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Coral restoration patents are disconnected from academic research and restoration practitioners

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Global warming and other anthropogenic impacts have driven coral reef degradation on a global scale to unprecedented levels of decline, with further dramatic deterioration predicted by the end of this century. Along with a drastic reduction in carbon emissions, we face an imperative to restore and maintain marine habitats to secure the ecosystem services they provide. While terrestrial systems have benefited from the agricultural revolution that provided industrial tools for effective habitat restoration, limited access to marine environments has inhibited similar levels of innovation resulting in a lack of cost-effective and scalable solutions. Commercial off-the-shelf technologies to cater to this growing industry are still absent. Here we conducted a systematic analysis of patent and scientific literature data as indicators of research and development (R&D) output in the field of coral restoration. We identify technology growth trends, key areas of technological development, and their geographical distribution. While the number of inventions filed for coral restoration is on the rise, similar to the published academic literature, the stakeholders leading both fields are unrelated. Academic research appears to lack translation into inventions for commercialization. Intellectual property protection further seems to be spearheaded by a few countries and is often limited in its application to national jurisdictions, with China dominating this sector. This does not mirror the distribution of current and need for coral restoration efforts globally. Here we discuss potential differences in cultural, socio-economic, and philosophical ideologies that drive these divergences and their impact as inhibitors or promoters of innovations targeting coral restoration solutions.

KEYWORDS
patents, coral restoration, artificial reefs, coral gardening, restoration technology

1 Introduction

Coral reefs are suffering from an onslaught of disturbances that have caused large-scale deterioration and unprecedented losses (De'Ath et al., 2012; Hughes et al., 2018). In the last decade alone, about 14% of coral reefs have been lost globally, largely attributed to climate change (Souter et al., 2021). Although corals have an intrinsic resilience and capacity for natural recovery (Barshis et al., 2013; Gouezo et al., 2019), the increased frequency and intensity of extreme climatic events is reducing the time between events and thus impairing their innate ability for recovery (Graham et al., 2011). Additionally, ongoing or recurrent local stressors limit coral larval supply, settlement, recruitment, and post-settlement survival (Fabricius, 2011; Fabricius et al., 2017; Wakwella et al., 2020), challenging natural recovery in many regions.

Climate change mitigation trajectories have been slow and global temperatures are expected to increase even in a zero-carbon emission scenario (Meehl et al., 2005; Tanaka and O'Neill, 2018; Yuan et al., 2019). Hence protection-based strategies alone may not suffice to guarantee ecosystem resilience and functioning over the next decades (Kleypas et al., 2021). Active interventions are thus increasingly demanded as crucial management strategies to address the large-scale deterioration of reefs by 'buying time' for recovery, increasing the resilience of reefs, and aiding in preserving and restoring reef ecosystem functioning (Van Oppen et al., 2015; Anthony et al., 2017; Morrison et al., 2020; Suggett & van Oppen et al., 2022).

Marine restoration has already proven valuable to recover degraded ecosystems and represents a key lever of the effort to rebuild marine life (Nam et al., 2016; Bersoza Hernández et al., 2018; Duarte et al., 2020; O'Connor et al., 2020; Tan et al., 2020). A set of strategic actions have been identified for rebuilding marine life by 2050, which include protecting vulnerable species and habitats, rebuilding marine resources through sustainable harvesting, improving water quality, reducing pollution, mitigating climate change, and actively restoring marine habitats (Duarte et al., 2020). Among these, mitigating climate change and improving restoration efforts were identified as the most crucial actions for recovering coral reefs. Nevertheless, coral restoration lags behind other marine habitats in cost, scale and success, and is frequently criticized for being unsuited to the magnitude of damage (Bayraktarov et al., 2016; Bellwood et al., 2019). Currently, restoration efforts are considered insufficient to satisfy global coral conservation objectives, such as achieving a modest recovery of coral reefs (e.g. 10% increase over current levels, Duarte et al., 2020). Coral reef restoration is still in its infancy, especially compared to terrestrial systems, for which restoration practices have been optimized over decades and benefited from technological innovations and funding through projects aimed at increasing carbon capture (Quigley et al., 2022). Although coral restoration is rapidly developing, it is still at a microscale, with most projects only measuring tens of square meters (Boström-Einarsson et al., 2018; Boström-Einarsson et al., 2020). Additionally, there is currently a lack of innovative and industrial tools which could balance cost and effectiveness, making successful large-scale projects achievable (Gibbs, 2021).

Until recently, the market size and demand for coral restoration projects were insignificant in attracting investors. With the growing interest in blue natural capital, the blue economy, and the emergence of large-scale projects, such as the Indonesia Coral Reef Garden (ICRG) Program (www.icrg.id), there is a current shift, with commercial entities entering the market (e.g., Coral Vita www.coralvita.co; Ocean Revive www.ocean-revive.com). Additionally, global initiatives to fund coral conservation and restoration (e.g., the UN Global Fund for Coral Reefs and the UN Decade on Ecosystem Restoration), as well as to invest in accelerating research and development (R&D) for coral restoration (the G20 Global Coral Reef Research & Development Accelerator Platform, CORDAP), have recently emerged as drivers to fast-track innovation for effective restoration solutions.

The growing demand for coral restoration requires increased R&D to deliver new scalable restoration techniques that can be translated into commercially available technologies. Understanding the link between science and industry is essential, especially considering that disjointed fields, lack of coordination, and knowledge sharing may present a considerable challenge preventing the translation of technological innovations into processes allowing upscaling restoration efforts. Here we provide a systematic analysis of patents and research publications in coral reef restoration technologies to identify technology growth trends, their geographical distribution, and to place the findings in the context of their application in actual restoration projects.

2 Methods

2.1 Patent data collection

We extracted country and institution performance from publicly available patent and literature data to identify the primary technology holders and innovators in the field of coral restoration. A boolean search query was conducted on the open-source patent database LENS.ORG (www.lens.org) on June 14th 2022. The search term was optimized by iterating search terms, starting with different search terms, and analyzing the resulting collection of patents in detail by randomly screening the titles and abstracts. This process was repeated several times until a high number of patents were returned, which were relevant to the field of coral reef restoration, but not too broad that they were out of context. This search identified the final search terms "title:(coral OR reef AND (restoration OR rehabilitation)) OR abstract:(coral OR reef AND (restoration OR rehabilitation)) OR claim:(coral OR reef AND (restoration OR rehabilitation)) OR (artificial AND coral AND reef)" and resulted in a total of 1741 patents on reef restoration. Next, we refined our search to specifically target coral restoration by conducting a Boolean search within the previous dataset using the search terms "Title: coral OR (Abstract: coral OR Claims: coral)." That dataset was cleaned using OpenRefine 3.5.2 software and visually inspected to remove false hits and duplicates. We then extracted information on the affiliations (name, country, and type), year of publication, IPCR classification, jurisdiction, patent family, legal status, and application type. Patents were categorized into eight different application types based on the scope of the application (i.e., artificial reefs and substrates; ex situ aquaculture; *in situ* nursery; materials, composites, and adhesives; protocols and methods; *in situ* condition optimization, heat resistance; others).

2.2 Scientific literature collection

We conducted a literature search for papers related to coral restoration technologies, techniques, and methods using Web of ScienceTM (WOS, Core collection, Thomson Reuters, New York, New York, U.S.A.) (last accessed on 20th June 2022). The Boolean search was directed using the search terms: [(coral reef OR coral) AND restoration AND (method OR tool OR technique OR protocol)] from Web Of Science, and filtered to retain only articles (i.e., no reviews). OpenRefine was used for data cleaning and removing duplicates. The dataset was manually screened to remove any references out of scope (primarily medical, and dentistry). Classification involved examining the material associated with each article (abstract and description) and determining the year of publication, name, and country of the institutions of all corresponding authors, and application type. Since databases may differ in coverage (Mongeon & Paul-Hus, 2016) the use of WOS alone may present a limitation to our analysis

2.3 Coral restoration project data

Data on coral reef restoration projects from scientific and grey literature was obtained from the Boström-Einarsson et al. (2020) dataset through the Dryad Digital Repository (latest update July 2020). We extracted information on the country, the affiliations leading the projects, and the type of work conducted.

3 Results

3.1 Restoration growth trend

Our results indicate a growing interest in coral restoration, mirrored by the growth in the number of filed patents, published scientific articles, and the growing number of active restoration projects worldwide (Figure 1). Overall, 1700 patents related to reef restoration were identified, with 171 patents and 433 scientific papers specifically targeting the restoration of coral reefs. Among those, patents and scientific publications reach back to the early 1990s, while the first documented coral restoration project, conducted in Guam, dates to 1979.

All three areas of activity (patents, scientific papers, and restoration projects) displayed an initial slow growth with low output, followed by a spike in the early 2000's when interest in restoration soared, potentially as a response to the 1998 El Niño event resulting into the first reported global coral mass bleaching (Hoegh-Guldberg, 1999). Numbers have since increased and particularly the last decade has witnessed an exponential growth of coral restoration activities around the world reaching peaks of 25 patents (17% $year^{-1}$), 63 publications (19% $year^{-1}$), and 29 restoration projects (14% $year^{-1}$) in recent years (Figure 1). All three areas of activity appear correlated to each other (Figure 2), with research effort and patent output showing the strongest positive linear relationship (R^2 = 0.82), followed by research effort and restoration projects (R^2 = 0.70), while patent output and restoration projects displayed the weakest relationship (R^2 = 0.57).

3.2 Geographic distribution

Regarding geographic distribution, nations showed pronounced differences in their role in patent filing, research rankings, and active restoration work (Table 1). Overall, 16 out of 194 countries (80 of these countries having coral reefs in their waters) hold patents targeting coral restoration. The patent market was highly geographically skewed with China (61.40%), the US (12.86%), and Japan (6.43%) dominating patent registrations, and together accounting for more than 80% of all patent filings. Among the 15 largest coral reef regions (accounting for 75.14% of reef cover), only four have published patents (<6% of all patents). Together, these only account for 22.35% of all restoration efforts. Most countries working on coral restoration projects did not have any registered patents nor contributed considerably to research efforts eventually leading to inventions.

Scientists affiliated with institutions across 57 countries contributed to research efforts on coral restoration, with the most significant contribution coming from scientists from US institutions (38.70%), followed by Australian (11.38%) and Israeli institutions (5.90%). In terms of active restoration projects, 43

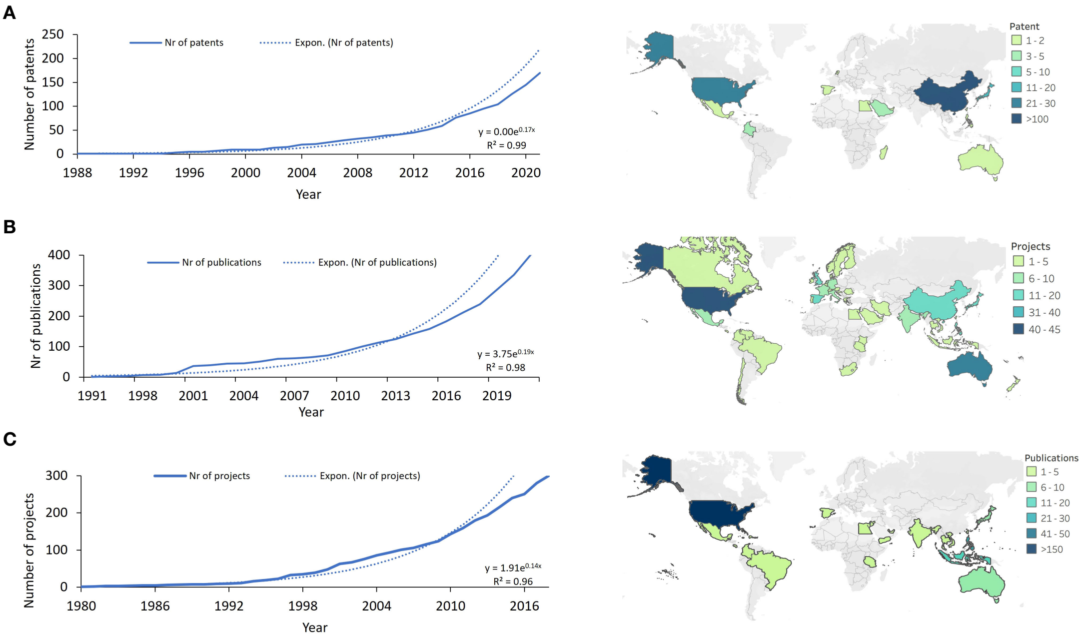

FIGURE 1
Left panel: growth trends, right panel: geographic distribution of **(A)** patent applications, **(B)** scientific publications, and **(C)** restoration projects.

countries have documented restoration projects, with the majority located in the US (13.86%), followed by the Philippines (12.54%), and Indonesia (6.27%). Inspecting all three areas of activity combined, indicates that the US is the only country that displays a strong presence in all three areas of activity.

3.3 Patent technologies

The patent market was dominated by inventions related to artificial reef structures (53.80%), followed by ex situ aquaculture (13.45%), and *in situ* nursery technologies (9.35%) (Figure 3). Each of the remaining categories contributed less than 6.5% of the patents. The lowest contributions come from patents targeting heat resistance and resilience in corals (1.75%). In contrast to their prevalence in the coral restoration patent pool, artificial reefs only represented 16.33% of the restoration techniques that are used in practice, with most active restoration projects focused on coral gardening (50.67%), in either *in-situ* (42.33%) or ex-situ (8.33%) nurseries (extracted from Boström-Einarsson et al., 2020b using search queries). Among the 171 coral restoration patents, 38.60% are currently active, 31.00% pending and the rest (30.41%) either inactive, discontinued or expired.

4 Discussion

Our findings indicate a surging interest in restoration, evidenced by the patents, publications, and projects surfacing at exponential rates, likely driven by concerns about the future of coral reefs resulting from the occurrence of global mass bleaching events. Despite the soaring interest in coral restoration, research effort, patent registration, and their application in coral restoration techniques appear uncoordinated, leaving them disconnected and isolated, thereby leading to inefficiencies in the innovation process. This mismatch is especially evident in the pronounced geographic skew and geographic disjoint efforts in the three areas of activity (Figure 1), with significant disparities in the roles played by each country.

Overall, the disconnect between the three areas of activity around the world, suggests that research-focused organizations may not take the extra step to translate the resulting knowledge into innovative and tangible management solutions. Additionally, where this happens and patents are filed, the new intellectual property does not appear to be tied to the demands of practitioners, which leads to the development of technologies that may not directly address their needs or there is a lack of awareness on their existence. This is particularly evident as we identified a discrepancy between technology development and actual application, with the patent market predominantly focusing on developing artificial reefs (e.g Reef Ball among others) while the most distributed strategy practiced by coral restoration managers was to transplant corals directly onto the reef (Boström-Einarsson et al., 2020). Further, only a few of the examined patent publications identified scalable solutions for coral restoration, whereas scaling up beyond the small footprint of most coral restoration projects is recognized to be an essential

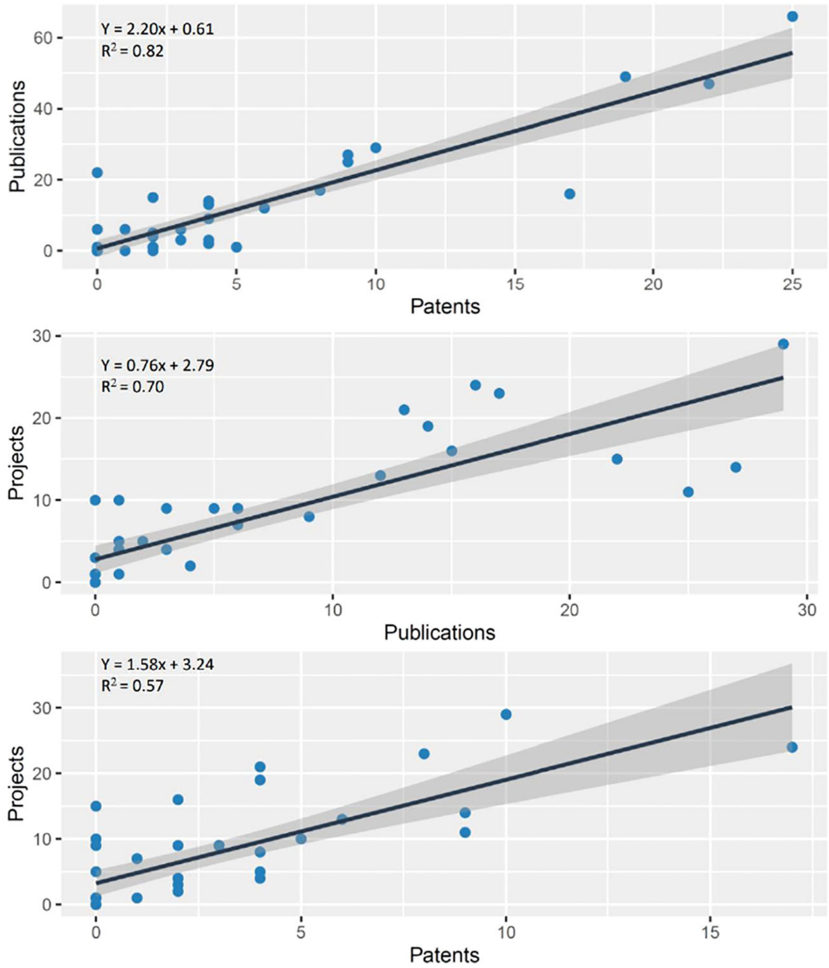

FIGURE 2
Scatterplots exploring the relationship between research effort (i.e., publications), active restoration projects, and technological innovation (i.e., patent output). The grey bands represent the standard error of the regression line.

underpinning of conservation success (Boström-Einarsson et al., 2018). Accordingly, there is insufficient cooperation and coordination between governments, researchers and industry which may be impeding the flow of information and ultimately hindering the potential acceleration of innovation required to face the conservation challenges these ecosystems face. This disconnect and lack of coordination is not limited to the field of coral reef science but appears to be of concern in other fields of ecology and conservation (Fisher et al., 2011; Hulme, 2014). This emphasizes a clear need for improved interdisciplinary communication and information exchange (Bayraktarov et al., 2019). Establishing communication channels that bring together the communities, industry, research organizations, and practitioners to nurture synergies and the development of an innovation ecosystem, conducive to the acceleration of coral reef restoration success is, thus, crucial to leverage the investment and strength of all three sectors and to identify the next critical steps for optimizing future operations effectively.

4.1 Cultural, social, and economic values impact the trajectory of restoration focus

The restoration of degraded habitats requires addressing not only the ecological, but also the political, economic, and social dimensions of restoration. Despite ecosystem health being the primary objective of restoration, the critical support from the general public, governments and industry is greatly dependent on human-centered goals and community engagement (Le et al., 2022). Consequently, shared social values and beliefs are central to restoration (Le et al., 2022; Westoby et al., 2020) and strongly influence the development and projections of all three sectors. The differences in focus of efforts (research, patents and restoration) between countries and the lack of collaboration between sectors may thus not only be reflective of potentially differing ecological needs but also political, cultural, and socio-economic influences resulting in different priorities. Here we discuss potential differences in cultural, socio-economic, and

TABLE 1 Geographic distribution of patent filings, scientific publications, restoration projects, and reef area.

Country	Patents (n)	%	Country	Publications (n)	%	Country	Projects (n)	%	Country	% global reef area
China	107	61.14	US	167.6	38.70	US	64	21.19	Indonesia	17.75
US	24	13.71	Australia	49.3	11.38	Philippines	38	12.58	Australia	17.22
Japan	11	6.29	Israel	25.5	5.90	Indonesia	19	6.29	Philippines	8.81
Korea	8	4.57	Philippines	14.5	3.34	Israel	17	5.63	France	5.02
Saudi Arabia	4	2.29	Spain	13.9	3.20	Singapore	11	3.64	Papua New Guinea	4.87
Colombia	3	1.71	Japan	13.7	3.17	Jamaica	10	3.31	Fiji	3.52
Philippines	2	1.14	International	12.6	2.90	Japan	9	2.98	Maldives	3.14
Madagascar	2	1.14	China	10.8	2.49	Australia	8	2.65	Saudi Arabia	2.34
Australia	2	1.14	UK	10.6	2.45	Maldives	6	1.99	Marshall Islands	2.15
Netherlands	2	1.14	India	10.0	2.32	Mexico	5	1.66	India	2.04
Egypt	2	1.14	Italy	9.8	2.26	Seychelles	5	1.66	Solomon Islands	2.02
NA	2	1.14	Mexico	9.7	2.24	Tanzania	4	1.32	UK	1.94
Taiwan	2	1.14	France	7.8	1.81	Egypt	3	0.99	Micronesia	1.53
UAE	1	0.57	Singapore	7.1	1.64	Bahamas	3	0.99	Vanuatu	1.45
Mexico	1	0.57	Germany	6.5	1.51	British Virgin Island	3	0.99	Egypt	1.34
Other (2)	2	1.14	Other (44)	74.6	14.69	Other (26)	97	32.12	Other (64)	24.86
Total	175	100	Total	433	100	Total	302	100	Total	100

philosophical ideologies that drive these divergences and their impact as inhibitors or promoters of innovations targeting coral restoration solutions.

The US is the only country that displays a strong presence in all three areas of activity, potentially providing evidence of a more efficient system where all three activities are integrated. The latter may be explained by the fact that the US is the nation with the highest funding available for coral restoration (Hein et al., 2021). Further, the US has a long history of coral reef restoration in the Caribbean region (Johnson et al., 2011). A wealthy industry nation, the US also harbors some of the most threatened reefs potentially providing a strong driver for these

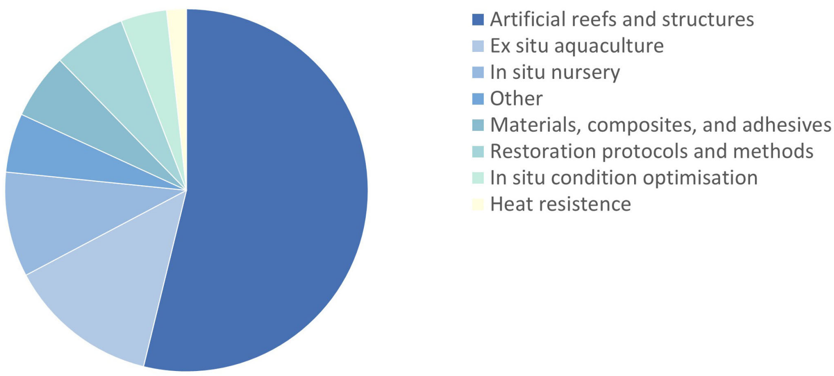

FIGURE 3
Categories of patents based on scope of application.

efforts. For example, the pillar coral *Dendrogyra cylindrus* is functionally extinct in the Florida Reef Tract and may only be recovered with ongoing restoration efforts (Neely et al., 2021). Overall, the Florida Reef Tract is in a dire situation with less than 2% coral cover (Towle et al., 2020). Additionally, the US has a longer history of collaboration between universities, governments and industry, with the introduction of an important technology policy (the United States Bayh-Dole Act in 1980) facilitating patenting and licensing of academic-led and federally-funded inventions, thus encouraging collaboration between universities and industry.

Successful and scalable restoration will require significant breakthroughs and cutting-edge technologies, but to date, there appears to be a lack of technologies that target this gap. A particular concern is the lack of high-quality equipment for coral restoration. Our research identified a lack of patents that are targeting the technologies required for restoration at-scale such as automation, artificial intelligence, and specialized vessels or vehicles (Gibbs, 2021). Additionally, very few patents have attempted to specifically target testing or increasing coral resilience and thermal tolerance (e.g., CN 110476837 A & CN 110476836 A), which may be reflective of the complexity of the problem (McClanahan, 2022). However, since heat stress is expected to be the most detrimental stressor to coral reefs in the future (Hughes et al., 2017), this represents an upcoming topic that requires further exploration. Hence, new programs are arising, such CORDAP (https://cordap.org), and the XPrize on coral restoration (https://www.xprize.org/coral), to catalyze research and innovation for effective deployment of coral restoration at scale. Further, databases, such as the Coral Tech established by the Coral Reef Consortium (https://www.coraltech.world/) are now available to highlight new technologies.

Currently, most scalable restoration solutions are still in the preliminary stages of R&D and to the best of our knowledge none of the currently patented technologies have been used in large scale restoration projects. In fact, most patents appear to have no commercial interest or value. The latter is especially apparent when probing into Chinese reef restoration patent technologies, which represents two thirds of all patents. Chinese patents mostly focus on the development of artificial reefs, which is the most common restoration practice in South-East Asia (Hein, 2021). Nevertheless, scrutiny of the patents, suggest that the purpose of patenting in China may not be to protect, commercialize and apply their inventions, but rather to lend credibility to their work (Chen and Zhang, 2019). China's subsidy patenting programs are largely responsible for the surge in patenting in the country, particularly at universities and research institutes, where patent applications can be critical for career promotions with little regard for their utility or economic value (Dang and Motohashi, 2015; Fisch et al., 2016; Chen and Zhang, 2019). China's dominance in patent filings thus likely has non-innovation motives but rather is based on socio-cultural/political dimensions, raising questions concerning the economic and ecological value of these technologies for advancing the field of coral restoration.

Commercializing coral restoration tools may raise ethical questions about equitability and inclusivity. Coral restoration is particularly needed in developing nations where most communities depend on the ecological functions' reefs provide. However, these nations generally do not have access to the large funds (Hein et al., 2021). With limited funding and a lack of capacity, R&D and IP protection become unavailable, reflected in the limited patent output in developing nations. For instance, Oceania's Island states have among the largest coral reef areas but no patents, minimal research efforts, and few restoration projects. Additionally, the same nations may be most likely negatively affected by commercial interests driving innovation in coral reef restoration, making new tools and technologies inaccessible due to lack of funds or specialized facilities and skills (Gibbs, 2021).

These ethical and social implications may discourage R&D efforts and the collaboration between industry and research facilities or practitioners due to divergent social and political ideologies between sectors and countries (i.e., industry for profit, practitioners NGO activists). It is essential to remove these barriers and focus on ensuring that the commercialization is done under ethical and inclusive principles. This will help to advance the field and to mitigate ecological imperialism and ongoing colonialism, a major critic of activities in this field (Gibbs et al., 2021). For instance, CORDAP is committed to develop technologies that will be universally accessible, with no licensing fee for coral reef applications. It also includes a requirement for mid- and low-income nations to be participants of all projects and activities funded, as well as providing training opportunities and access to advance research infrastructure to scientists from developing nations (CORDAP Scientific and Advisory Committee, 2022).

The commercialization and industrialization of coral restoration may drive down costs due to economy of scale and mass production, and pay back R&D efforts, providing further funds for continued research. Developing nations could benefit from patents and the commercialization of their inventions, which may be economically transformational and fuel a restoration economy. The restoration business and blue economy are in fact booming, contributing billions to national economies and even more in terms of indirect socio-economic linkages, creating jobs for planning, developing, administering, and producing materials for restoration (BenDor et al., 2015; McAfee et al., 2021). The economic returns on investment and the future value of the ecological services provided by restored land should incentivize continued funding (Kubiszewski et al., 2020). For instance, the Indonesia Coral Reef Garden (ICRG) Program (https://www.icrg.id) mobilized national COVID-19 relief funds to undertake the largest coral restoration yet accomplished, restoring 75 ha of degraded coral reefs in Bali, while providing much needed employment under a severe economic crisis due to the freeze of tourism revenues during the pandemic. The success of this program has led to an eagerness of both communities and government to contribute further, with the government announcing a plan to restore a further 1,000 ha of reef by 2024 and coral farming companies now mushrooming, producing corals by clonal reproduction that are both outplanted to restore local reef as well as exported for aquarium trade.

4.2 Future outlook

The success of large-scale coral restoration, an essential underpinning of the aim to partially rebuild coral reefs (Duarte et al., 2020) requires drawing lessons from past attempts, making use of new automated and mechanized technologies, and ensuring that economies of scale will follow fairly. As such, sustainable socio-ecological management of coral reefs will be in large part determined by human values (Hein et al., 2019; Perring et al., 2018) and the resulting benefits to the communities supporting the action. Understanding the human dimensions such as the philosophies, cultures and socioeconomics of restoration is now perhaps just as crucial for restoration as knowledge on the ecological processes (McAfee et al., 2021).

The commercialization and industrialization of coral restoration have ethical implications, and it is of utmost importance to ensure accessibility and the equitable distribution of restoration technologies (Osborne et al., 2021). At the same time, there is an urgent need to incentivize R&D and technological advances to overcome current bottlenecks and achieve the groundbreaking innovation required. As such, we require new integrated approaches that may foster research translation, innovation, and commercialization to promote meaningful restoration outcomes. CORDAP may provide the framework to precisely tackle this gap and has launched its first call for proposals this year. Finally, it is crucial to remember that active restoration and technological innovations are not a panacea and that effectively rebuilding coral reefs requires actively removing local stressors as well as addressing global change.

Data availability statement

The datasets presented in this study can be found in online repositories. The names of the repository/repositories and accession number(s) can be found in the article/ Supplementary Material.

Author contributions

CD conceptualized and designed this study, with refinements by CR and SS-R. CR compiled and analyzed the data, with input from SS-R. CR wrote the manuscript with contributions from SS-R and CD. All authors contributed to the manuscript and approved the final manuscript.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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Supplementary material

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fmars.2022.1093808/full#supplementary-material

SUPPLEMENTARY FIGURE 1
Adopted PRISMA flowchart.

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