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Review

Shaping Improvised Directions for More Efficient Coral Reefs Rehabilitation Attempts

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Abstract

Coral reefs directly support more than 500 million people globally, usually in poor countries. More than 40 years ago, scientists initiated the discussion on coral reefs habitat destruction. Scientific research has covered various impacts on coral reefs including human pressures and climate change. Evidently ocean warming and acidification emerged as the main threats in the past decades.

Currently, tropical coral reefs and their community are expected to face a tremendous increasing risk as global-warming raises. Such emerged combined stressors (human and climatic drivers) lead to slow recovery of corals with expectations of shift in species biodiversity and composition. Hence, coral reefs rehabilitation interventions have strikingly increased over the past decade.

These interventions are carried through both, advanced science-based projects (such as coral microbiome engineering, ecological processes recruitment as well as community-based projects. The later occurs because of poor communication among the main three parties in charge (practitioners, MPAs managers with policymakers, and scientists) which in turn has led to unsatisfactory results in these rehabilitation attempts. The analysis of these results here revealed that most deficiencies are related to projects design.

Engagement of these respective parties in a scientific framework through “adopting a cautionary coral reefs rehabilitation strategy” will manage the general steps of adaptive decision making, and elude knowledge gaps that exist in certain drivers (Bioecological and Socio-economic) and common deficiencies in projects design. This will help quantifying rehabilitation measures and shaping these improvised directions for more efficient rehabilitation attempts.

Avoiding this strategy is highly likely to result in another direct human impact on coral reefs in the Anthropocene.

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In this review, we summarize the story of past gains with evidence to new shaping of rehabilitative intervention directions for more resolutely efficient attempts. This is represented via simple pathway diagrams, and updated map which indicate the relationship between attempts objective and outcomes and charts showing drivers for success of coral rehabilitation. We attempt to answer the following question: How necessary is it to have a unified coral reefs rehabilitation cautionary strategy with an action plan?

Keywords: coral restoration, coral rehabilitation, human impact on coral reefs, climate impact on coral reefs, restoration strategy

Highlights

- Based on multiple and combined stressors (human and climatic drivers) on tropical coral reefs and their community, rehabilitation interventions strikingly increased in the last decade.
- These interventions were carried out on two pathways:
  - Advanced science-based projects,
  - Community-based projects scope.
- Poor communication among the main three parties (practitioners, MPAs managers with policymakers, and scientists) leads to unsatisfactory results in the past attempts.
- Engaging these parties in a scientific framework through "adopting a cautionary coral reefs rehabilitation strategy, with an action plan" will organize the general steps of adaptive decision making, and elude:
  - Knowledge gaps that exist in certain drivers,
  - Common deficiencies in projects design.
  - Quantify rehabilitation measures,
  - Shaping existing improvised directions for efficient attempts.
- Avoiding this strategy is likely to result in another direct human impact on coral reefs in the Anthropocene.

Introduction

Coral reefs support 500 million people globally since reported by [1] until [2] while they remain to be amongst the most endangered ecosystems on earth [3, 4]. In the seventies of the last century, scientists initiated the discussion on corals habitat destruction [5]. Publications covered various impacts including human pressures [6, 7]. Climate change, evidently ocean warming [8] and rising acidity [9] emerged as the main threat in the past decades [10]. Currently, tropical corals are at risk; expected to turn into huge risks as global-warming increases [11]. Such multiple stressors (human and climatic) came with emerged "combined stressors" lead to slow recovery of corals [12] with expectations of changing species composition and biodiversity [13].

It is evident that conserving corals through rehabilitation and restoration attempts is a serious challenge to humankind, that aims to "using artificial substrates to improve the natural settlement conditions and fisheries [14, 15] transplanting coral to degraded areas [16, 17]; respectively" or combining both by transplanting corals to artificial substrate [18]. Popular retrieval techniques are categorized according to their purpose and level of sophistication (Fig. 1 and Table 1) so they serve as tools to: "move population away from threatened habitats [19], providing a specific habitat [20], restoration [21], conservation [22], protection [23], mitigation [24], aquaculture [25], tourism industry [26] or provide new coral sites for recreation or fishes [27]".

Trials to cope impact stressors and destructive forces worldwide started from the collection of coral souvenirs and trading in the past [28] till the multiple cascading climatic drivers [29]. Interestingly, artificial reefs were debatable regarding their ability to award benthic communities [30]; now scientists emphasize that project design must be aligned with its objectives [31].

The disciplines of biological conservation and ecological restoration interventions increased in the last decade (Fig. 2 and Fig. 3) reaching two pathways: (1) advanced science-based projects (such as microbiome engineering [32], ecological processes recruitment [33]), (2) community-based projects scope. The last, occurs as a result of poor communication among practitioners, policymakers and scientists [31]. A lot of restoration work was done without:

- Implementing scientific-based management actions before restoration attempts [34],
- Monitoring programs for receptor [31] and donor sites, when done, have they matched the real objective?
- Documenting outputs, which hindered sharing knowledge and experiences. (Fig. 5).
- Therefore, project design must be scientifically based first as building the case starts with decision makers until it becomes automated.

In the context of Goal, no 14 "life below water" of The United Nations Sustainable Development (SDGs-UN), we argue that rebuilding corals reefs faces human and climate impacts that a powerful scientific adoption of "Coral Rehabilitation Cautionary Strategy, with an action plan" is highly needed. Mechanisms of Cautionary Strategy to be implemented are to be issued

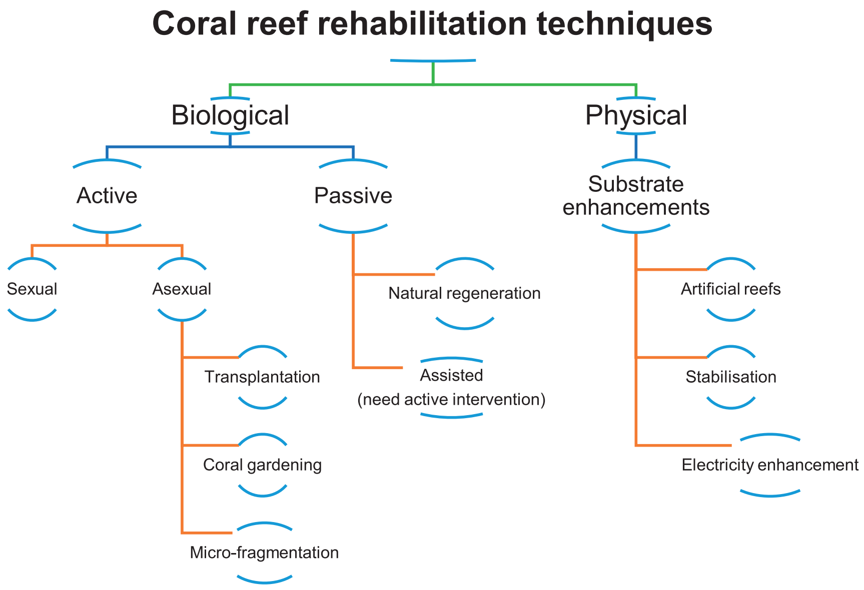

Fig. 1. Coral reefs rehabilitation techniques used diagram, cases around the world.

by (SDGs-UN) to develop transformative actions, offering outlines of functional integration amongst respective parties with careful evaluations.

Material and Methods

Extensive internet survey on coral restoration case studies using "coral + rehabilitation and/or restoration" to sort out the two pathways done around the world: (1) advanced science-based projects (peer-reviewed publications), (2) NGOs, community-based or governmental projects scope reports or websites (grey literature) (supplementary materials sheet number. "S1"). Analysis of this survey tabulated results were considered the relationship between cases objectives and outcomes according to the eight inferred objectives by [31, 35] "S2". Many other extensive surveys to identifying different common coral restoration techniques used, using most of the common keywords "S3" trying to sort-out the main differences between them (Fig. 1 and Table 1), challenges with a historical glance (Fig. 2) "S4" then produce an updated map for coral reefs rehabilitation attempts around the world (Fig. 3) with spatial distribution "Supported Doc2" (extracted from the data set of [36], with updates) indicating relationship between objectives and outcomes extracted from the "S4" sheet and integrated chart that indicates the statistical analysis results illustrating the number of rehabilitation cases in each of the eight inferred objectives "S4".

Some important countries with long experience on coral restoration never been counted before in the peer-reviewed literature, because the language barrier. So, we conducted same internet survey in languages other than English to identify them, then used the applicable data gained with our statistics.

Our main survey criteria were: identifying the active coral restoration techniques only, without the passive ones. We reviewed here all restoration techniques (published, reports, or web activities) as we could to avoid bias.

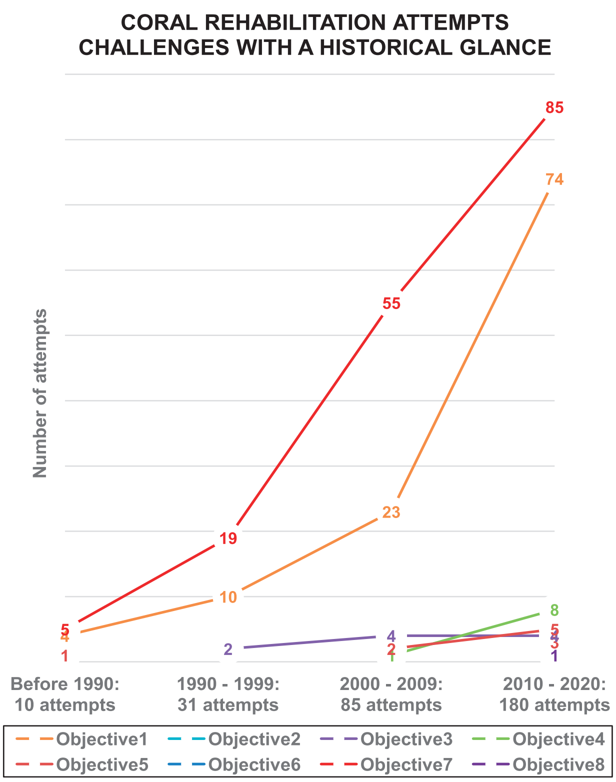

Fig. 2. Coral rehabilitation attempts around the world challenges according to [31] with a historical glance, updated to include other cases from the Red Sea [14, 16, 115] and South china Sea ex. [80, 116]. All cases were classified depending on different rehabilitation objectives "Eight inferred objectives according to [31, 35]".

Table 1. Main differences between main coral reefs rehabilitation techniques.

Technique	Also known as	Main Objective	Advantages/Disadvantages	Spatial Scales
1. Sexual	Larval propagation, enhancement, sexual propagation, or larval reseeding.	Enhancing larval settlement at sites (in-situ) with reduced or failure recruitment. (or ex-situ) to create a new landscape.	Increasing genetic diversity, enabling higher rate of adaptability and boost resilience [72]. Rising rehabilitation scale on declined reefs [92]. It may take 3 years [100], while coral recovery from natural stressors (ex. bleaching) can take 10 years or more [101].	Most scalable methods (beyond a hectare) [31].
2. Asexual	Transplantation, asexual propagation, direct transplantation, gardening, coral aquaculture or farming, fragmentation, micro-fragmentation, out-planting.	Methods deal with the impacted sites or for commercial use, involve transferring a coral fragment from a donor to a recipient reef at several stages. Whether coral fragments are to be fixed directly or indirectly to main substratum or to a new artificial, this makes difference in nomenclature of the methodology.	Mostly deal with impacted sites or for commercial use [31]. Avoiding the demographic post settlement larval mortality and slow growth in most coral species [100], even a rapid growth in some methods as micro-fragmentation [102]. Popular in community based conservation [103]. Partiality of using clonal processes in gardening methods correlatively limits different genotypes propagation, therefore the resilience. To maintain the genetic diversity, coral larvae incubation [104], fertilization [105] will encourage the resilience of the site from stressors. Literature lacks any information concerning „donor site monitoring".	4-10.000m^2 with an average of 300m^2 [31, 36]. Micro-fragmentation methods are the best with some massive species on a large scale [102].
3. Substratum enhancements	Artificial-reefs [106, 107], Substratum stabilization [108], Substratum enhancement with electricity [109].	Physical rehabilitation; aims to create a suitable hard substrate for the coral ecosystem; using artificial reefs, bottom stabilization, or limestone formation to simulate the reef structure complexity features.	Choice of artificial reefs material influences the success of coral settlement [106], complexity [110] accordingly, forming coral ecosystem perfect habitat (coral settlement, fishes, plankton, crustacea etc.). it's always integrate with coral transplantation [111]. Even existing shoreline structures (breakwaters, etc.) considered a kind of artificial reef method [106]. Stabilization rationale is to stabilize disrupted substrate (from storms or ship groundings), to enhance recruits survival rate on loose bottom [108]. There are no clear conclusions on the electricity enhancement method [31].	Ranged from few m^2-688.000 m^2 [21] in the artificial reefs.
4. Passive rehabilitation	Indirect rehabilitation, natural or assisted regeneration, site management option, disturbance mitigation.	Biological rehabilitation; conventional passive measures of protecting, managing, and conserving coral habitats (marine conservation option or tool).	Most, least cost pathway in areas with high sexual breed potential, while it also require ongoing adaptive management [112]. Management tools addressing reef declining broader reasons [44].	Scalable methods (about 500.000 m^2 of restored reef) [113, 114].

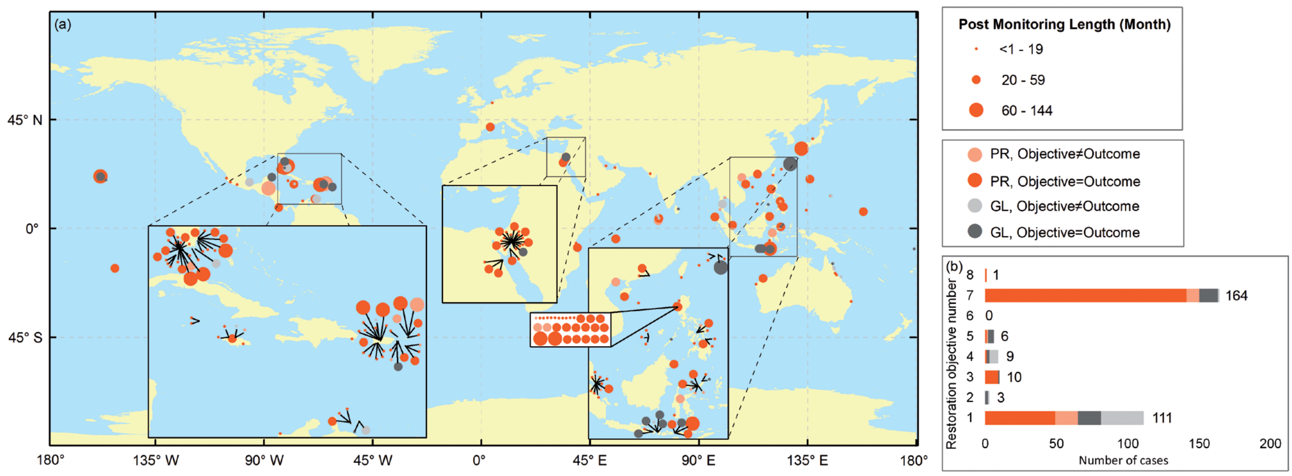

Fig. 3. a) Map of coral reefs rehabilitation attempts around the world [36], modified to include other cases from the Red Sea [14, 16, 82] and South china Sea [80, 116]. Circle size indicates spatial distribution according to the post monitoring period/month. Circle color indicates harmony between objectives and outcomes. While PR = rehabilitation cases deduced from the Peer Reviewed Literature & GL= Grey Literature. b) The integrated chart is indicating number of rehabilitation cases in each of the eight inferred objectives, according to [31, 35] (sheets number "S2" and "S4"), with same circle color indicator above.

For analysis of the collected data from the internet, all data obtained were tabulated "S1-S4", graphed, and analyzed using Excel program, GIS, MATLAB, and Prism software.

Results and Discussion

Coral Reefs Rehabilitation and Restoration Perspectives

To date, coral reefs rehabilitation was exercised as a management option. Historically protecting marine habitats were centralized on passive protection, while in recent decades active restoration received much attention [31] in all main reef zones [37]. Most attempts of coral reefs rehabilitation intended to: (1) enhancing settlement conditions by installing artificial substrates [15] especially in loose substrates [38], (2) transplanting coral to degraded areas [17], or (3) combining both [18].

The awareness of artificial reef prime practices were fisheries improvement [39], which has evolved to support many activities. A limited evidence on how active restoration influence resistant to climate drivers [40], or how plantation period manipulates biological feature like coral transplanted propagation; till coral epigenetics got to use as an adaptive-management tool for rehabilitation [41], however we believe that restoring coral reefs ecosystem will fill a variety beyond the roles mentioned in the last section.

Previously, rehabilitation and restoration phrases led to uncertainty that may be used in a wrong context [42]. For better grasp:

On a linguistic level "https://www.merriam-webster.com", we may infer, that rehabilitation does involve restoration, but not the other way round. On a scientific level, rehabilitation [43, 44] and restoration states [11, 31, 35, 45] mean different things to different authors (restoration definitions; may come partially agreed on or contradicted) which created a debate over the terms in different disciplines "https://www2.cifor.org/rehab/_ref/glossary/Restoration.htm".

We can safely say now that: coral restoration efforts are mainly depending on the transplantation techniques (asexually), and coral rehabilitation efforts is mainly depending on substrate enhancements techniques (sexually) with or without larval induction.

In this article, we argue that rehabilitation is more efficient in the context of coral reefs saving attempts. Additionally, losing coral habitat on multiple levels is the original subject matter for both scientists and environmental policymakers which necessitates rising the interventions boosting reefs resilience and conservation of its structure and function, within an inclusive framework.

Challenges of Coral Reefs Rehabilitation: Techniques Used Around the World

Regardless of corals rehabilitation attempts, the top priority challenge is the suitability of policies, legalized frameworks and adequate cooperation between local management and contiguous countries to develop cooperative management of the reefs. [34] described this challenge in south China Sea as a case study, and [46] suggested that local level of management actions could enhance coral resilience to climate change threats, with a large scale only [47] and reducing greenhouse-gas emissions (climate impact management); they added. Nevertheless, the integration of coral under the long-term, multidisciplinary adaptive management frameworks has an advantage as a strategy

Fig. 4. Transplantation attempts observed on extreme turbid environment, South China Sea: (a, b) hexagon artificial reef, (c, d) plastic net extended on steel tables. (e, f) Artificial reefs attempts, Red Sea, Egypt; sexually technique. Figures (e and f) © Wentao Niu.

for addressing the scientific doubts in biological, physical, and socio-economic aspects that has a role in coral ecosystems [35].

In this review, we summarize the most common cases of active coral rehabilitation techniques (Fig. 1 and Table 1), regardless the suitability of institutional or legal frameworks for the countries.

Coral reefs rehabilitation attempts occurred in 57 countries [31] (with updates), most of them lack rigorous their efficiency assess [35]. Fig. 2 could sort-out coral rehabilitation attempts, objective, and challenges with a historical glance.

Generally, the publication on coral reef systems has doubled in the past decade; (ex. coral ecosystem function and biodiversity [48] and other topics. Fig. 2 shows effort spent on rehabilitation paths in the past decade as well. However, this statement does not meet reality where about 54% from the total cases around

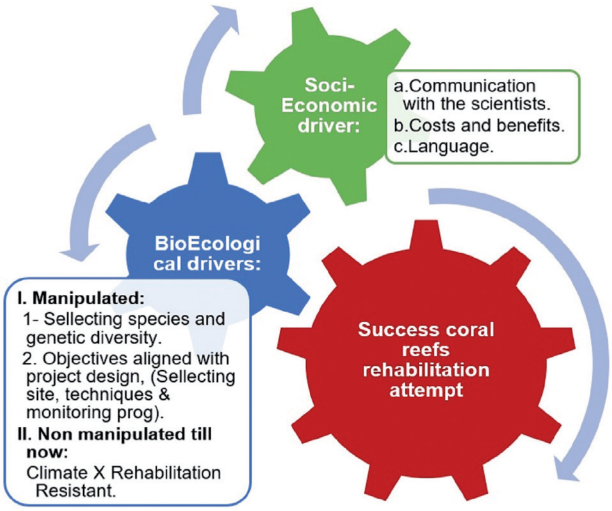

Fig. 5. Rehabilitation pathway diagram, success to coral rehabilitation.

the world adhered only to scientific research purpose (objective no. 7) not actual restored areas, more than 15% of them lack scientific base cases (grey literatures or its objective ≠ outcome cases) Fig. 3. (See the supplementary materials sheet number. "S1" Attempts done. And sheet number "S2" Objectives of restoration; indicator numbers, according to [35, 36].

Table 1 indicates the main differences between main coral reefs rehabilitation techniques methods (summarized in Fig. 1). Thus, as a resilience-based management component whether active biological or physical rehabilitation, with a hint to the passive contrast.

(Supplementary material sheet number "S3"; "Coral reef rehabilitation techniques used, countries attempting with authors (consequently to the published date) collected from cases around the world").

Knowledge Gaps Among Respective Parties

This section is devoted to discussing knowledge gaps in certain drivers. The purpose is to clarify how lack of communication amongst the involved parties (rehabilitation practitioners, MPAs coral reef managers with policymakers, and scientists) leads to unsatisfactory results in the past rehabilitation attempts. Additionally, we show that engaging these parties in a scientific framework by the means of adopting a cautionary coral rehabilitation strategy will elude the common deficiencies in project design and quantify measures of rehabilitating coral reefs and gives directions to improve coral reefs rehabilitation attempts.

Bioecological Drivers to Success of Coral Rehabilitation

Genetic diversity, objectives with aligned project design, and avoiding common deficiencies (as certain biological and ecological drivers) are crucial to successful rehabilitation interventions.

Genetic Diversity in the Asexual Reproduction

Coral holobionts are known to harbour wide functionally different microbiome including zooxanthellae taxa [49], fungi, bacteria, viruses and archaea [50]. In the case of environmental disturbance, such as elevation in temperature and water acidification, coral-symbiont relationship starts to breakdown causing bleaching and decline of coral reefs [51]. Bleaching severity relies on the type of contributory microbiome, dominance of some coral symbiotic zooxanthellae taxa fluctuate following to bleaching events [52].

It is evident that different coral colonies react differently to the environmental disturbance and this implies the heritage of beneficial traits either by corals or their associated microbiome which favors their resilience, this coral performance can be used for selective breeding in coral rehabilitation under environmental stresses [53]. However, this theory is not always successful as the genes of corals or symbiont proved to be resistant to some environmental stresses sometimes maladapt to the transplantation environment during restoration techniques [53]. Thus, site should be selected carefully to match the needs of the transplanted colonies. In addition, careful selection of genotype is a strategic to the success of corals rehabilitation using transplantation [54]. NOAA recovery plan suggests a 0.5 as a target for the genetic diversity ratio in some (*Acropora* sp.) [55]. While, [56] marks at least 35 randomly selected colonies to hold fully 90% from original inhabitance genetic diversity; when local genetic variation knowledge is absence.

Accordingly, genetic diversity is a key issue when targeting resilience to stressors in rehabilitation interventions [55, 57]. Particularly, coral-microbiome plays many significant roles in the key-biological processes for coral flourishing [32, 57].

Harmony between Rehabilitation Objectives and the Project Design

Rehabilitation objectives with aligned project design and its monitoring programs is fundamental for the success of such attempts. Scientifically, choosing the best site ecological parameters, coral species and rehabilitation technique with suitable monitoring programs are highly effective in all rehabilitation project designs. Unless chosen carefully, it will be considered another path of human destruction to the coral in the Anthropocene (Fig. 3).

– Ecological parameters:

Shifting in coral reefs community composition occurs from the climatic and non-climatic frequent stressors; that increases with increasing stressors complexity. Till over community thresholds whereas community structure changes [58]. Hence, non-building reefs come to replace coral reefs as spotted widely so far [59]. For example, the impact of rising temperature and acidity of ocean on the physiology and behavior of species associated with coral reefs is driving down populations [60] and cause bioerosion [61]. Also, extreme events generated by sea level rise (SLR) [62], or rising coastal nutrient or sediment runoff [63]. The above combined stressors lead to phase shift [64], and may use to compare resilience of (coral reefs to its associated biota) for further understanding [59].

Choosing the best ecological factors of rehabilitation site, coral species and method of rehabilitation is crucial to successful active rehabilitation attempts. Coral recruitment as well as attraction of reef fishes will occur if succession takes place after coral transplantation or propagulation based on landscape rehabilitation concept [65]. Combining the ecological processes like predation, herbivory and nutrient cycle is important in supporting coral rehabilitation [33]. [66] suggests a metapopulation-connectivity examination when design for coral rehabilitation, while [67] suggested that it be discussed more precisely. [65] added, monitoring physical parameters, and simulating larval dispersion and spawning are substantial for coral rehabilitation success.

– Monitoring program:

A global registration of total restored area of coral is absent, [68]. In this regard, [31] recently reviewed more than 360 world case studies of active coral rehabilitation attempts, most of which had no long term monitoring program for the restored site "60% <1.5 year and mostly with only 100 m^2 spatial scale"; even, no coherence between stated objectives and actual monitoring measurements prevents accurate scientific evaluation and knowledge management of the outcomes; they added that monitoring of coral cover, complexity and proportion of breeding corals may provide a suitable indicator of restored habitat value. [35] reviewed 83 attempts, "60% tested the biological response of coral nubbins to transplantation, with no clear stated objectives". Quantifying growth rate of coral for aquaculture purpose was expansively studied (previously reviewed by [69]).

Additionally, a required long term monitoring between natural and artificial reefs (in same environment) to assess the success of attempt function [70], four years for the community assemblages to be stabilized [71], five years to be more similar for natural community-composition [70]. In general, this suggests that rehabilitation tools that have not expanded for implementation on large scale are one of the technical limitations of coral reefs adaptation [72].

[65] questioned the nubbins lifespan from diverse donors that varied according to colony size and polyp age affect fertility. [73] answered with new rehabilitation optimization key factors to maintain the greatest propagative output (mode of polyp budding, shape, timing and duration of fragmentation and species). However, assessing coral colonies volumetric productivity "amount of product produced per m^3 of rehabilitation design timely" to monitor the early stages of corals development (transplanted or spawned) is effective to assess rates and kinetics of growth and consequently to predict survival chances. This technique is missed in literature except for [74] who in-vitro related growth rates and kinetics to productivity. This comes in accordance with [25] that seems applicable in the in-situ. Early stages of colonizing organisms' development were monitored in [70]. Monitoring the early stages of colonizing and successive species will guide us to the right direction of rehabilitation projects designs [75, 76].

Furthermore, we found no monitoring programs for the donor sites assessed in literature, and post-settlement or transplanted colonies mortality for the restored sites were reported high [77].

– Avoiding common deficiencies in project design:

An example of transplanted corals attempts with no proper project design is *(Acropora* sp*.)* around Weizhou Island (Beibu Gulf, South China Sea). They were dominant species until 1950 then sharply declined because of explosives used by fishers causing degradation, turbidity, and eutrophication leading to community composition shift [78] in addition to global worm [79]. Poor maintenance was provided after transplanting huge amount of (*A. pruinose*) attached to stainless-steel sticks on hexagon artificial reef made from normal cement. Fig. 4b) shows no attachment to the sticks or the hexagon reef science 2018, neither new coral spats were observed in this extreme turbid environment despite of its long stay. Another example is gardening (*A. pruinose* branches) attached to plastic net on steel tables. No new coral spats were observed for 2-4 years. The growing branches crowded affecting one another after years of growth with no maintenance or re-transplant them (Fig. 4c,d). A similar situation is occurring around Sanya, [80].

In these cases, project design, sites, and materials were not properly selected. Also, no maintenance nor monitoring of transplanted colonies occurred. The *(A. pruinose*) has likely disappeared in the vicinity of the Weizhou Islands [78] and Sanya [81], except on the coral gardening tables for the Chines case.

Forward Hurghada Red Sea, Egypt started attempts with good project design (artificial reefs, breeding techniques), however funding soon ended with no monitoring, maintenance programs [82] (Fig. 4e,f) nor publication record.

Climatic Change: Can Active Coral Rehabilitation Contribute to Resilience?

Multiple impacts of climatic and human drivers are projected to reduce corals resilience to consequent changes [83]. Projected declines of corals by extra (70-90%) at 1.5ºC raising; with losses reaching (>99%) at 2ºC, as deduced from the SR 1.5 report [83], however, small zones have demonstrated some resilience to climate drivers [84]. The efficiency of alternative rehabilitation approaches to increase climate stressors resilience will be limited unless warming and ocean acidification are rapidly controlled [64].

Hence, adaptation interventions to consolidate coral reefs resilience are needed when the traditional measures of reefs preservation become inadequate to tackle global change impacts [85]. Approaches such as wide-spread coral transplantation [19] or artificial reefs using [86] are already in use with considerable challenges [64]. In contrast, other approaches like assisted colonization [87], supported evolution [88], or associated symbiotic [89] and others still at phase of "proof-of-concept" [64].

There is limited evidence that corals rehabilitation contributes to climate-related drivers' resistance (warming, acidification, increasing storm intensity and SLR), [83] including enhanced bioerosion [90]. Considering both mitigation and adaptation measures of corals [64], the effectiveness of mitigation measures was assessed for the first two drivers (quantified relative to Representative Concentration Pathway "RCP, 8.5") to be low to high impact respectively. These rehabilitation approaches may be ineffective if warming skip 1.5ºC [29]. In contrast, others used microbiome engineering (direct selection) targeting the thermal tolerance microbes [91], recently, microbiomes indirect selection was used to understand how coral microbiomes respond to climate change as „www.aims.gov.au/evolution-21".

These manipulation experiments will distinguish the crucial accompanies microbes that support coral holobiont adaptation to future climate [32]. At a tactical level we believe that, quantifying how much coral rehabilitation contribute to resilience. To get less than the projected coral declines with 1.5 report [29] cannot be estimated with current information.

Socio-Economic Drive to Success of Coral Rehabilitation

Poor communication between the respective parties, language barrier, and attempts costs and benefits (as certain social and economic drivers) are crucial to successful rehabilitation interventions.

Poor Communication and Collaboration between Multiple Key Stakeholders with the Scientists

Corals rehabilitation key stakeholders are: rehabilitation practitioners, MPAs managers and policymakers together with scientists. Corals rehabilitation contractors must use advanced techniques supported by science base [65], especially sexual propagation requires expertise technology, labor, and costs than the asexual techniques [92]. While, owing to poor communication between scientists and other key stakeholders, a considerable proportion of coral rehabilitation attempts has been done without scientific input or monitoring programs [31], in addition to the environmental policymakers. Many of these outcomes have not been documented nor knowledge shared to learn from past successes and failures.

In general, feasibility to rebuilding marine life in the face of climate change needs powerful narrative with scientific evidence enhanced to societal benefits [68] to fill the knowledge gaps of the human response to the climate change [93] in the ecosystem-based adaptation option. It is evident that coral reef needs protection, and that many of the cited human impact must be avoided through enforcement of scientific-based management and rehabilitation programs.

Language Barrier

English journal articles were uncommon in some important countries with experience in coral research. For example, half of coral publications in China were published in Chinese language since 1950, composing around 655 articles, book, and reports [34].

Also, a large number of publication and reports have been published in different languages from different parts of the world such as: Pacific (Japanese [94], Filipino, Indonesian, Malayan languages), Atlantic and Caribbean (Spanish and Portuguese), all about 36% for publications concerned-conservation only [95]. Such languages are not discoverable in the bibliometric search criteria carried out using the English language composing Gray-literature (under or graduated works) or unpublished reports such as the case of Colombian [96].

Costs and Benefits

In spite of adaptation measures involving different techniques of corals transplantation has been extensively studied [64]. The evidence is limited on the cost of ecosystem based adaptation measures to estimate cost per-unit over large spatial scales [83]. As an adaptation option [93] and due to adopted broad range corresponding to the economy of the country that hosts rehabilitation, the technique applied [64] and uncertainty [97]. Yet, studies of these interventions relative cost and benefit also contain limited evidence on the thorough analysis across different measurements [98].

The entire price of any ecosystem based measure basically cover cost of principal, maintenance, land and sometimes permits [23]. For example, unit rehabilitation cost is the highest for coral reefs among the ecosystems [83] being 50.000 USD/200 m^2 for 3 sites with a specific artificial reef in Egypt [82], 30.000-90.000 USD/100 m^2 for the artificial reefs in the UK [99] and 100.000-1.000.000 USD/hectare for the major physical rehabilitation [44].

The effectiveness of the mitigation measure for the climatic drivers in relation to the reefs system rehabilitation (as mentioned above) were also assessed from the cost perspective. Assessment showed cost to be high per hectare of coastal area but with no benefits for the local measures action implemented [64].

Reducing human impact, marine pollution and mitigating climate change are necessities, but it cannot be realized merely by cooperation of people or small entities. Thus, what is recommended to be done now may fold under the following conclusion wedges.

Conclusions

Such an important opportunity to scale integrated coral rehabilitation solutions are as follow:

1. Protecting vulnerable coral habitats and species:

– It seems evident that if the current rate of destruction continues (anthropogenic and climatic), reefs ecosystems will most likely suffer continued significant degradation, lead to irreversible decline.

– Losing coral habitat on multiple levels must be the subject matter for both scientists with environmental managers and policymakers. That necessitates rising the interventions boosting reefs resilience and conservation of its structure and function.

2. Adopting coral rehabilitation cautionary strategy with an action plan.

– Certain major physical damage to the corals creates substantial area of unstable rubble and sand that is unlikely to recover over many decades unless physical rehabilitation interventions take place with the help of an expert guidance.

– Core management actions (passive rehabilitation) must be performed before active rehabilitation attempts. Rehabilitation of corals is only complementary to the management tools that addresses the broader causes of reefs degradation.

– Corals small-scale rehabilitation attempts are not adequate to the scale of the climate change crisis.

– Monitoring early stages of corals development (transplanted or spawned) is likely effective to assess both rates and kinetics of growth to predict the survival chances.

– Avoiding project design mistakes in (site selection, corals species and its genetic diversity, used materials, ideal techniques, clear maintenance, and monitoring programs for donor and post transplanted colonies) is the most important scientific step during coral sexual or asexual interventions.

– Needs for powerful narrative supported by scientific evidence and its broad societal benefits in the ecosystem-based adaptation options (adopting rehabilitation strategy) will control the large coral rehabilitation works undertaken with neither scientific input nor detailed monitoring programs with a responsible consumption.

– Avoiding this strategy with its action plan is expected to result in another direct human impact on coral reefs in the Anthropocene.

– Multiple terms of reefs rehabilitation techniques are not the matter; choosing the appropriate technique that does not cause a destruction for both donor and receptor habitats is the most important matter.

– Country economy, applied techniques and uncertainty affect the interventions relative cost and benefit when coral rehabilitation attempts chosen as an adaptation option.

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Conflict of Interest

The authors declare no competing interests.

Author Contributions

Abd-Elgawad, envisioned and led the project, collecting data, performed all analyses, secured funding, and wrote the manuscript. Cai, Mohamed and Hellal contributed to the conceptual ideas, design, and writing. Hellal contributed to data analysis. Guo, contributed to data collection with different languages and MATLAB developing work. All authors contributed edited and approved the manuscript.

Data Availability

Data and information (on the geography's attempts, distribution, etc.) are provided in supplementary material (sheets name: S 1-4) for this paper (avaiable in https://doi.org/10.15244/pjoes/144554).

Code availability: All MATLAB code and GIS files packages are available on request or directly from the authors.

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