Current Trends and Future Path Analysis of Coral Reef Restoration: A Systematic Review and Analysis

[1] Birendra Kumar Sahu, Kalinga University, Raipur, India.

[2] Dr. Moniza Nurez Khan, Kalinga University, Raipur, India.

Abstract: The Coral Reefs (CR) have suffered significant damage due to both local and international stresses, prompting the use of several proactive restoration approaches to rehabilitate degraded corals. Summarizing recovery activities comprehensively is challenging due to inconsistent reporting. This research examines the legislative structure for CR rehabilitation, which is part of the goal of two government agencies (Marine Industries and Fishery and Environmental and Forests) and includes national laws and federal, presidential, and ministry directives. The research comprehensively analyzes CR Restoration (CRR) initiatives, cataloging 530 entries nationwide from 2000 to 2023. Most (72%) of these records originate from the last decade, with a significant portion (40%) documented in online news items instead of scholarly studies or publications. This analysis documented 120k synthetic CR units erected, alongside 53k coral transplanting units (comprising both coral nursery and straight out-planting onto corals); 965k pieces of hard coral had been established. Concrete (45%) and steel buildings (23%) are the preferred restoration elements. Projects are coordinated by various governmental, non-governmental, business, and community-based organizations. This review indicates that the rules have facilitated a variety of practitioners in executing CRR; however, projects frequently lack coordination with broader networks of restoring professionals or researchers, and merely 15% of the discovered projects incorporated a post-installation tracking structure. Integrating specific goals and sustained monitoring programs during project development while emphasizing information exchange and collaboration with the global scientific society can significantly enhance restoration results. This will enable the nation to realize its significant capacity as an international leader in restoring devastated CRs.

Keywords: Coral Reef; Restoration; Review; Aquaculture.

(Submitted: June 10, 2024; Revised: July 16, 2024; Accepted: August 14, 2024; Published: September 30, 2024)

I. Introduction

Coral Reef (CR) ecosystems have experienced an unparalleled decline in habitat-forming coral species during the last few years (Antony et al., 2022). CR faces a range of persistent and sudden human-induced disturbances, such as deteriorating water quality, harmful fishing procedures, over-exploitation of CR organisms, and epidemics of coral threats and diseases; in the last twenty years, climate change has become the foremost danger to CR. This was underscored during the worldwide marine heat motion, resulting in the most widespread coral bleaching disaster and affecting distant and unspoiled CRs. Although dynamic structures such as CRs possess an inherent ability for natural restoration, the escalating rate and extent of mass coral bleaching and severe storms reduce the time and capability for recovery between catastrophes. Chronic or recurrent disturbance episodes frequently undermine larvae availability, coral larvae placement and recruiting, and post-settlement survival (Dietzel et al., 2021). The absence of spontaneous recruitment and inadequate time for recuperation after disturbance occurrences render spontaneous recovery improbable or unfeasible in numerous sites. Addressing habitat loss on various fronts is expected to be the primary concern for environmentalists and administrators in the Anthropocene, resulting in heightened interest and enthusiasm for strategies that enhance the durability of CRs or support the safeguarding and reconstruction of CR functionality and structure.

Marine preservation has prioritized passive habitat preservation over restoration efforts (Sheaves et al., 2021). The latest study indicates that optimum conservation results must encompass safeguarding habitat and rehabilitation. Rehabilitation is a prevalent practice in natural ecosystems and a recognized management strategy for coastal ecosystems like marshes and oyster CRs. Yet, it remains contentious for CR in scholarly discourse and marine management. Opponents of Coral Reef Restoration (CRR) contend that (1) it diverts attention from addressing global warming and other ocean environmental challenges and (2) it is futile, except it can rebuild CRs at the ecological level (Vandenberg, 2025).

Advocates of CRR argue that (1) measures can safeguard coral ecological diversity shortly while addressing significant threats like global warming and poor water quantity, (2) are essential for the regrowth of threatened and uncommon coral organisms in the Caribbean, in which their natural population upkeep has deteriorated, and (3) enhance conservation efforts and foster dedication to CR protection by involving neighborhoods in restoration initiatives. Global temperatures are anticipated to rise for several additional years, even under a zero-carbon output situation (Huang & Zhai, 2021). If successful, localized restoration efforts effectively mitigate the temporal disparity between extensive warming initiatives and the significant lag effects anticipated from indirect strategies for management. Considering that disrupted CRs are prone to a decline in genetic variety due to many disruption episodes during this timeframe, the ongoing restoration of coral types and genomic variety provides a temporal advantage for recovery after mitigating or eliminating stressors (Good & Bahr, 2021).

Notwithstanding prevalent apprehensions, particularly within the field of science, active rehabilitation of coral has been progressively employed as a method to rehabilitate CRs on a small scale, particularly by the tourism sector. Due to inadequate interaction and collaboration among CRR professionals, CR executives, and researchers, a significant fraction of CRR efforts have been conducted thus far without scientific involvement or thorough observation (Vardi et al., 2021). Many CRR initiatives and methodologies remain undocumented in the field of science. A lack of records, cooperation, and experience sharing diminishes the capacity to profit from previous triumphs and mistakes, heightening the risk of redundantly testing analogous approaches and assumptions (Smith, 2024).

II. Methods

The research compiled instances and explanations of restoration of coral techniques from four different places: 1) original research (i.e., released peer-reviewed academic articles), 2) informal sources (e.g., scientific papers and related to technology summaries authored by field experts), 3) online explanations (e.g., websites with videos and blogs detailing initiatives), and 4) a web-based questionnaire directed at restoration professionals. The research considered solely those studies in coral reconstruction involving more than one scleractinian coral life cycle phase. This ignores indirect CRR initiatives, including disturbance reduction (e.g., predator elimination, controlling illnesses, etc.) and passive restoration measures (e.g., legislation against destructive fishing or enhancement of water clarity). It omits numerous synthetic CRs, particularly those intended for fishery improvement (i.e., fish aggregating equipment), and if reefs were not incorporated in the methodology.

The research diligently ensured the avoidance of case study duplication among the four distinct reports, so guaranteeing that every story in the report and databases corresponds to an individual initiative. Over 40 kinds of data were documented from every instance study and input into a central repository. The information encompassed (1) a data origin, (2) particulars of the case research (e.g., position, duration, geographical size, goals), (3) specific methodological specifics, (4) coral characteristics (e.g., genus, organisms, appearance), (5) surveillance specifics, and (6) results and findings.

Although the extensive search allowed us to circumvent bias from the restricted published material, the research recognizes that utilizing sources lacking thorough peer review creates an alternative bias. Numerous government papers experience an unofficial peer review, yet survey findings and internet narratives offer a subjective representation of restoration successes. To minimize subjective evaluation of instances, the research chose not to decode findings or survey responses but to record only those openly articulated in each paper.

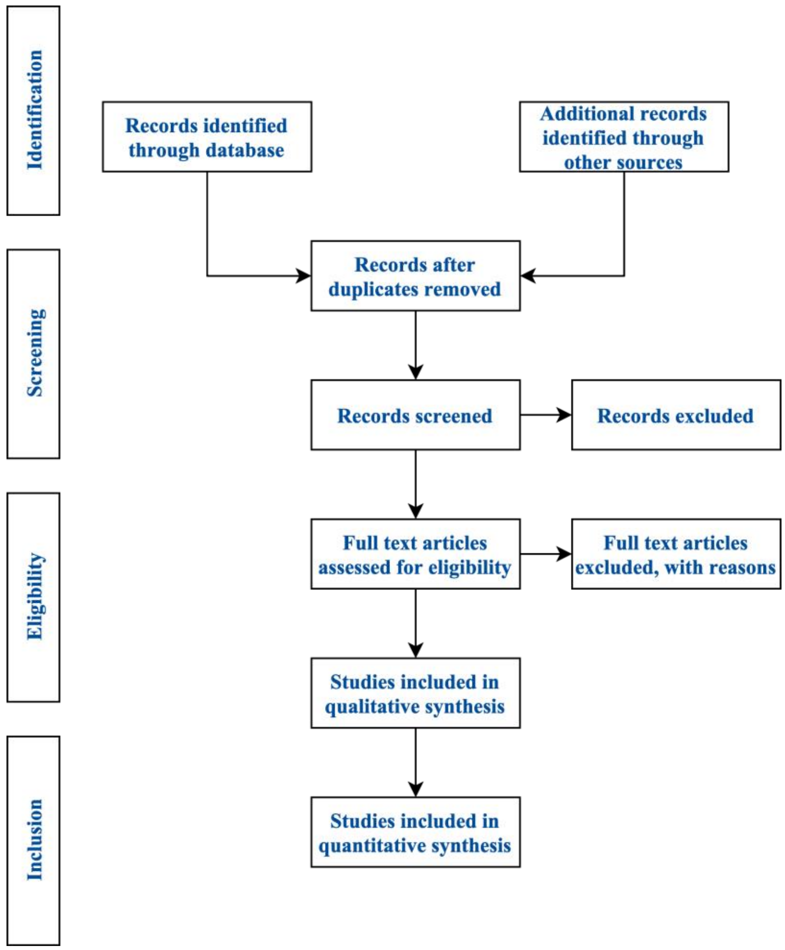


Figure 1: Workflow of the Research

Across every repository, the search criteria yielded 4,088 articles after eliminating redundancies. All article bibliographies and descriptions were uploaded into the web-based software Evidence, where their headlines and summaries were reviewed, extracting 800 papers about CR patterns in CR environments (Figure 1). A comprehensive review was performed on 525 papers. Information was retrieved from 135 that satisfied any or all of the additional inclusion standards: 1) specified a date, exact setting, and installation depth, 2) detailed the precise size and quantity of CRs in the research, and 3) articulated a goal for CR installation.

The papers were classified into two groups: 1) the ones that directly assessed the achievement of the goals of CRs, and 2) those utilized for research studies or as actual submergences (e.g., unintentional ship foundations, disposal of vehicles, or construction substances as garbage). All 135 research from both subcategories were examined for 1) study time, 2) explicit delineation of CR sizes, 3) selected taxonomic collections, and 4) sociocultural and environment-responsive factors employed to evaluate the attainment of the conservation aims of the CR. Altitude and length were obtained for each CR and classified into marine domains. All 135 papers were utilized to analyze the spatial-temporal trends of augmented reality installations as documented in scientific research. To analyze worldwide CR frequency with time and ensure a precise match of criteria utilized in the research, the research incorporated all structures identified as CRs with an essential dimension ≥ 0.3 m.

To guarantee the ecological significance of findings about preservation effectiveness, studies documenting advancements in achieving conservation goals for implemented CRs met all previously mentioned secondary inclusion requirements and two additional requirements. (1) The observed CRs were required to be ≥ 1 m to facilitate comparing them to natural reef developments and knolls; and (2) in investigations addressing numerous CRs, single CR structures were classified as distinct if they stood a minimum of 3 m from the following neighboring CR. This gap represents the study definition of a CR and the methodologies employed to guarantee the connection of motile creatures and larvae among CRs. Research indicates that CR situated more than 2 meters apart can establish separate benthic populations. A total of 50 papers met all requirements for inclusion and were utilized in this evaluation of preservation goals.

III. Results and Discussions

'Environment restoration' constituted the predominant purpose for 75% of initiatives, while 'research' was the least preferred objective at 5% (Figure 2). The purpose of 'creating a tourist destination' varied greatly among participant types, cited by 80% of tourism initiatives, 40% of commercial initiatives, and 43% of initiatives, while only 20% of academic and none of the governmental initiatives stated it. A discernible trend (although non-significant) was observed regarding the goal of 'study,' which was identified as the primary aim in 35% of governmental initiatives, compared to 8% of educational initiatives and none other.

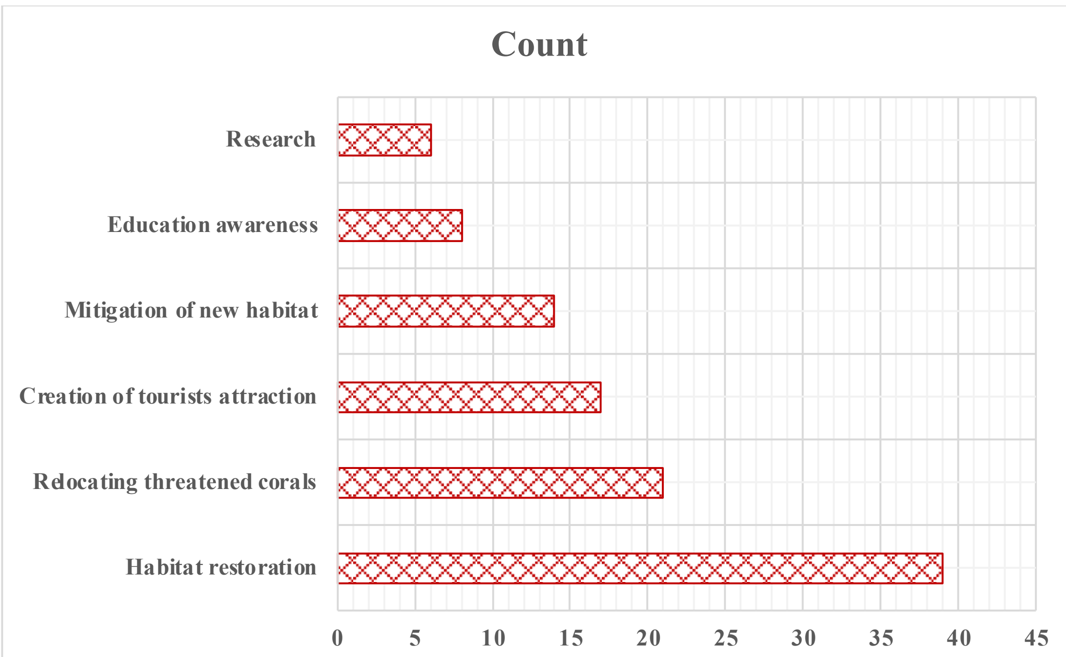
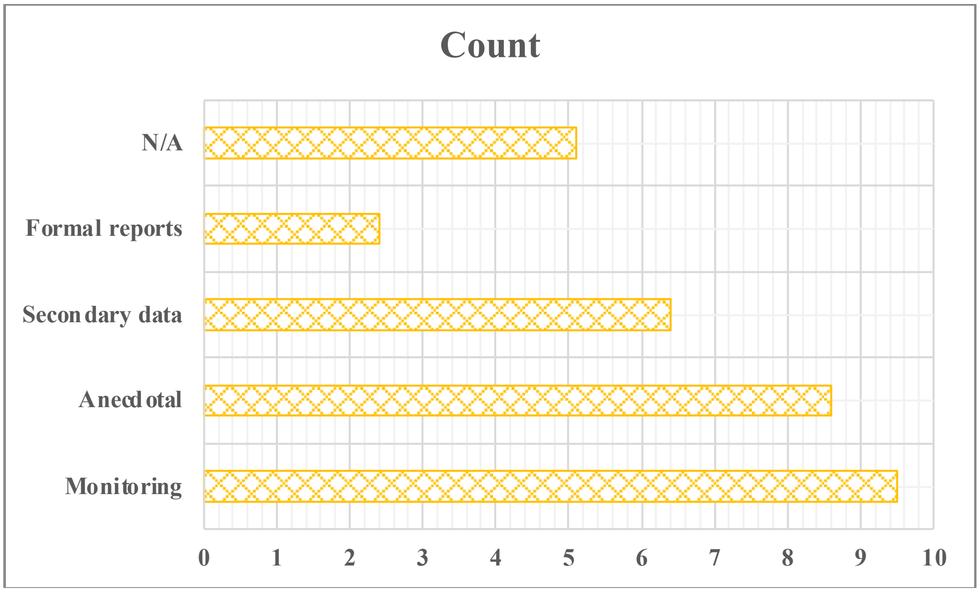


Figure 2: CRR Analysis

Evaluation of the factors contributing to reef degradation was absent in 34% of the programs. It was incorporated more often in massive endeavors (82%) than in small-scale initiatives. The evaluation of the source of deterioration was consistent across various types of companies. The predominant evaluation method employed was tracking, but circumstantial or additional data was utilized to determine the reason for the deterioration in approximately fifty percent of cases (Figure 3(a)). The selection of transplantation foundation showed slight variation among projects that conducted prior assessments of the root cause of deterioration and those that did not. The surroundings at the chosen sites were evaluated in the majority of projects (75%). The assessment of surroundings did not vary among different respondent categories. Surveillance constituted the predominant method for evaluation (Figure 3(b)). However, none of the participants referenced the review of getting corals in the recipient location.



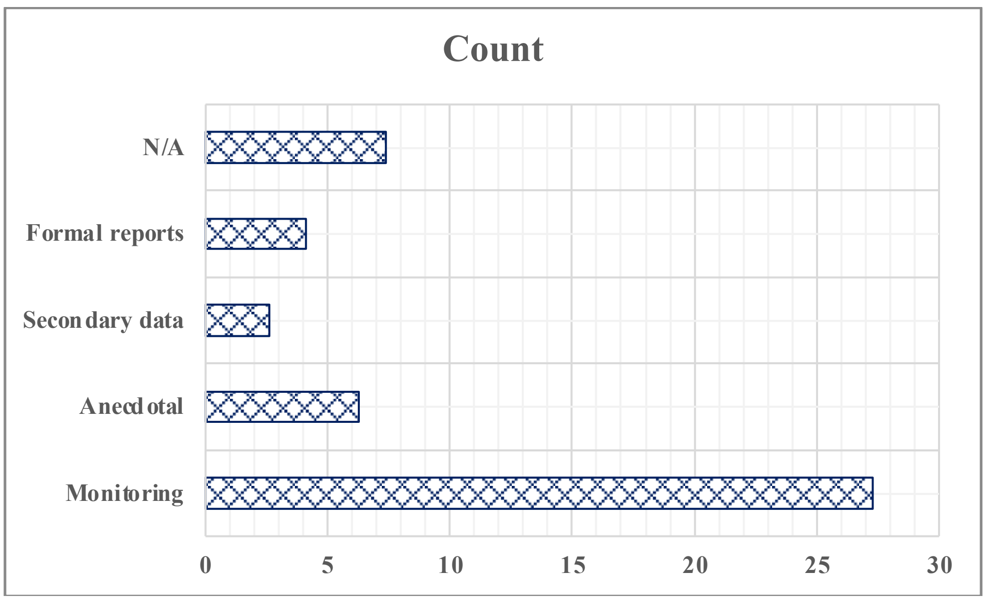


Figure 3: CRR Analysis (a). n=35, and (b). n=40

The upcoming phase of CRR is expected to bifurcate into two distinct scales: 1) small-scale site management initiatives and 2) large-scale, reef-wide initiatives. The former encompasses local initiatives with socio-economic aims, particularly those initiated and directed by the tourism sector and citizen researchers. Although widespread adoption by principal customers can attain scalability, these initiatives are expected to utilize existing technology to enhance coral coverage at specific high-value locations. The latter group is essential on an ecosystem level and necessitates significant spatial expansion of programs to address future difficulties facing CRs. CRR is an evolving discipline, and large-scale initiatives require significantly different methodologies than those outlined in this analysis. Although numerous previous efforts have been relatively minor, isolated, and unconnected, treatments at the reef size must be interdisciplinary. They will probably require a certain level of robotics and extensive coordination and connectivity to address the issue's magnitude. Among the strategies outlined in this research, only a few have shown the capacity for scalability beyond one hectare of regenerated CR. Preferably feasible ways include utilizing sexually produced propagules to restore coral communities and ecosystems.

IV. Conclusion

CRs are considered the most biodiverse globally, although they endure severe local human-induced stress. When integrated with hazard mitigation measures (such as enhanced water quality, the prohibition of blast boating, and warming avoidance), CRR is expected to significantly contribute to overseeing these highly diversified and endangered environments. The policy structure promotes a notably wide range of engagement in restoration operations, characterized by minimal centralized regulation relative to other nations. This has resulted in varied participation in numerous reconstruction efforts nationwide, coordinated by a multi-disciplinary group of professionals employing an extensive array of methods and supplies. Substantial obstacles persist in realizing its full potential as a global leader in coral regeneration. By enhancing effectiveness in achieving target-driven results, ensuring uniformity in environmental monitoring, and fostering deliberate international information trade, the restoration initiatives serve as a transformational asset for the area and a model for worldwide emulation.

References

[1] Antony, S., Unnikrishnan, K., Aswin, S., Dev, V. V., Arun, V., & Krishnan, K. A. (2022). Heavy metals in coral reef sediments of Kavaratti Island, India: An integrated quality assessment using GIS and pollution indicators. *Marine Pollution Bulletin*, *180*, 113721. https://doi.org/10.1016/j.marpolbul.2022.113721

[2] Dietzel, A., Connolly, S. R., Hughes, T. P., & Bode, M. (2021). The spatial footprint and patchiness of large-scale disturbances on coral reefs. *Global Change Biology*, *27*(19), 4825-4838. https://doi.org/10.1111/gcb.15805

[3] Sheaves, M., Waltham, N. J., Benham, C., Bradley, M., Mattone, C., Diedrich, A., ... & Newlands, M. (2021). Restoration of marine ecosystems: Understanding possible futures for optimal outcomes. *Science of the Total Environment*, *796*, 148845. https://doi.org/10.1016/j.scitotenv.2021.148845

[4] Vandenberg, J. (2025). Colonial legacies and restoration futures: Examining the risks of dispossession from coral reef restoration in the Indonesian aquapelago. In *Aquapelagos* (pp. 65-81). Routledge India.

[5] Huang, M. T., & Zhai, P. M. (2021). Achieving Paris Agreement temperature goals requires carbon neutrality by middle century with far-reaching transitions in the whole society. *Advances in Climate Change Research*, *12*(2), 281-286. https://doi.org/10.1016/j.accre.2021.03.004

[6] Good, A. M., & Bahr, K. D. (2021). The coral conservation crisis: interacting local and global stressors reduce reef resiliency and create challenges for conservation solutions. *SN Applied Sciences*, *3*(3), 312. https://doi.org/10.1007/s42452-021-04319-8

[7] Vardi, T., Hoot, W. C., Levy, J., Shaver, E., Winters, R. S., Banaszak, A. T., ... & Montoya-Maya, P. H. (2021). Six priorities to advance the science and practice of coral reef restoration worldwide. *Restoration Ecology*, *29*(8). https://doi.org/10.1111/rec.13498

[8] Smith, E. A. (2024). Risk and uncertainty in the ‘original affluent society’: Evolutionary ecology of resource-sharing and land tenure. In *Hunters and Gatherers (Vol I)* (pp. 222-251). Routledge. https://doi.org/10.4324/9781003571971-18