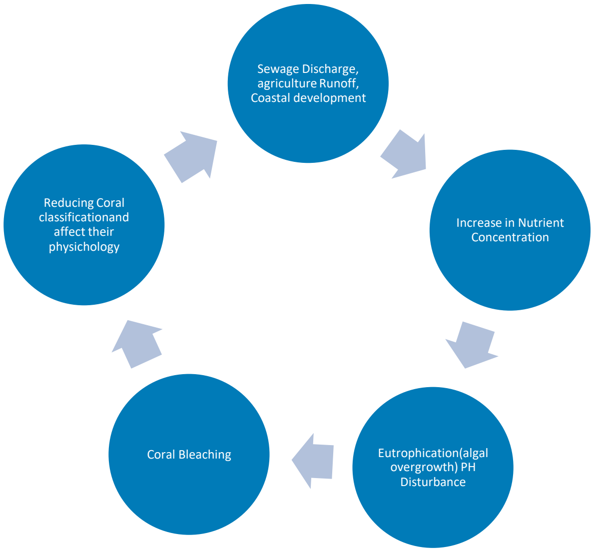


Figure 9: This cyclic flow represents how nutrient pollution from different sources contributes to reef degradation.

2.2.2 Chemical Pollution

A significant reduction in coral cover and reef functions results from water pollution, which significantly raises the prevalence of illnesses and infections (Figure 10). Accordingly, one of the biggest risks to coral health is declining water quality(Ouédraogo et al., 2023). Globally, UV filter exposure puts around 10% coral reefs at threat, 40% of those are found near the coast and are more vulnerable to exposure because each year 6000–14000 tons of sun screen lotions consisting of 1-10% of UV compound oxybenzone are discharged, affecting the reef environments(Watkins & Sallach, 2021). According to a study, oxybenzone constitutes a significant threat to reefs by harming the coral larvae (Stylophora pistillata). It acts as a genotoxic and phototoxic agent, leading to malformation, damage to DNA, and coral bleaching, particularly in Hawaii and the U.S. Virgin Islands, which highlights its effects on the reef ecosystems(CA, 2018). Organic UV filters are indirectly introduced into marine environments by runoff, wastewater effluents, industrial discharge, and household usage, as well as through human skin as it is rinsed off during leisure activities. Few experiments have investigated the implications of UV filters in coral reef sediments. Some studies have shown the bioaccumulation of chemical substances in reef organisms (Watkins & Sallach, 2021). Since tropical and subtropical reefs are popular tourist destinations, the absence of monitoring studies emphasizes the critical need to track the environmental impact and spread of UV filters. A small number of analyses have been carried out on the ecotoxicological effects of UV filters and degradation products (Maipas & Nicolopoulou-Stamati, 2015). Ongoing chemical pollution has significantly impacted tropical coral reef ecosystems. Polycyclic Aromatic Hydrocarbons have been detected in coral reef habitats, which indicates the hazardous and ecological consequences. PAHs in a variety of environmental media have major impacts across coral habitats, especially in the South China Sea. PAHs' trophic transmission or biotransformation in coral reef food webs shows ecological risk and bioaccumulation, highlighting their ability to cause long-term ecosystem harm(Han et al., 2022).

Oil leaks have happened globally in the marine ecosystems. Long-term exposure to oil pollution can affect the coral's ability to reproduce and attract new members. Additionally, oil and dispersing chemicals can also damage the symbioses that corals have with a variety of microorganisms, which are necessary for host homeostasis, such as bacteria, viruses, dinoflagellates, and archaea(Silva et al., 2021).

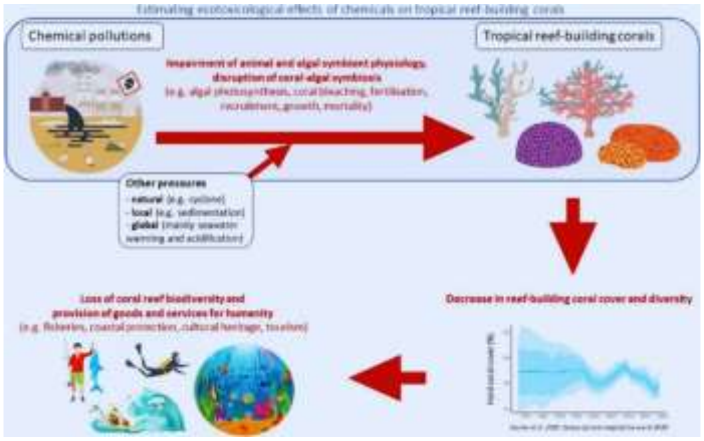


Figure 10: A graphical representation that shows how the decline in reef biodiversity and diminished supply of goods and services to humans are caused by the cascade of eco-toxicological implications resulting from seawater pollutant exposure on corals, which serve as the foundation of the warm water marine ecosystem. http://dx.doi.org/10.1186/s13750-023-00298-y

2.2.3 Overfishing and Destructive Fishing

Mortal conditioning, like overfishing, especially targeting large fish, is damaging coral reefs(Shantz et al., 2020). Dangerous fishing methods, like using explosives, poison, or special boots, harm the coral reef ecosystems by damaging their structures. Overfishing can disturb the entire food web of coral reefs.

It can reduce the large number of small fishes that eats the algae, causing overgrowth and harming the corals. Most reefs around the world are suffering because of overfishing(El-Naggar, 2020). In the Caribbean, large parrotfish are frequently caught for food. These acqautic species playing a vital role by consuming the green algae that grow on coral surfaces. When too many large parrotfish are removed, algae can grow out of control and harm corals.(Shantz et al., 2020). The majority of reef conservation analyses have looked only at local overfishing, not at how fishing patterns might affect reef health on larger regional scales(Milne et al., 2022). Coral reefs along Pakistan's coast are being damaged by human activities. Too much overfishing by over 15,000 boats has caused a 60-90% drop in fish population(Ahmad et al., 2024).

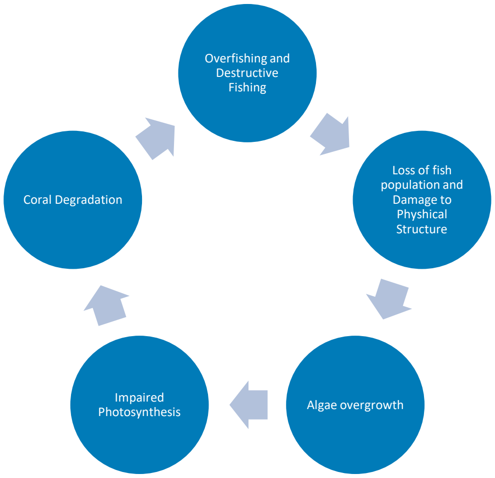


Figure 11: This cyclic diagram represents how overfishing and destructive fishing practices contribute to reef degradation.

2.2.4 Climate Change

Changing Climate is a major human-induced hazard to the reef ecosystem. It is mostly caused by the production of greenhouse gases such as carbon dioxide (CO2), methane (CH4), and nitrous oxide (N2O) from practices like the fossil fuels incineration, illegal cutting of trees, and industrial procedures. These gases cause the atmosphere to retain heat, would cause global warming and increasing the sea surface temperature. Climate change can also lead to stronger storms and cyclones, which physically damage the coral structures and disturb the balance of coral ecosystems. It alters the ocean currents and vertical mixing, which affects the dispersal of coral larvae and the availability of nutrients in the reef environment. Additionally, rising sea level- due to melting ice and thermal expansion- can reduce the light reaching shallow reefs, impacting coral growth(Najeeb et al., 2025). Some researcher estimates that, seventy to eighty percent world's reefs will loss by upcoming decades due to climatic events(Pessoa, 2025). Increase in temperature contributes to the production of Reactive oxygen species which can destroy algae and reef cells. Climate change leads to ocean acidification which lowers ocean PH and affect the corals. As coral secretes calcium carbonate for their skeleton formation this become difficult as lower PH decreases carbonate ion concentration(Adeniran-Obey et al., 2024a). Rising ocean temperatures, acidity, and cyclone intensities linked to CC are putting coral reefs in the Great Barrier

Reef under more and more stress(Mentzel et al., 2024). Future of this ionic reef is highly uncertain due to combined affect of heatwaves and cyclones(Byrne et al., 2024).

Table: 1

Climate change	Impacts
Ocean Warming	Weaker reef tissues and coral morphology
Higher Temperature	Reef Disorders
	Bleached corals
	Impact other reef creatures
Severity of the tropical storms	Reef loss physically
Heavy rainfall and floods	Water with low salinity extends further along the reefs.
Rise in sea levels	Severe natural disasters
	Erosion along the shore
	Certain reefs are disappearing
Shift in oceanic currents	Impact the upwelling's nutrient supply
	Impact the connection between reefs (for example, the larval supplies from reefs)
Wind patterns and trends in atmospheric movements	Alter the current atmospheric conditions
Events of El Niño Southern Oscillation	Severe weather conditions that increase the likelihood of bleaching

Climate change factors that affect the coral reef ecosystems.
https://doi.org/10.3389/fmars.2025.1518701

2.2.5 Coastal Development

Building too much near the coast without proper planning harms the coral reefs. As the coastal population is expected to double by 2050, increased construction can lead to pollution and sedimentation that harm the coral reefs. According to some studies, even small development can lead to major damage. Activities like dredging and port operations have caused large-scale coral death, such as in the

Lakshadweep Islands. Without strict laws, the harm may outweigh the economic gain(Najeeb et al., 2025). Recent studies found that the Datan reef has many types of fish and even endangered sharks. But in some places, fish numbers are going down. If construction starts again, it could damage the reef and hurt local fishing. This shows how coastal development harms marine life(Heard et al., 2021). Coastal development is one of the major reasons for reefs destruction in the Mexican Caribbean. Within the region, tourism has increased greatly, with 10 million tourists visiting the coastal areas every year. This rise in tourism increases the establishment of lodging facilities, resorts, and additional infrastructure near the shoreline. This puts pressure on the nearby coral reefs. Local population growth is thrice as much as national norms, also creating pressure on coastal areas. Urban regions see more infrastructure causing pollution, waste, and damage to nearby coral reefs(Rioja-Nieto & Álvarez-Filip, 2019).

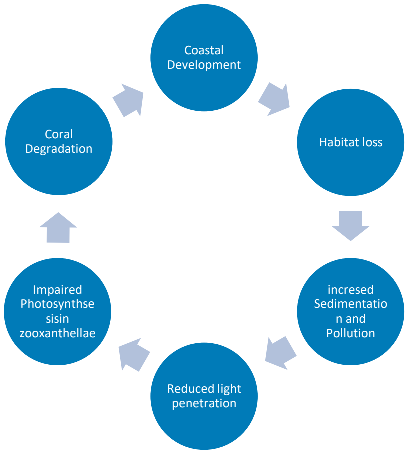


Figure 12: This cyclic flow diagram represents how coastal development contributes to coral reef degradation.

2.2.6 Plastic Pollution

Among the multiple stressors threatening the coral reefs, plastic pollution has emerged as a major concern alongside climate change and overfishing. Plastic pollution causes physical injuries to coral structures, increases disease transmission, and disturbs the marine food web(Pinheiro et al., 2023). Most of the plastics come from land and end up in the ocean, where they make up a lot of trash(Lartaud et al., 2020). Plastic debris harms corals not only by physical contact but also by blocking sunlight, releasing toxins, and reducing the oxygen(Law & Rochman, 2023; Vered & Shenkar, 2023). Corals touching large plastic particles pose a much greater threat to coral conditions(up to 89%)(Rahman et al., 2023; Vered & Shenkar, 2023). Harmful chemicals in plastics like phthalates can leak into the water, disturb coral-algae relationships, and even interfere with coral hormones. Some of these chemicals also harm coral larvae, stopping them from settling and growing properly(Isa, 2023; Mueller et al., 2022; Vered & Shenkar, 2023). Corals eat microplastics, which can harm their DNA and affect certain genes responsible for their protection against harmful substances like reactive oxygen species(ROS)(Zhang et al., 2023). A large-scale survey across 25 locations of the Pacific, Atlantic, and Indian oceans revealed that microplastic debris, human man-made objects larger than 5cm, was present in seventy-seven percent of the eighty-four surveyed reefs, consisting of the most distant and unspoiled habitats(Pinheiro et al., 2023). Microplastics, tiny plastic pieces, have been found in different places like the South China Sea, the Great Barrier Reef, and the Coral Triangle in Southeast Asia. Coral reefs in remote areas like the Maldives are often affected by microplastics because they aren't near a lot of human activity(Tan et al., 2020).

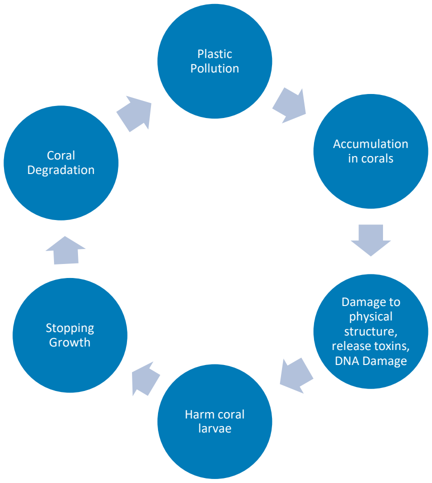


Figure 13: This cyclic flow diagram represents the detrimental effects of plastic pollution that contributes to reef degradation.

3. EFFECTS OF CORAL REEF DEGRADATION

3.1 Ecological Consequences

3.1.1 Reduced Ecosystem Services

Reefs are essential to hundreds of millions of human beings as hotspots for biodiversity, offering ecosystem services including food production, employment possibilities, carbon capture and storage, and offering defence from unfavourable weather scenarios(Eddy et al., 2021). Environmental changes like high temperature and more dissolved organic carbon (DOC) can increase the nitrogen fixation in corals, disturbing the nutrient balance and weakening the coral-algae symbiosis. This leads to coral bleaching and death, followed by algae overgrowth on dead corals, which further stresses nearby corals. As this cycle continues, it reduces important ecosystem services such as reef stability and nutrient cycling(Rädecker et al., 2015).

3.1.2 Loss of Marine Habitats:

Coral reefs sustain a vast number of different organisms and offer ecological benefits to hundreds of millions of consumers(Webb et al., 2021). Coral reefs are home to many sea animals, like fish and turtles. They give these animals food, shelter, and a place to lay eggs. If the reefs disappear, many of these animals might die because they'll have nowhere to live and breed(Ranjan et al., 2023). In Bahia, Costa Rica, coral reef degradation between 19995-1996 and 2014-2016 led to reduced omnivorous and meso-predators fish (e.g, sharks, groupers) due to live coral cover and overfishing, while herbivores and detritivores increased in abundance, likely due to higher macro-algal cover and predator decline(Arias-

Godínez et al., 2021). Coral bleaching caused by climate change leads to severe coral loss, reducing fish populations by over 60% in some cases. This loss affects the biodiversity, fish behavior, and reef ecosystem functions(Pratchett et al., 2018). The destructive grazing of parrotfish, especially on degraded reefs, contributes to erosion of reef structures, resulting in habitat loss and transformation from hard coral dominance to soft-bodied organisms. This change not only reduces the habitat complexity but also signals a loss in biodiversity and ecological functions within the reef ecosystem(Kuffner & Toth, 2016).

3.2 Socioeconomic Impacts

3.2.1 Coastal Erosion

Coral reefs are well known for helping to reduce the waves, which protect the buildings, coast, and people and other things(Burke & Spalding, 2022). About 850 million consumers depend on reefs for building materials, coastline defence, food supplies, and other resources. Coral reefs help to prevent erosion by absorbing wave energy. According to some studies, they can reduce up to 97% of wave energy. However, reefs are vulnerable to human and natural disturbances like pollution, overfishing, and Global warming, leading to their decline. This loss weakened their ability to protect coastlines, putting nearly 200 million people at a greater risk. Coral mortality increases wave energy reaching the shore, resulting in more severe erosion(Zhao et al., 2019). The large-scale death of coral reduces the complex structures and their ability to break up the ocean waves. As a result, ocean waves become stronger and bigger, which can cause more erosion along the beaches of tropical islands and beaches. Therefore, compared to many other marine ecosystems, coral reefs offer a larger coastline protection service(Harris et al., 2018). Although many studies have examined coral decline, few focus on its connection with coastal erosion, making it a challenging but important area for research(Zhao et al., 2019).

3.2.2 Fisheries Decline

Coral reefs play an important role in fisheries as they help millions of people who rely on them for small-scale fishing for their livelihoods. According to some studies, when corals are covered and reefs are damaged, fish population declines, biodiversity drops, and the food chain becomes shorter. Models show that coral loss can reduce fish productivity up to 60%(Rogers et al., 2018). Approximately six million fishers work in reef fisheries, providing livelihood and food to millions of people in reef countries(Hamilton et al., 2022). Many commercially important fish species, including snapper, grouper, parrotfish, and shrimp, depend on healthy corals for their habitat and survival. But when corals degrade due to ocean acidification and other stressors, fish habitat shrinks, prey availability declines, and fish lose their ability to detect predators. This led to a drop in fish population and declines in fish productivity. Economic models show that coral reef fisheries losses could reach $14-$20 billion by 2100 due to coral decline under high emission scenarios(Speers et al., 2016).

3.2.3 Economic consequences

Coral reefs are very important for the subsistence of thousands of people on every continent. Every year they provide nearly $30 billion in net benefits through three fishing, tourism and protecting shorelines(Chaijaroen, 2022). Coral reefs attract visitors from over hundred countries or regions around the world. A 2017 report shows that coral reef tourism brings in $39 billion each year. If coral reefs are destroyed or damaged, the number of tourists will drop, and local businesses that depend on tourism will suffer greatly(Ranjan et al., 2023). Reef degradation not just harms the environment other than consumers' income along well-being. According to estimates, coral reefs generate $3.3 trillion a year from the goods and services they supply, of which $36 billion comes from tourism. Before the COVID-19 pandemic, the scuba diving business in India, Malaysia, and Thailand alone was valued at almost $4.5 billion annually. Coral reefs also help to reduce flood damage by saving up to $4 billion every year. If coral reefs are lost or damaged, many countries will face big economic declines. This would likely lead to lower income, job losses, more poverty, and food insecurity for local people, along with a drop in tourism(Sing Wong et al., 2022).

3.2.4 Loss of Cultural and Spiritual Values

Indigenous peoples living along the coast have vital cultural ties to coral reef ecosystems, and they consume 15 times as much fish as non-Indigenous people(Eddy et al., 2021). Coral reef degradation results in the loss of cultural and spiritual values, particularly for indigenous communities. In Melanesian culture, coral reefs hold deep spiritual significance, with beliefs in place spirits inhabiting reef animals such as rays, sharks, and dolphins. These spiritual connections influence cultural practices, including sea burials that may lead to the closure of entire reef areas for ritual purposes(Najeeb et al., 2025).

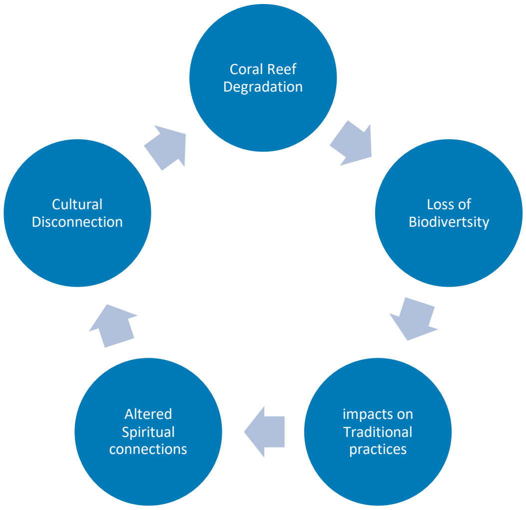


Figure 14: This flow diagram represents a relationship where coral reef degradation led to cultural disconnection.

4. RESTORATION STRATEGIES FOR CORAL REEF ECOSYSTEMS

Coral reefs over the globe have lost a lot of their corals in recent years, particularly last three to five years. Because of this, it’s clear that stronger initiatives are required locally as well as globally to protect reefs in the future. The most effective way is through coral restoration, which is now the most commonly used method to stop the coral loss and help to recover. As per the Society for Ecological Restoration (SER), ecological restoration is "the process of assisting the recovery of an ecosystem that has been degraded, damaged, or destroyed"(Hein et al., 2021). Reef rehabilitation can be done in two main ways including passive restoration and active restoration. Active restoration (also called direct restoration) involves actions like adding or reintroducing coral to help reef recovery. Like coral fragment planting, coral reproduction support, or improving the environment for reefs(Boström-Einarsson et al., 2020). Passive restoration (also called "natural regeneration" and "indirect restoration") depends on natural recovery after harmful factors are removed. Like predator removal (corn-of-thorn starfish), it does not involve planting or adding the new corals. The ability of coral reefs to survive depends on their management through restoration, regular management (such as marine-protected areas and catchment management to improve water quality), and international and national governmental commitments to lower the production of greenhouse gases (such as the 2015 Paris Agreement)(Van Oppen et al., 2017).

4.1 Active Restoration Techniques

4.1.1 Coral Gardening

It involves cultivating and transplanting coral fragments, which is a widely used restoration method. However, it must be tested for effectiveness in specific regions before being expanded on a large scale(Dehnert et al., 2023; Rinkevich, 2025). It includes growing coral in nurseries before moving them to natural reef areas(Mulà et al., 2025). In the first stage, coral fragments are collected and grown in protected areas. Once they reach to suitable size, they are transplanted into natural habitats. The growth of several reef organisms has been accomplished via mid-shelf nurseries. Land-based coral gardening is less studied and mostly used; its major benefit is that environmental factors like light and temperature can be controlled to support the coral growth and survival. These nurseries support the growth of helpful algae and recreate a partnership between coral and other organisms, improving the coral health(Schmidt-Roach et al., 2020). In coral nurseries, daily care is important to support the coral health and growth. This involves regularly cleaning the reefs to remove algae, unwanted organisms, and predators. Using remote sensing to find the best location for planting corals is an effective way to improve restoration success over large areas(Darkhal et al., 2025).

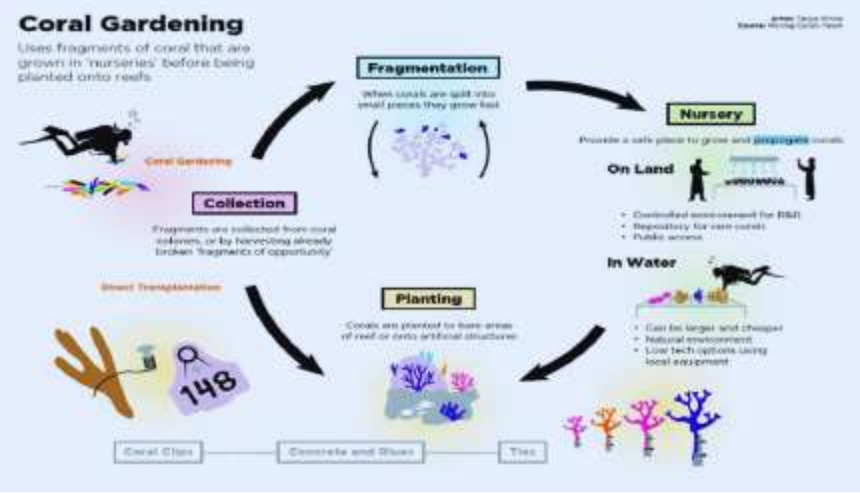


Figure 15: The coral gardening methods involve collecting coral pieces, breaking them into fragments, growing them in nurseries either on land or in water, and then planting them back on the reef. https://doi.org/10.1371/journal.pone.0273325

4.1.2 Micro-Fragmentation

Micro fragmentation is mainly an ex-situ process that helps the coral tissues grow much faster and in natural conditions. It involves placing small coral pieces (about1cm), all from the same coral colony, 2-3cm apart on an artificial surface. These small fragments grow quickly from their cutting edges, forming a thin tissue layer that joins together when they meet. This can double or even quadruple their size in just a few months. When placed on dead coral fragments can quickly recover and restore the colony, helping to revive large endangered coral species(Knapp et al., 2022). In a study from Thailand, coral micro-fragments (1-3cm) showed 90% survival, with Favites abdita having the highest (97.29%). The fastest growth was seen in 1cm fragments, highlighting micro-fragments as an effective restoration technique(Yeemin et al., 2024). Cladocora caespitosa, the only reef-building coral in the Mediterranean, is endangered due to mass coral mortality and slow recovery. Micro-fragmentation was first applied to this species using an in situ nursery, aiming to develop restoration protocols. This method helps to produce many corals from a few donors and may support future restoration by identifying colonies with multiple resistance(Cardinale & Danovaro, 2024). Micro fragmentation makes it possible to utilize large corals, but more study is required to fully understand its advantages and disadvantages, as well as how it stacks up against other approaches. The majority of corals utilized for transplantation come from native colonies or coral fragments, which may not be effective and viable overtime. It might be difficult to compare the costs of micro-fragmentation with other strategies because of uneven reporting, disparate goals, or diverse coral transplant suppliers(Mostrales et al., 2022).

4.1.3 Coral Propagation or Land-Based Restoration

Larvae-assisted rehabilitation, additionally known as sexual propagation, coral larvae restoration, larval survival enhancement, and juvenile coral "reseeding," is the process of artificially enhancing larval recruitment and settlement by introducing a high number of larvae of corals to damaged reef areas (McLeod et al., 2022). However, because it requires a lot of work and experience, it is less tractable than asexual propagation(Caruso et al., 2021). Coral reefs restoration through larval rearing and sexually produced juveniles plays a key role in preserving coral ecosystem services. In a study, Acropora cervicornis fragments were grown in shallow and deep nurseries. Corals in deep water nurseries show higher growth rates and require less maintenance and reduced biofouling(Arias-González et al., 2022). Raising larvae on reefs either in situ or ex-situ maximizes both production and restoration. Using devices like net sheets, tents, or underwater robotic vehicles, they are released onto reefs once they are capable. Larval-based restoration makes use of corals' ability to produce millions of larvae, lower mortality, and lessen loss due to the distribution of coral larvae(McLeod et al., 2022). The primary benefits of using larval propagation strategies are that they enhance genetic variety within recovered coral populations, facilitating greater adaptability and improved durability aftermath of changing climates(Bayraktarov et al., 2020).

4.1.4 Micro-algal Removal

In many coastal reefs, fleshy macro-algae can increase in quantity due to abrupt environmental changes, long-term nutritional enrichment, and decreased grazing, compete with and overgrow corals. Maintaining the geographical predominance in structure building reefs has been the goal of active macro-algae removal, a management strategy that has been suggested and tested to lessen algae-coral interaction, thus creating room for reef reproduction (Ceccarelli et al., 2018). Biological, chemical, and manual methods are some of the techniques used in the control of marine macro-algae. Thermal treatments (such as heating or cold shock), chemical treatments (such as bleach or salt), osmotic shock (such as freshwater and salinity treatments), and mechanical or manual removal by hand, assisted by vacuum or dredge pumps, are a few examples. These methods are site and species-specific and rely on the management goal(Neilson et al., 2018). Sea urchins and several reef fish families (such as surgeonfish (Acanthuridae) and parrotfishes (Scaridae) were recognized as the primary regulators of coral reef macro-algae by the 1970s(Butler IV et al., 2024). Despite its detrimental impact related to coral species, although there is little amount of research on the removal of macro-algae as a reef restoration technique. There were eight research cases acknowledged, exemplifying the possible accomplishments and shortcomings of macro-algae eradication targeting both invasive and naturally existing macro-algae in warm temperate and tropical coastal areas. Findings suggest that some macro-algal species require retaining debris and herbivory for effective removal(Ceccarelli et al., 2018).

4.1.5 Substrate Stabilization

Substrate stabilization is a restoration technique that lessens the impacts of turbulence by removing the rubbish around the coral and stabilizing it with a substrate like cement(Won & Liva). Stabilization activities are frequently conducted in reaction to reef strikes by ships or oceanic storms, which generate fields of scattered debris, restricting effective coral germination(McLeod et al., 2022). In Indonesia, reef star structures were used to stabilize rubble slopes and support coral attachment. Bushy Acropora fragments had much higher survival than expansive forms. when this method is combined with midwater nurseries, it helps scale up restoration effectively (Watt-Pringle et al., 2024). Stabilization of the substrate may result in changes to the coral community, effects on the biota of the environment, and the formation of carbonate sediments. Careful risk assessment is necessary because ill-preparedness can introduce infections that cause coral to shift, become damaged, or disappear. Reef intervention policies, particularly in Australia, have not prioritized substrate stability, even though it has been recognized as a potentially beneficial approach(Ceccarelli et al., 2020).

4.1.6 Artificial Reefs

One widely used method for reef recovery involves placing man-made substrates commonly called "artificial reefs"(Tanaya et al., 2025). These structures which may be submerged in mid-water, or floating on the surface, have been proposed as a potential tool for restoring marine resources, increasing the number of fish species that can be caught, preserving ecological environment, and offering the shelter and breeding ground both for fishes and invertebrates (Nguyen et al., 2022), along with other rehabilitation approaches including direct transplantation, coral gardening, substrate manipulation, and larval propagation. Artificial reefs that serve as coral habitat include structures built on natural coral reefs to serve as a substrate for coral colonization, as well as existing structures such as breakwaters, seawalls, shipwrecks, and energy platforms. Some studies comparing artificial structures with surrounding natural coral communities have revealed that the coral cover on mature artificial structures can be as high as, or even higher than, that of natural reefs (Tanaya et al., 2025).

Coral transplantation and the construction of artificial structures have been popular restoration strategies in Indonesia for over 40 years. In July 1979, the Indonesian Navy erected the first artificial reefs in history. The purpose was to restore the coral reef at the Seribu Islands, north of Jakarta, by submerging tires, rickshaws, and old automobiles. The goal was to create a habitat that would draw fish, topographic complexity, and stable substrate for the settlement of coral and other invertebrates(Razak et al., 2022). In the Arabian Gulf, the formation of ARs has many advantages for marine ecosystems, such as improving commercially important fish species, encouraging travel and recreational diving, halting habitat loss, and reducing the impact on coral reef habitats. Projects to improve lobster habitat reefs in Iran and Oman, as well as the Marawah Marine Biosphere Reserve in Abu Dhabi, are two examples(Al Kindi et al., 2025). Despite the large number and diversity of AR initiatives and objectives, their overall efficacy has rarely been shown. The assessment of AR performance is challenging because of the multivariable factors and covariation among descriptors that must be considered. By improving performance evaluation through the use of suitable monitoring approaches that align with the structure's original purpose, the current study offers recommendations to increase the AR success rate(Vivier et al., 2021).

4.1.7 Coral Transplantation:

Coral transplantation is the most effective way for improving coral diversity in the affected reef areas, which has been the subject of much recent research (Lange et al., 2024; Winanto et al., 2025; Zhao et al., 2025). Expanding the rehabilitation of damaged coral, the fundamental idea is the replacement of outdated corals with those that are fresh, which has been accomplished by transplanting juvenile corals, broken coral parts, or mature coral clusters throughout the restoration sites. The transplanted corals' growth and survival rates are frequently employed as evaluation criteria. Coral transplantation was first used along Costa Rica’s Pacific Coast. In this project, researchers collected 110 healthy coral units across adjacent habitats and placed them on the damaged reef. After three years, 79 to 83% corals were still alive. Montipora digitata was transplanted to a damaged reef, and in 15 months, the volume of the coral rose 3.84 times. Similar coral transplantation projects in China also show good results. Currently, one of the most significant technologies for restoring coral reefs worldwide is coral transplantation(Yang et al., 2024). Success in coral relocation depends upon coral variety, along with environmental circumstances. Improving transplantation methods and restoration results requires an understanding of the physiological and metabolic changes that occur in corals after transplantation(Zhao et al., 2024). Recently, a survey was carried out on Wazhizhou Island, China, which found that the transplantation of corals greatly led to an increase in coral cover (Lange et al., 2024; Zheng et al., 2021).

Table 2: Comparison of Coral Reef Restoration Strategies

Sr.no	Restoration Strategy	Description	Benefits	Challenges
1	**Coral Gardening**	Transplanting and growing coral fragments in nurseries (Dehnert et al., 2023).	Improve coral health, enhance the relationship between coral and algae, and provide physical conditions (Schmidt-Roach et al., 2020).	Daily care includes regular cleaning of algae (Darkhal et al., 2025).
2	**Micro Fragmentation**	An ex-situ technique, cutting corals into small pieces on artificial reefs(Knapp et al., 2022).	Grow faster in natural conditions, double their size in just a few months(Knapp et al., 2022).	Limited studies, Unsustainable in the long run, cost comparison uncertainty(Mostrales et al., 2022)
3	**Coral Propagation**	Growing coral larvae on artificial areas, then moving on to reefs once they are capable(McLeod et al., 2022).	Preserve ecosystem services(Arias-González et al., 2022), maximize production and restoration(McLeod et al., 2022)., enhance genetic diversity(Bayraktarov et al., 2020).	Requires a lot of work and experience(Caruso et al., 2021).
4	**Micro-algal Removal**	Micro-algae removed chemically, physically and biologically (Neilson et al., 2018).	Enhance coral reproduction (Ceccarelli et al., 2018).	Depending on management goals, site, and species-specific (Neilson et al., 2018, limited research (Ceccarelli et al., 2018).
5	**Substrate Stabilization**	Involve removing the rubbish around coral and stabilizing with substrate(cement)(Won & Liva)	When combined with midwater nurseries exacerbates restoration (Watt-Pringle et al., 2024)	Risk of infections due to ill-prepared methods, changes in the coral community and environmental biota, lack of policy priority despite

				potential benefits (Ceccarelli et al., 2020)
6	**Artificial Reefs**	Manmade structures underwater or floating on the surface to mimic natural reefs and restore marine organisms(Nguyen et al., 2022)	Preserve natural ecosystems, increase reproduction of fish and other marine organisms(Nguyen et al., 2022)	Poor monitoring methods, success rarely proven, and too many influencing factors(Vivier et al., 2021).
7	**Coral Transplantation**	Replacing the dead corals with new ones (Yang et al., 2024)	Most effective way to increase the coral cover(Yang et al., 2024)	Effectiveness depends on coral types and environmental conditions(Zhao et al., 2024)

4.2 Passive Restoration Techniques

The ability of reefs to thrive depends on their management through restoration, protection (like designated marine sanctuaries and catchment management focused on better water integrity), along with international and local policy commitments aimed at to lowering atmospheric emissions (such as climate treaty adapted in 2015 in Paris)(Van Oppen et al., 2017).

4.2.1 Marine Protected Areas

The concept Marine Protected Areas (MPA) represents regions within coastal and submerged zones, including surrounding waters and their associated plant life, wildlife, historical elements, and societal components which are officially specified by authorities along with practical methods for preserving either the whole or some of the comprised ecosystem(Dharmadasa et al., 2021). MPAs can offer a variety of ecological and social advantages by reducing direct habitat degradation, human extractive activities, and a variety of local stresses(Benedetti-Cecchi et al., 2024). The most effective approach for minimizing habitat destruction and detrimental effects across coral habitats involves setting up ocean conservation areas through ecosystem-based strategies(Da Silveira et al., 2021). Marine protected areas safeguard approximately 18.7% of the 527,072 km2 of coral reefs worldwide, but an extremely minimal percentage (<0.01%) lies within low-risk zones, and fully protected underwater areas prohibit poaching(Najeeb et al., 2025). It is the primary technique for rehabilitating fish populations, which reduces the effect of fishing and hence increases quantity and variety (Cox et al., 2017). MPA now covers 4.8% of the world's marine area(Brander et al., 2020). The major goal of marine protected areas is biological conservation. Even so, there has been increasing evidence that MPAs could help people both directly and indirectly, including through enhancing human wellness and reducing vulnerability to climate change. As a result, MPAs frequently provide a wide range of uses such as boosting the tourism industry, preserving historically significant areas, and protecting the fishing industry(Arkema et al., 2024). MPAs can improve ecosystem health by allowing the recovery of biomass, improving egg and larvae production, contributing to biomass exports through spillover (for adults), as well as increasing ecological resilience within their borders, and protecting habitats and biodiversity(Hernández-Andreu et al., 2024).

4.2.2 Controlling Crown-of-Thorn Starfish (COTS)

The eradication of reef consuming starfish from the coral habitats is essential to reduce the occurrence of this coral eating organisms, thereby enhancing the reef regeneration along with development. So in response of this reefs become able to withstand multiple drivers, including poor water conditions, coral whitening process, windstorms, and threats from various other destructive species(Kopecky et al., 2025; Lockie et al., 2024). There has been a notable presence of coral eating fishes throughout the Indian and Pacific Oceans, ranging from the Red Sea to Southeast Asia and Polynesia. Since 1990, many more outbreaks have been reported, even in areas outside the world's largest reef systems. Therefore, effective governance plans must be resilient to situations in various geographical locations. Recently, there has been research on COTS management. Cheap and accessible chemicals like vinegar and acidic compounds demonstrate efficiency in reducing coral eating starfish, alongside COTS Bot, a self-governing submersible craft for eliminating coral eating starfish, formulated for operation in the world’s major reef habitats(Milne et al., 2023). The traditional process of hand-culling starfish is time-consuming and challenging to remove from diverse coral environments(Lockie et al., 2024). Instead of eliminating starfish from corals, current culling initiatives in the Indo-Pacific region destroy them in situ by injecting them with deadly chemicals. Concerns about high biomass have led to the continued use of hand collections in places with little equipment, or the Maldives. For example, the most successful way to destroy corn-of-thorn starfish was using sodium bisulfate, a dry acid, and big-bore needles until 2015(Pratchett et al., 2019; Theobald et al., 2024).

5. DISCUSSION

Coral reef degradation is a growing global issue with ecological, social, and economic consequences. The results of a literature review and case studies of coral reefs highlight that they are significantly damaged by an integration of environmental and artificial pressures, with climate change, overfishing, and coastal development being considered the most important drivers of rapid coral loss. These drivers are interconnected and accelerate the coral damage, which reduces the ecosystem’s resilience. The major theme that emerges from this review is the important role of climate change, especially the increase in ocean temperature, resulting in extensive coral whitening phenomena. The severity along frequency of coral pigmentation in the Caribbean, Indo-Pacific, and Indian Ocean are rising due to continuous thermal events, including those that were documented in 1997, 2010, 2014, 2017, and most recently in 2023-2024. Tropical coral reefs already inhabit areas near the extreme temperature limits, which makes this worse. Even modest changes in sea surface temperature can disturb the symbioses relationship between corals and zooxanthellae, elevating infectious susceptibility, along with reduced reproductive ability. These shifts imply future climate events will probably make the climate-induced reef destruction more severe. Apart from the bleaching events, several research highlights that reef illnesses, particularly Yellow band disease (YBD) and Black Band diseases, have proven to be causing significant loss of coral tissues and death. These diseases are mainly caused by environmental stressors, including warming, pollution, and sedimentation, as well as several microbial communities, including the Cyanobacteria and sulfate-reducing bacteria. For example, Yellow Band (YBD) spread rapidly after its first identification in Florida’s Keys, and Black Band disease (BBD) was documented across the Indo-Pacific region, the Caribbean, and the coastline of the Red Sea. Another important discovery is sedimentation as a pervasive threat. Land-based sedimentation smothers the corals, stops them from growing, reduces light availability, hinders larval settlement, and increases the energy demand for corals to clean themselves. Even though the thin layer of corals stops them from attaching to the substrate. Additionally, sedimentation disturbs the relationship between corals and zooxanthellae, which stops photosynthesis, particularly in areas of unplanned coastal development and with significant runoff. Another significant natural cause of reef degradation is predation by corallivores such as crown-of-thorn starfish. Despite being frequently ignored, these predators indirectly change the behavior of herbivores and directly contribute to the breakdown of coral’s soft body layers, ultimately resulting in algae overgrowth and a decrease in reef reproduction. Because herbivory and predation are essential to the reef’s ecosystem composition along functioning, they exhibit extreme vulnerability to disturbance in the tropical balance. Among the anthropogenic threats, water pollution, especially nutrient pollution, chemical pollution, and plastic pollution, were recognized as the main contributors to reef degradation. Excessive nitrogen and phosphorus runoff from agriculture and wastewater lead to eutrophication, bioerosion, and microalgal blooms. This not only enhances the competition between algae and coral for the sake of light and space but also weakens the reef tissues. Furthermore, nutrient pollution directly affects the coral physiology, prolongs bleaching and coral classification, and indirectly leads to an increase in the growth of competitive organisms. Plastic pollution, particularly micro-plastic and macro-plastic also a growing concern for coral reefs. These contaminants physically damage the coral tissues, block sunlight, and may introduce chemicals that disturb coral algae symbioses and destroy reefs’ DNA. The identification of plastic on remote reefs such as the Maldives, South China Sea, and Coral Triangle highlights that it’s a global issue.

Furthermore, overfishing and destructive fishing methods are equally profound. Such as poisoning and explosive fishing practices can disturb the food web reduce the small herbivory fish essential to control the algae's uncontrolled growth. Removal of species such as parrotfish and groupers leads to algae-dominated corals. This issue is most noticeable in regions such as coastal Pakistan and, Caribbean, where the intensity of fishing practices reduces the potential supply of fish stocks along with reef resilience. Among ecological consequences of reef ecosystem deterioration, the loss of biodiversity, habitat collapse, and impaired ecosystem functioning have emerged as the most critical issues. For example, practices as overgrazing by Parrotfish in the Caribbean and fishing practices in Costa Rica result in reef erosion. This not only reduces the ecosystem services (CO2 cycling, climate regulation, and sediment trapping) while also contributes to for reaching environmental outcomes, which alter reef community equilibrium. In addition to ecological consequences, socio-economic impacts are equally important. As globally hundreds of individuals rely on reefs to acquire coastal protection, food security and income. Coral reefs bring millions of visitors and generate significant revenue, but loss of biodiversity and reefs reduces their aesthetic beauty and recreational value, which leads to loss of jobs, national income, and tourism. In Island nations such as Palau, Kiribati, and Micronesia, a reduction in fish stocks increases the risk of malnutrition. In Indonesia, reef erosion similarly leads to long-term impacts on children's education and nutrition, even though the economic situation has improved in the country. Similarly, loss in coral reefs makes the coastal communities more vulnerable to waves and storms in areas such as the Maldives, South Africa, and the Reef Island Nations by reducing the ability of coral structures to absorb the waves. To recover from these challenges faced by coral reefs, several restoration efforts have been developed and are used globally to restore the corals. Direct ecological interventions include reef gardening, coral reproduction techniques, micro-fragmentation, artificial reef deployment, and substratum stabilization. Coral gardening and coral transplantation have shown their success in some regions, but due to their labor-intensive nature and high maintenance cost, these techniques have limited use. Although micro-fragmentation, due to its high development potential, is a beneficial technique but still its future efficiency and cost maintenance are uncertain. Larval propagation is a technically challenging technique, but it helps a lot in improving the genetic diversity and enhancing ecosystem functioning. Both artificial reefs and substratum stabilization provide habitat and structural support to corals, but they still require careful site planning and continuous monitoring. Passive restoration strategies, such as controlling predators (removal of crown-of-thorn starfish) and establishment of marine sanctuaries, provide additional benefits to preserve corals. Although marine protected areas play a very important role in preserving biodiversity and reducing human intervention but they still face challenges such as inadequate finances, weak enforcement mechanisms, along poor governmental flexibility. Despite these developments, several challenges and gaps still exist. Restoration strategies are frequently site-specific, small-scale, and poorly incorporated into the larger conservation plans. Throughout this review, it has also been found that there is a limited use of advanced monitoring technologies such as GIS and remote sensing to monitor the reef conditions regularly and to find the best location for coral restoration. Furthermore, many restoration projects lack stakeholder engagement, standardized success criteria, and regular monitoring. In conclusion, this review emphasizes the need for urgent, coordinated, scientifically grounded, and community-driven strategies to stop the destruction of reefs. Efficient initiatives have to incorporate social and ecological concepts, combine local action with global climate obligations, and emphasize a sustainable future. Degradation of these ecosystems can eventually be stopped through public awareness, sustained innovation, and a policy framework.

6. CONCLUSION

Coral reefs are biologically important ecosystems on the planet as they offer various kinds of environmental benefits, including biodiversity support, safeguarding the shoreline, along with supporting leisure activities. But unfortunately, these habitats are under immense threat by a combination of artificial and natural factors. This review considers the multiple causes of corals reefs degradation, such as coral bleaching, climate change, sedimentation, predation, overfishing, and coastal development, with especially focus on pollution, including plastic pollution, nutrient pollution, and chemical pollution, particularly UV filters, polycyclic aromatic hydrocarbons, and oil spills. These challenges damage the coral structure, prolong the bleaching events, damage coral larvae and DNA, bioaccumulation, affect coral reproduction and disturb the relationship between reefs and algae. This review analyzes the gaps in understanding the long-term challenges associated with chemical pollutants on reefs specially UV filters and PAHs bioaccumulation in corals. Furthermore, the absence of systematic monitoring, effective implementation of marine pollution regulations, lack of stakeholder's involvement, and limited use of advanced technology continue to obstruct the reef restoration efforts. Therefore, more research is required into the eco-toxicological effects of pollutants, to understand the regional factors behind coral degradation, and better management measures should be developed to address the pollution from industrial discharge, sunscreen, nutrients, and plastic contamination. This review also examines the potential for reef restoration by active and passive restoration strategies. Additionally, some methods, such as micro-fragmentation, coral gardening, and artificial reefs, despite their potential in localized settings, still face economic and ecological barriers that hinder the scalability of these approaches.

The successful analysis of reef ecosystems, along with the advancement in marine protected areas, provides vital havens for reef organisms, but their success depends on robust administration, enforcement, and community engagement. Furthermore, comprehensive and integrative management plans such as adaptability to changing climates, sustainable fisheries, along with pollution prevention are needed to mitigate the risk associated with the coral reef ecosystems. A strong commitment to minimizing human interventions in the marine ecosystem, the integration of traditional wisdom with scientific methods, and concerted worldwide actions are required to ensure the continual existence of these prestigious ecosystems. We can still stop the continual degradation of coral reefs and restore their services by enhancing the cooperation between the government, researchers, the public, and the commercial sectors, ensuring they continue to be available to future generations.

7. RECOMMENDATIONS

The following recommendations are suggested to enhance the reef's resilience and preservation based on the evaluation and synthesis of challenges and restoration strategies discussed in this review.

Improve Climate Change Mitigation and Adaptation

- Enhance global collaboration and implement international treaties. For instance, the international climate treaty in 2015 aimed to lower the release of greenhouse gases worldwide.
- To help the coral reefs grow and adapt to restore the healthy reefs, use species that can better withstand climate change.
- To respond to the bleaching events, develop and implement the early warning systems.

Address Regional Anthropogenic Challenges

- Enforcement of pollution control measures to control the release of nutrient runoff, untreated wastewater, and plastic pollution.
- Regulate the unsustainable coastal development near the vulnerable reef regions through environmental impact assessment and a zoning system.
- Ban uncontrolled or destructive fishing practices through public awareness and fishery management.

Advances in Monitoring and Data Collection Systems

- Use advanced tools like GIS, remote sensing, and drones to regularly monitor coral conditions such as coral disease outbreaks, microalgal growth, coral cover, sedimentation, chemical pollution, and plastic debris.
- To assess the effectiveness of coral restoration, establish standardized and long-term matrices.
- Make the data available online on different platforms to boost the cooperation among researchers, governments, and non-governmental organizations.

Improve and expand the restoration strategies

- Enhance the use of flexible, cost-effective restoration strategies such as coral reefs, larval settlement, and micro-fragmentation.
- Use reef species that are well adapted to the local area and have high genetic diversity when designing the restoration methods.

Enhance Marine Protected Areas (MPAs) Management

- In biologically rich areas improves the connection and coverage of marine protected areas.
- Allocate enough funds for public training and awareness, flexible governance, and regular enforcement of laws.
- Marine protected areas should be integrated into national plans and policies to enhance climate resilience and to protect biodiversity

Incorporate the planning and policy with the Reef Restoration

- All the policies, such as catastrophe mitigation, coastal protection, and national development plans, must integrate the coral reefs.
- By promoting the partnership between the public and private sectors, green taxes and trust funds enhance the environmentally friendly funding system.
- Incorporate the international standards, like the Sustainable Development Goals, into national policies.

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