RESTORATION ECOLOGY
The Journal of the Society for Ecological Restoration
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REVIEW ARTICLE

Coral restoration: a mapping review through a scientometric analysis

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Reef restoration has gained attention as it has strategic actions and powerful means in sustaining and maintaining coastal ecosystem services. This scientometric study systematically analyzes the current trends and research hotspot in coral restoration across the last five decades (1971–2022). The metadata (12,667 articles with 652,860 cited references) were obtained from the Clarivate Web of Science platform through the Core Collection database, associated with the CiteSpace and R-software for further analysis. The results indicated that the trend of coral restoration is increasing in paper/year, with the United States, Australia, and China as major contributors to the related research. Furthermore, James Cook University, Australia had the largest number of articles, and the Consortium of Research Libraries of the United Kingdom was the most influential institution on coral restoration. The highly cited keywords are "Great Barrier Reef," "climate change," and "coral reef," while the most influential keywords are "coral," "model," and "Atlantic." A total of 23 clusters in the field with "coral reef," "phase shift," "bacterial communities," "coral restoration," "symbiotic dinoflagellate," "stony coral tissue loss disease," "bleaching event," "ocean acidification," "oyster reef," and "quantitative reconstruction" are among the top cluster size labeled. Early-stage researcher may use both keywords and cluster analysis to find topics attractive to their future research projects. In addition, this study contributes toward evaluating recent scientific productivity about coral restoration as well as informing researchers and policymakers regarding funding, future strategic planning, and potential collaboration opportunities.

Key words: climate change, coral recruitment, growth, recovery, reef restoration mapping, research patterns, restoration review

Implication for Practice

- Innovative coral restoration techniques identified through scientometric analysis can facilitate new restoration projects planning and ensure cutting-edge research and practices.
- The strategic allocation of resources to high-impact areas that are informed by current research trends, can foster interdisciplinary collaboration and enhance the efficacy of conservation efforts.
- Adaptive management strategies, leverages scientometric data to guide evidence-based policy and practical interventions, tailored to specific environmental contexts. Moreover, promoting open access to coral restoration research is crucial for facilitating knowledge exchange, stimulating innovation, and improving restoration methodologies.

Introduction

Sustainable Development Goal 14 aims to conserve and sustainably use the oceans, sea, and marine resources for sustainable development (Oegroseno 2018). Coral restoration could be one of the main benefits of this target, mainly target 14.2, which main goal is to protect and restore marine and coastal ecosystems (Rees et al. 2018; Virto 2018; Nunes et al. 2019). Coral reefs are known as the most vulnerable marine ecosystems, composed of unique biological structures built by the remnants of coral colonies and encrusting macroalgae, which leave behind their calcium carbonate skeletons (Miththapala 2008; Gattuso et al. 2014; Hoegh-Guldberg et al. 2019). More than half of

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Author contributions: TCS, CDMS conceptualized the study; FBS led methodology, software, supervision, and secured funding; TCS, FL, GS, ZF were responsible for data curation and visualization; MNA, FBS drafted and revised the manuscript; all authors reviewed, edited the manuscript, and contributed to the final version.

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doi: 10.1111/rec.14229

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the world's reefs are prone to degradation due to heavily increased human-induced disturbances or anthropogenic changes in the late twentieth century (Burke et al. 2011; Yasuhara et al. 2012; Woodruff et al. 2013; Good & Bahr 2021; González-Barrios et al. 2023), exacerbated by climate change elements such as marine heatwaves, flooding, or sea level rise that have been occurring longer and more frequently in the last couple of decades (Ashraf et al. 2023; Hsieh et al. 2023; Kay et al. 2023; Thirukanthan et al. 2023).

The cumulative impact of both historical and recent disturbances has begun to surpass the natural resilience thresholds of coral reefs (Baskett et al. 2014; Hoegh-Guldberg et al. 2019; Mellin et al. 2019). This evolving scenario underscores the urgent need for intervention strategies that bolster the ecosystems' intrinsic resilience capacities (Johnson et al. 2011; van Oppen et al. 2015; Hernández-Delgado 2024). Coral reef restoration emerges as a pivotal intervention in this context, aiming not only to repair damage but also to enhance the reefs' inherent ability to withstand future disturbances (Anthony et al. 2017; Vardi et al. 2021; Hilmi et al. 2023). This perspective is supported by empirical evidence and theoretical frameworks presented in seminal works (Hughes et al. 2010; van Oppen et al. 2017; Hein et al. 2021; Hilmi et al. 2023), which collectively underscore restoration's potential to amplify resilience. Nevertheless, it is recognized that the efficacy of restoration in reinforcing resilience is a subject of ongoing debate and research. Coral restoration commonly employs several methods, including asexual and/or sexual propagation, substratum enhancement, and others (Omori 2019; Boström-Einarsson et al. 2020; Schmidt-Roach et al. 2020). On top of that, branching corals such as *Acropora* are commonly used for restoration due to their fast-growing ability, which helps accelerate coral reef recovery (Denis et al. 2013; Schopmeyer et al. 2017; Boström-Einarsson et al. 2020).

The amount of research produced up to date on every scientific aspect of coral reefs is so large that it is not so easy to analyze, and then a scientometric approach may help to identify and visualize multidisciplinary patterns (i.e. science, innovation, and technology) across the last decades through statistical and quantitative analysis (Upham & Small 2010; Kim & Zhu 2018; Hein et al. 2020). The growing demand for coral restoration has attracted various stakeholders to search available publications about recent research trends and gaps, as well as scientific databases. This approach directly or indirectly increases the visibility of recent literature, such as coral restoration's advanced techniques. Despite the growing research on coral restoration worldwide, there is a lack of a mapping assessment of the current level of scientific knowledge in this area. Thus, this review is aiming to quantitatively map the current literature trends in coral restoration around the world using the Web of Science Core Collection (WOSCC) database and the CiteSpace tool.

A scientometric analysis can provide researchers, practitioners, governments, philantrophics, and communities with basal information (e.g. number of scientists involved, funding, etc.) to address conservation measures and research topics. The present study will span across some useful information that is often neglected and considered not really informative, such as for example, main contributors, publication years, countries, open access, and funding agencies, as well as the authors and organizations involved. This mapping review goes through a publication's reference and a cluster characteristic analysis. A compilation of keywords trends, distribution, and burstness clustering was made to understand the main topics and interests of the publications. Previous reviews on coral restoration have primarily concentrated on outlining different restoration methodologies. However, there is a significant body of research encompassing the ecological and physiological aspects of corals, coral reefs, and reef restoration. This broader scope of literature necessitates a comprehensive scientometric analysis to fully map and understand the evolving landscape of coral restoration research (Omori 2019; Boström-Einarsson et al. 2020; Roch et al. 2023). This research will not only aid in the identification of research trends on coral restoration but also contributes and support scientists in their literature review by providing a scientometric analysis of the existing publications on coral reef restoration.

Methods

Search Strategy

Current literature trends on coral restoration around the world was searched by filtering the WOSCC database and the CiteSpace tool. The search string included the following synonyms: (1) "coral*" OR "reef*" OR "coral reef*" OR "barrier reef*" OR "atolls" OR "fring* reef*" OR "coral island*" OR "atoll lagoon*" OR "biogenic deposit*" and (2) "restor*" OR "rehab*" OR "reclamation" OR "rebuild*" OR "re-build*" OR "recover*" OR "renew*" OR "re-new" OR "renovat*" OR "reestablish*" OR "re-establish*" OR "heal*" OR "repair*" OR "reconstruct*" OR "re-construct*" OR "remediation." The data were queried and retrieved on the same day from the WOSCC on 8 June 2023 to avoid being inconsistent due to Clarivate's daily data updates. This filtering search process is structured around three primary phases: (1) identification of initial resources, (2) rigorous screening for relevance, and (3) assessment of eligibility based on predefined criteria. It is important to note that our literature review spans a comprehensive timeframe, covering studies and publications from 1975 through 2022. This temporal scope was selected to ensure a broad and in-depth analysis of the evolution of coral reef restoration practices and their impacts over nearly five decades.

Obtaining and Analyzing Data

Detailed flowchart outlining our systematic approach for identifying, screening, and determining the eligibility of documents is presented in Figure 1. CiteSpace (Version 6.2.R3 [64-bit] Advanced for Windows 11 and supported by Java 17.0.2+8-LTS-86, 64-bit) was used to generate the visualization of analyzed graphs, especially for the scientometric analysis. Meanwhile, for the descriptive data, R (version 4.0.2) was used

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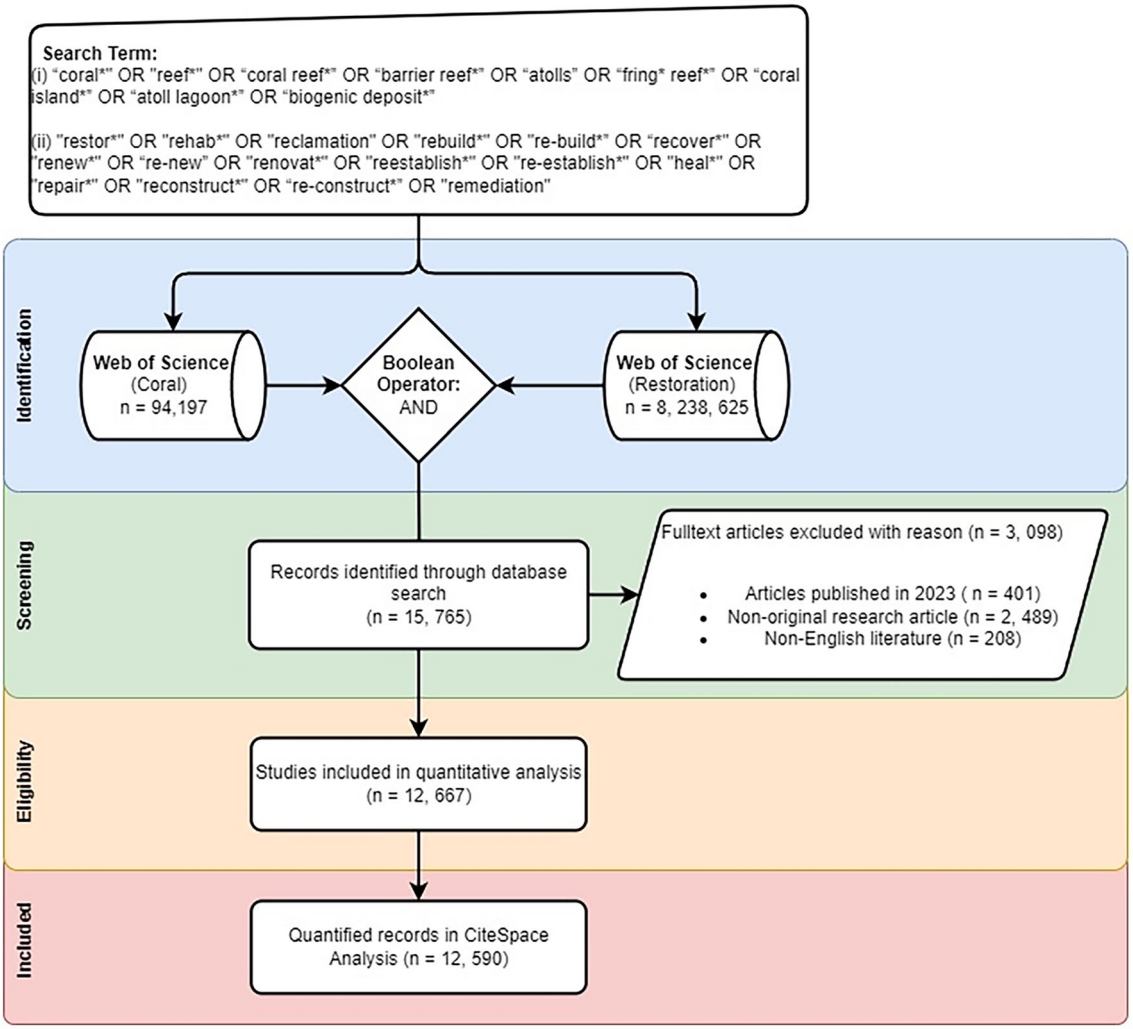


Figure 1. Flowchart of the present study for coral restoration using the Web of Science Core Collection database generated from 1975 until 2022.

to perform the basic statistical analyses of the data from the WOSCC database.

As for the scientometric methodological approach, a comprehensive analysis of keyword co-occurrence, cluster analysis, and timeline co-citation to map the landscape of research within the study domain was conducted. The keyword distribution analysis focused on identifying prevalent and emergent research themes, highlighting areas receiving significant attention and those potentially understudied (Radhakrishnan et al. 2017; Zou et al. 2022). Concurrently, cluster analysis was performed to discern latent semantic themes and group research documents by term correlations, employing the mean silhouette index (ranging from −1 to 1) to quantify cluster homogeneity, with higher values indicating greater similarity among cluster members (Chen & Morris 2003; Radhakrishnan et al. 2017; Zhong et al. 2019). Additionally, timeline co-citation analysis provided insights into the evolution of scientific collaborations and knowledge trajectories, facilitating the identification of recent developments and potential future research directions (Chen et al. 2022).

In the context of CiteSpace, the term "centrality" refers to the position of a node or keyword at the intersection or hub of two large networks or thematic communities. This measure indicates the strategic importance or influence of a node within the network, linking diverse research areas or discussions (Chen 2016, 2018; Chen et al. 2022). "Burstness," on the other hand, denotes a sudden and significant increase in the frequency of a particular keyword, topic, or reference within scientific publications. It highlights emerging trends or shifts in research focus that have gained rapid attention in the scholarly community over a specified period (Chen 2016, 2018; Chen et al. 2022).

Search Results

The search string yielded a total of 15,765 publications. Following the application of exclusion criteria, approximately 12,667 publications remained for a comprehensive literature review. For the CiteSpace analysis, approximately 12,590 articles were included. Additionally, there were a total of 652,860 cited references available for cluster analysis. The discrepancy in these

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figures may be attributed to the omission of some raw data from the articles in the database at the time of the search.

Publication Output (Publication Years, Countries, Open Access, and Funding Agencies)

The descriptive results of the coral restoration's publication output (Fig. 2) showed a total of 12,667 articles, and it indicated an increasing trend over the years, with 2021 having the highest publication record ($n = 1118$ articles) (Fig. 2A). Among these, there are a total of 155 countries involved in the coral restoration efforts worldwide (Fig. 2B). The United States, Australia, China, and England are among the top four countries publishing about coral restoration in the world. More than half of these publications (54.8%) have been made available online (Fig. 2C), and the top 10 funding sources are mostly (80%) from the most productive countries in the world (Fig. 2D).

Authors and Affiliations Analysis: Descriptive Analysis

In summary, there are a total of 34,066 authors involved in coral restoration publications around the globe. In contrast with the number of publications by country (which put Australia in second place), 7 out of 10 top authors are from Australia's region (Table 1). The scientometric analysis shows that P. J. Mumby emerges as the most central and influential author in the field of coral restoration, with the Consortium of Research Libraries in the United Kingdom and James Cook University in Australia being the most prominent organizations, as shown in Figure 3. Specifically, P. J. Mumby from the University of Queensland, Australia, leads with a total of 103 publications. He is followed by T. McClanahan, N. A. J. Graham, and K.-F. Yu from the United States, the United Kingdom, and China, respectively. Regarding institutional involvement, there are 7229 entities worldwide contributing to coral restoration research. Among these, institutions from Australia, the United States, France, and China are the most prolific, with James Cook University at the forefront, boasting 867 publications. This analysis underscores the significant global effort and the key contributors to the ongoing study and preservation of coral ecosystems.

Scientometric Analysis Results

Keyword Analysis and Distribution

The top 10 highly cited keywords in knowledge about coral restoration are "Great Barrier Reef" ($n = 1208$), "climate change" ($n = 1065$), "coral reefs" ($n = 1050$), "growth" ($n = 947$), "community" ($n = 904$), "patterns" ($n = 890$), "recovery" ($n = 863$), "diversity" ($n = 846$), "reefs" ($n = 695$), and "management" ($n = 667$). These keywords form the core of the discourse around coral restoration, emphasizing the

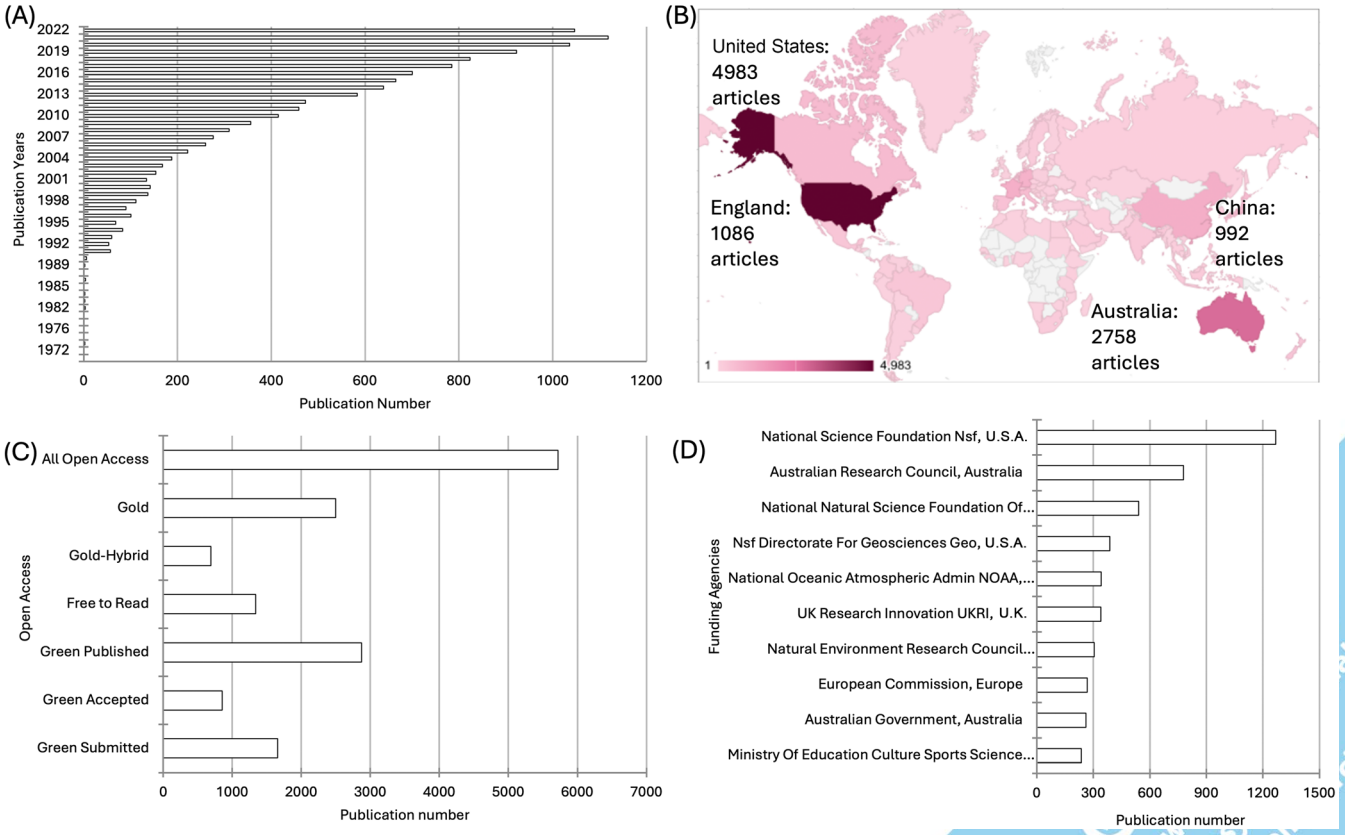


Figure 2. Publication output in term of (A) publication years, (B) countries, (C) open access, and (D) funding agencies for the coral restoration from 1975 until 2022 based on Web of Science Core Collection database.

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Table 1. Top 10 authors and affiliations in the area of coral restoration based on the descriptive data from Web of Science Core Collection.

Top 10 authors			*Top 10 affiliations*	
Authors name	*Current affiliations (2023)*	*Number of publications*	*Affiliations, country*	*Number of publications*
Peter J. Mumby	University of Queensland (Australia)	103	James Cook University, Australia	867
Tim McClanahan	Wildlife Conservation Society (U.S.A.)	87	University of California System, U.S.A.	649
Nicholas A. J. Graham	Lancaster University (U.K.)	76	Centre National De La Recherche Scientifique (CNRS), France	613
Yu, Ke-Fu	Guangxi University (China)	75	Australian Institute of Marine Science, Australia	577
Jian-xin Zhao	The University of Queensland (Australia)	70	Udice French Research Universities, France	574
Bette L. Willis	James Cook University (Australia)	65	University of Queensland, Australia	569
David G. Bourne	Australian Institute of Marine Science (Australia) James Cook University (Australia)	64	State University System of Florida, U.S.A.	529
Morgan S. Pratchett	James Cook University (Australia)	63	National Oceanic Atmospheric Administration (NOAA), U.S.A.	459
Hoegh-Guldberg Ove	University of Queensland (Australia)	59	University of Hawaii System, United States	402
Madeleine J. H. Van Oppen	Australian Institute of Marine Science (Australia) University of Melbourne (Australia)	59	Chinese Academy of Sciences, China	343

geographic, ecological, and management dimensions of the field (Table 2).

Further analysis of keyword frequencies, shown in Figure 4A, reveals a diverse array of 1034 keyword variations, indicating a broad scope of research focus areas. The centrality scores of keywords such as "corals" (score: 0.07), "model" (score: 0.05), "Atlantic" (score: 0.05), "growth" (score: 0.04), "pattern" (score: 0.04), "temperature" (score: 0.04), "assemblages" (score: 0.04), "reconstruction" (score: 0.04), "algae" (score: 0.04), and "survivorship" (score: 0.04) underscore their pivotal roles in shaping the research landscape by linking multiple studies and themes.

The study of keyword burstiness highlights newer, rapidly emerging topics such as "structural complexity," "coral restoration," "thermal stress," "adaptation," and "susceptibility." These represent shifts in research priorities possibly due to recent environmental changes and technological advancements in the field. Additionally, the strength analysis of keywords over the past two decades identifies enduring themes with significant impact, such as "coralline hydroxyapatite" (score: 29.32) and "red sea" (score: 25.53). These keywords denote sustained research interests and are indicative of areas that have accumulated substantial scientific backing.

Cluster Analysis of References

Reference Co-Citation Cluster Analysis

This cluster analysis on coral restoration revealed 10 distinct clusters, each characterizing unique research themes and trajectories (Table 3; Fig. 4B). Here, we provide a detailed description of each cluster and their prominent research directions.

(a) Cluster #0: coral reef—this cluster pertains primarily to research around coral reef ecosystems. The prevalence of the label "coral reef" across all three labeling metrics emphasizes the significance of this ecosystem in the corpus. The mean publication year is 2014, which suggests that this is a relatively established but still ongoing research field.

(b) Cluster #1: phase shift—this cluster investigates the transformation from coral to algae-dominated systems. It represents a critical area of study, given the growing concern over ecosystem shifts due to environmental pressures (McManus & Polsenberg 2004; Graham et al. 2013; Crisp et al. 2022). The average publication year was 2006, indicating that this issue has been a topic of interest for a longer period of time compared to cluster #0.

(c) Cluster #2: bacterial communities—this cluster concentrates on understanding the complex dynamics between bacterial communities and coral reefs, highlighting the integral role of microbial communities in coral health (Tout et al. 2014; McDevitt-Irwin et al. 2017; Pollock et al. 2019). The average publication year is the same as that of cluster 1, underscoring a long-standing research focus on microbial interactions.

(d) Cluster #3: coral restoration—this cluster, with a focus on the Great Barrier Reef (GBR), is evidently centered on restoration efforts and strategies (Suggett et al. 2019; Moriarty et al. 2020; Becken & Curnock 2022). The average year, 2017, reflects the recent increased inventions in response to rapid reef degradation.

(e) Cluster #4: coral bleaching—concentrated on the impacts of bleaching events on coral reefs and symbiotic dinoflagellate relationships (Baird et al. 2009; Sully et al. 2019; Mumby et al. 2021), this cluster delves into the ecological and environmental causes and consequences of coral bleaching, with a relatively older average year, 1997.

(f) Cluster #5: stony coral tissue loss disease—this cluster is specifically targeted toward understanding and addressing

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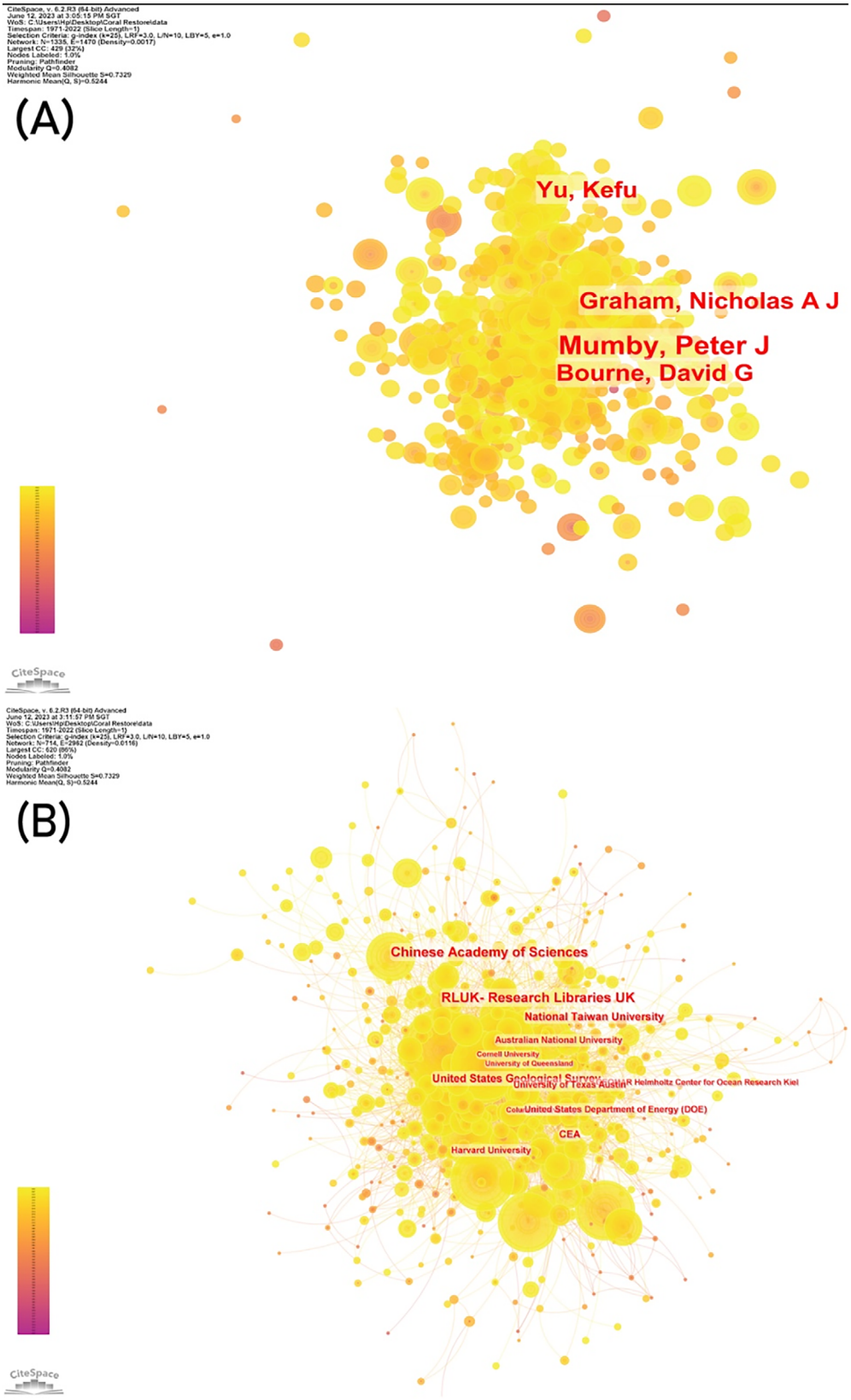


Figure 3. (A) Author and (B) affiliation analysis based the centrality score, calculated automatically through the CiteSpace software, with the red color showing the higher centrality score.

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Table 2. Top 25 keywords with the strongest citation burst, based on the CiteSpace analysis in the area of coral restoration.

Keywords	*Year*	*Strength*	*Begin*	*End*	*1975–2023*
record	1989	18	1989	2006	
growth	1991	21.21	1991	2006	
event	1991	12.13	1991	2011	
Australia	1992	12.84	1992	2007	
red sea	1993	25.61	1993	2007	
corals	1990	20.66	1993	2005	
Montastrea annularis	1993	15.34	1993	2006	
coralline hydroxyapatite	1994	28.87	1994	2007	
Porites	1995	12.23	1995	2012	
disturbance	1991	18.79	1997	2008	
reef corals	1993	16.69	1997	2007	
damage	1997	11.08	1997	2007	
zooxanthellae	1991	19.59	1998	2009	
El Niño	1990	12.45	1999	2008	
Indian ocean	2000	13.06	2000	2011	
sea surface temperature	1990	12.81	2001	2007	
regeneration	1996	12.35	2004	2010	
mass mortality	1991	12.54	2005	2010	
black band disease	1998	12.85	2009	2015	
band disease	2001	10.99	2011	2015	
structural complexity	2017	15.16	2018	2023	
coral restoration	2015	16.1	2019	2023	
thermal stress	2015	12.33	2019	2023	
adaptation	2012	12.1	2019	2023	
susceptibility	2009	11.24	2019	2021	

the recent epidemic of stony coral tissue loss disease, as signified by the average year of 2016 (Alvarez-Filip et al. 2019; Muller et al. 2020; Alvarez-Filip et al. 2022).

(g) Cluster #6: bleaching event—similar to cluster 4, this cluster concentrates on research pertaining to coral bleaching events, indicating its continued relevance and significance to the field of coral research.

(h) Cluster #7: ocean acidification—exploring the impacts of ocean acidification on coral reef's health and resilience, this cluster has emerged in response to the rising CO_2 levels in ocean waters, as suggested by the average year, 2010 (Hoegh-Guldberg et al. 2007; Pandolfi et al. 2011; Albright & Cooley 2019).

(i) Cluster #8: El Niño—this cluster explores the relationship between El Niño events and coral health, focusing on coral-based reconstructions to understand past climatic events, as suggested by the relatively older average year of 1993 (Gomez et al. 2014; Claar et al. 2020; Hein et al. 2020).

(j) Cluster #9: oyster reef—this cluster indicates a branching out of research interests beyond coral reefs and their associated challenges, as suggested by the average year, 2013 (Reeves et al. 2020; Howie & Bishop 2021; Richardson et al. 2022).

Keywords Co-Citation Cluster Analysis

Additionally, this study uncovered eight primary keywords co-citation clusters (Fig. 4C) within coral restoration research based on the 12,667 total publications searched, each offering unique insights. The major descriptors and notable findings are given below:

(a) Cluster #0: coral reef (size: 191, silhouette: 0.797, major descriptors: "Great Barrier Reef," "climate change," "coral reefs")—this cluster focuses on the coral reef ecosystems, particularly the GBR, and the impact of climate change on these ecosystems.

(b) Cluster #1: coral reef/end-Permian mass extinction (size: 166, silhouette: 0.668, major descriptors: "Evolution," "model," "coral-reefs")—this cluster investigates the relationship between coral reefs and the end-Permian mass extinction event, with a focus on the evolution of coral reefs.

(c) Cluster #2: bacterial communities (size: 160, silhouette: 0.767, major descriptors: "diversity," "climate change," "ecology")—this cluster explores the role of bacterial communities in coral reefs, particularly in the context of climate change and ecological diversity.

(d) Cluster #3: Ca ratio (size: 144, silhouette: 0.813, major descriptors: "Temperature," "scleractinian corals," "variability")—this cluster examines the Ca ratio in scleractinian corals, and how temperature and variability factors affect it.

(e) Cluster #4: coral reef/coral recruitment (size: 143, silhouette: 0.61, major descriptors: "growth," "reef," "restoration")—This cluster focuses on coral recruitment, a critical process for the growth and restoration of coral reefs.

(f) Cluster #5: oyster reef (size: 139, silhouette: 0.631, major descriptors: "Reefs," "*Crassostrea virginica*," "ecosystem services")—this cluster investigates oyster reefs, specifically

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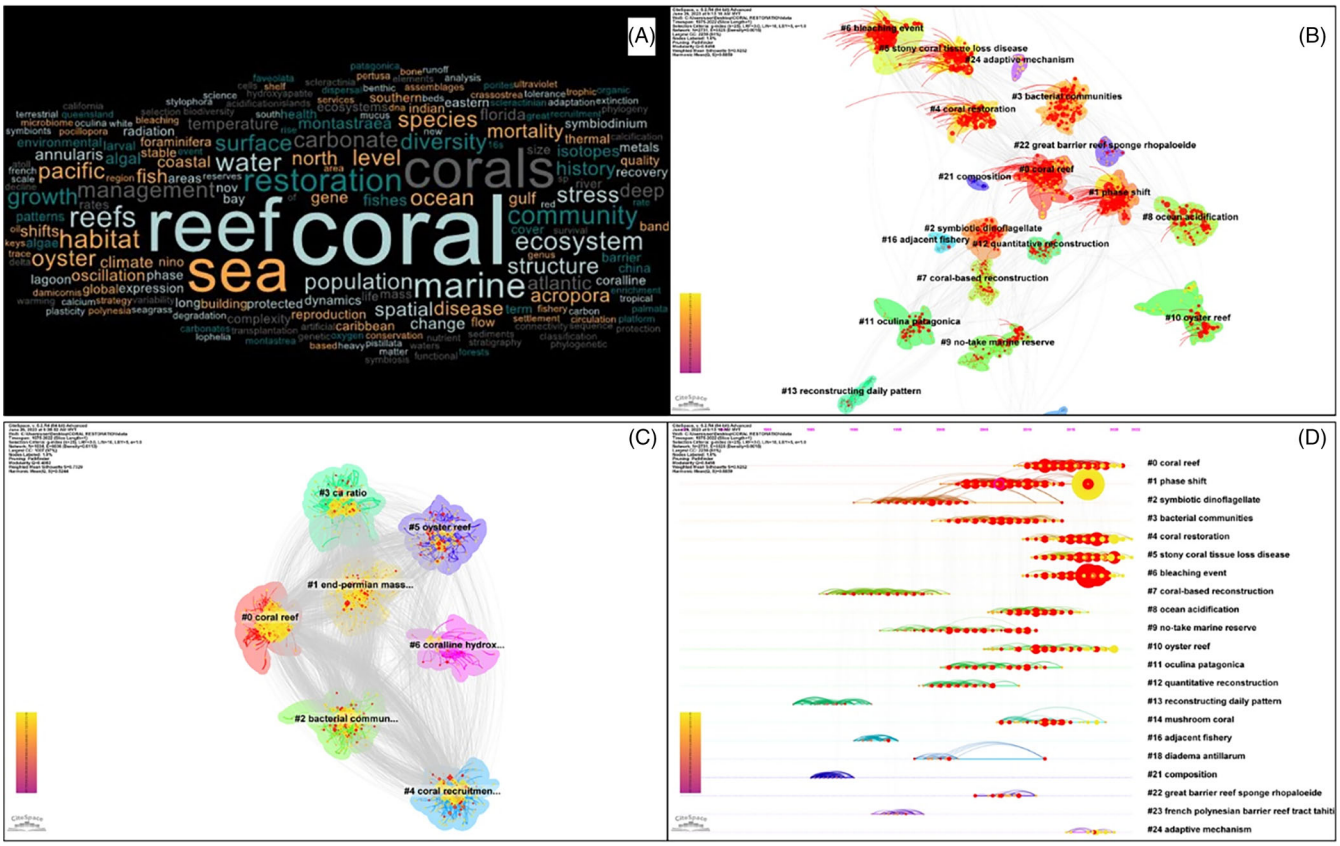


Figure 4. Keywords distribution appeared in the publications related to the coral restoration, (A) based on the Web of Science Core Collection platform, (B) cluster analysis of cited references for coral restoration, (C) cluster analysis of the keywords in the knowledge about coral restoration, based on the CiteSpace analysis, and (D) timeline view of co-citation in cluster analysis about coral restoration.

the species *C. virginica*, and their role in providing ecosystem services.

(g) Cluster #6: coralline hydroxyapatite (size: 55, silhouette: 0.928, major descriptors: "Coral," "reconstruction," "regeneration")—this cluster delves into the topic of coralline hydroxyapatite, a material used in the reconstruction and regeneration of corals.

(h) Cluster #7: delayed recovery and the spacing of major extinctions (size: 9, silhouette: 1, major descriptors: "Early Oligocene," "periodicity," "mass extinctions")—this small but distinct cluster examines the concept of delayed recovery following major extinction events, with a focus on the Early Oligocene period.

Timeline Co-citation Cluster Analysis

From the year 2020 onwards, there has been a significant surge in research activities in several key domains, such as cluster #0 (coral

Table 3. Cluster analysis of coral reef restoration references utilizing LSI (Latent Semantic Indexing), LLR (Log-Likelihood Ratio), and MI (Mutual Information) algorithms.

Cluster ID	*Size*	*Silhouette*	*Label (LSI)*	*Label (LLR)*	*Label (MI)*	*Average Year*
0	295	0.901	coral reef	coral reef	oceania	2014
1	271	0.919	coral reef	phase shift	oceania	2006
2	198	0.904	bacterial communities	bacterial communities	oceania	2006
3	176	0.938	Great Barrier Reef	coral restoration	oceania	2017
4	175	0.882	coral bleaching	symbiotic dinoflagellate	oceania	1997
5	166	0.936	stony coral tissue loss disease	stony coral tissue loss disease	oceania	2016
6	149	0.918	coral reef	bleaching event	oceania	2016
7	137	0.904	ocean acidification	ocean acidification	oceania	2010
8	137	0.944	El Niño	coral-based reconstruction	coral reef	1993
9	82	0.975	oyster reef	oyster reef	oceania	2013

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reef), cluster #4 (coral restoration), cluster #5 (stony coral tissue loss disease) and cluster #6 (bleaching event), indicative of a heightened scholarly focus on these areas, as shown in Figure 4D.

References Burstiness

The emerging of co-cited references in coral reefs restoration has been indicated in Table 4, in which Hughes et al. (2017) is the most referred co-citation with the highest strength value discussed about the issues on coral restoration. The study highlights the critical situation of global warming and the recurrent mass bleaching events affecting corals, particularly during the period of 2015–2016. Intriguingly, 2 years subsequent to this, Hughes et al. (2019)—albeit with a different research team—emerged as one of the most frequently co-cited references within the realm of coral restoration. This later study elucidates how global warming compromises the stock-recruitment dynamics of corals globally, underscoring the interconnectedness of climate change impacts and reef ecosystems' health.

Discussion

Authors and Affiliations

The examination of 15,765 publications, refined to 12,667 after screening and further distilled to 12,590 for CiteSpace analysis, underscores the varied landscape of coral reef research. Current research literature on coral restoration shows the trend of an increase in the number of publications from 1975 through 2022, with an expected increase every year. The remarkable number of authors and institutions participating in this restoration effort shows the global attention it is receiving. Our scientometric and descriptive analysis highlighted James Cook University in Australia as a leading institution in this domain, while the National Science Foundation from the United States is highlighted as a significant funding agency. The analysis also points to the Atlantic Ocean as a key focus area for coral reef restoration, with the GBR identified as a critical site for restoration efforts (Kuffner & Toth 2016; Suggett et al. 2019; Cook et al. 2022).

The GBR in Australia is the region where 70% of the top 10 authors originate. The majority of leading researchers and affiliations in the field are primarily engaged in understanding how climate-induced variations in water temperature critically impact coral reef recovery and reconstruction efforts (Baker et al. 2008; Gurney et al. 2013; Souter et al. 2021). This has necessitated the development of coral restoration models that are pivotal for enhancing coral growth and survival, thus improving management practices in response to climate change (Quigley et al. 2019; Neil et al. 2021; McLeod et al. 2022). Additionally, there is a significant emphasis on investigating the thermal adaptation of coral reefs to better gage their resilience against changing climates (Rowan 2004; Graham et al. 2013; Drury 2020). Complementing these studies, recent research also spans areas including coral microbiomes, interactions among reef organisms, and the dynamics of these ecosystems. These studies are instrumental in refining coral restoration methods and models to assess the effectiveness of various mitigation measures (Quigley et al. 2019; Marchioro et al. 2020; Maire & van Oppen 2021; Neil et al. 2021; McLeod et al. 2022; Scharfenstein et al. 2022),

Table 4. Emerging of co-cited references in coral restoration.

References	*Year*	*Strength*	*Begin*	*End*	*1975–2023*
Hoegh-Guldberg (1999)	1999	39.34	2000	2004	
Hughes et al. (2003)	2003	55.34	2004	2008	
Gardner et al. (2003)	2003	32.78	2004	2008	
Bellwood et al. (2004)	2004	50.35	2005	2009	
Pandolfi et al. (2003)	2003	33.54	2005	2008	
Corals	2006	36.42	2006	2011	
Montastrea annularis	2007	83.13	2008	2012	
Mumby et al. (2006)	2007	37.64	2008	2012	
Hoegh-Guldberg et al. (2007)	2007	33.86	2008	2012	
Bruno and Selig (2007)	2008	34.45	2010	2013	
Bruno et al. (2007)	2010	48.16	2011	2015	
Baker et al. (2008)	2011	40.38	2012	2016	
Hughes et al. (2010)	2011	35.56	2012	2016	
Beck et al. (2011)	2012	78.79	2013	2017	
Pandolfi et al. (2011)	2013	43.83	2014	2018	
De'Ath et al. (2012)	2015	52.39	2016	2020	
Gilmour et al. (2013)	2015	33.64	2016	2020	
Graham et al. (2015)	2015	32.81	2017	2020	
Bates et al. (2015)	2017	91.7	2018	2023	
van Oppen et al. (2014)	2017	58.22	2018	2023	
Hughes et al. (2017)	2018	81.98	2019	2023	
Hughes et al. (2017)	2018	70.39	2019	2023	
Hughes et al. (2018)	2018	46.47	2019	2023	
Hughes et al. (2018)	2019	35.18	2020	2023	
LaJeunesse et al. (2018)	2017	32.83	2021	2023	

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thereby integrating ecological, biological, and management perspectives to address the multifaceted challenges posed by climate change to coral ecosystems.

Countries and Open Access

The Florida coral reef in the United States and the GBR in Australia are among the top two coral reef areas of great interest (Wynveen et al. 2013; Suggett et al. 2019; Moriarty et al. 2020; Becken & Curnock 2022). The foundational efforts in coral restoration have been significantly documented by the Coral Restoration Foundation, which operates both as an exploration and education hub in Florida, United States. Australia figures as one of the main countries where reef restoration efforts that are published happen. As the sole country with the authority to manage this unique geographical feature through the authorities governed by the Great Barrier Reef Marine Park legislation, it bears the responsibility of restoring the GBR ecosystem, which has endured multiple bleaching events over the past few decades (Day 2017; Stuart-Smith et al. 2018; Becken & Curnock 2022). Countless restoration projects have been done to bring the GBR back to its healthy condition, involving lots of researchers and yielding tons of scientific publications in the attempt to do so (Dight & Scherl 1997; Ban et al. 2011; Comte & Pendleton 2018). Additional coral restoration efforts in other parts of the world also occurred continuously to cope this degradation issue, including the Indo-Pacific and the Atlantic region where coral coverage has sharply declined over the past half-century (Hughes et al. 2013; Suggett & van Oppen 2022; González-Barrios et al. 2023).

Additionally, the accessibility of research findings plays a crucial role in conservation and restoration efforts. In this context, open access articles have emerged as a critical component for disseminating information widely, thus facilitating broader engagement and application in coral restoration endeavors (Fonseca & Benson 2003; Gaikwad & Chavan 2006; Turner et al. 2015). Previous studies also showed that recent advances in coral restoration can be made through genetic cryopreservation, and enable the fertilized coral to be preserved using gold nanorods (Daly et al. 2018; Hagedorn et al. 2019; Narida et al. 2023). Such information is at the technical level, and further sharing of the information and vital techniques are required to advance the conservation-related activities. Additionally, open access information is important for future coral restoration, and thus freely available literature's options should be increased compared to the current status of half of the literature being made available in WOSCC.

Clusters and Timeline

The reference co-citation clusters emphasize the connectivity and co-occurrence of cited references, providing a broader understanding of the overarching themes in coral restoration research. For instance, cluster #0 in both analyses focuses on coral reefs, highlighting the importance of these ecosystems in the research corpus. Similarly, cluster #1 in the reference co-citation focuses on phase shifts in coral reefs, which parallels the keyword co-citation cluster #1 that investigates the relationship between coral reefs and the end-Permian mass extinction event (Brayard et al. 2011; Chen & Benton 2012; Martindale et al. 2019).

On the other hand, the keyword co-citation clusters provide more specific and nuanced insights, highlighting emerging trends and underexplored domains in the field. For example, keyword cluster #2 explores the role of bacterial communities in coral reefs, particularly in the context of climate change and ecological diversity (McDevitt-Irwin et al. 2017; Pollock et al. 2019; Maire & van Oppen 2021). This offers a more granular insight into the complex dynamics between bacterial communities and coral reefs, which is not explicitly highlighted in the reference co-citation analysis. Similarly, keyword cluster #3 examines the Ca ratio in scleractinian corals and how temperature and variability factors affect it (Pretet et al. 2014; Bell et al. 2017). This specific focus is not mirrored in the reference co-citation clusters, demonstrating how the keyword co-citation analysis can reveal more specific research directions.

By concurrently analyzing both co-citation and keyword clustering results, we can identify broader research areas and their specific focal points. This dual analysis approach also helps us pinpoint common themes, divergences, and underexplored areas in coral restoration research, thus providing a thorough understanding of the historical development, current state, and potential future directions of this field. Such a comparative analysis significantly enhances the robustness of bibliometric studies, offering a more detailed and nuanced understanding of the field. However, global reviews reveal that many projects are short-term and small-scale, often lacking clear objectives and consistent monitoring, necessitating better coordination and standardization (Boström-Einarsson et al. 2020). Effective coral restoration must integrate innovative methods with broader climate change mitigation efforts to ensure long-term success and resilience (Boström-Einarsson et al. 2020; McLeod et al. 2022).

The timeline co-citation analysis, provides a valuable tool for understanding the evolving research landscape and for identifying emerging trends and research priorities in the field of coral restoration (Chen et al. 2022). Particularly noteworthy from 2020 onwards is the marked increase in research endeavors across several critical areas. Our results highlight a pronounced increase in articles, as evidenced by the thematic convergence of clusters #0 "coral reef" and #4 "coral restoration."

Clusters #0 and #4, labeled as "coral reef" and "coral restoration," respectively, share a common thematic focus on coral reef ecosystems and their preservation. The amalgamation of these clusters offers a more holistic perspective of the research terrain in this domain. This spike in citations is indicative of an amplified scholarly focus on deciphering the intricate dynamics of coral reef ecosystems, especially in the context of escalating environmental stressors, and on formulating and executing efficacious strategies for coral restoration (Schopmeyer et al. 2017; Omori 2019; Delgado & Sharp 2020). This combined focus underscores the critical necessity for proactive intervention to restore and conserve coral reef ecosystems, reflecting the pressing issues confronting these ecosystems and the urgent need for effective strategies to address these challenges (Omori 2019; Boström-Einarsson et al. 2020).

Cluster #5, named "stony coral tissue loss disease," has experienced a recent upswing in research interest. This disease has inflicted significant mortality in coral reefs, and the increased

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research activities reflect the urgency of comprehending and tackling this epidemic (Estrada-Saldívar et al. 2020; Muller et al. 2020; Walker et al. 2021).

Cluster #6, referred to as "bleaching event," has also seen a surge in research activities. Coral bleaching events, often instigated by elevated sea temperatures, pose a significant threat to coral reefs. The upsurge in research interest in this area highlights the importance of understanding these events and developing strategies to mitigate their impacts (Ainsworth et al. 2021; Mumby et al. 2021; Shaver et al. 2022).

Lastly, cluster #24, termed as "adaptive mechanism," has witnessed a surge in research interest. Understanding the adaptive mechanisms of corals and other reef organisms is crucial for predicting their responses to environmental changes and for informing conservation and restoration efforts (Baums et al. 2019; Rinkevich 2019, 2021).

Based on the keyword burstiness, the study suggested that in the previous 3 years, most of the research on coral restoration has focused on the ability of coral reefs toward various problems such as climate change and disease, and most of the literature are stressing about coral's adaptation and its susceptibility toward disease (Hoegh-Guldberg et al. 2019; McClanahan et al. 2023; Mohamed et al. 2023). The overall analysis of these clusters underscores the multifaceted nature of coral restoration, encompassing diverse themes such as coral reef related projects (coral reef, phase shift, coral restoration, coral bleaching, and bleaching event), climate change elements (ocean acidification, El Niño), microbe and disease (bacterial communities, stony coral tissue loss disease), and related ecosystems (oyster reef).

Conclusion

This mapping review not only highlights the importance of understanding research trends in reef restoration and enhancing tools for new researchers but also underscores the significance of integrating historical and future environmental contexts into planning. Such integration significantly reduces restoration risks and enhances the sustainability of these efforts, ensuring a comprehensive approach to reef restoration (Burdett et al. 2024). Ecological restoration encompasses more than just species growth; it involves a holistic approach to reach an ecosystem recovery and sustainability. In this study, the utilization of scientometric methodology provides a comprehensive overview of the reef restoration's landscape, identifying key contributors, institutions, and thematic areas. This approach aids not only in understanding the current state of coral restoration research but also in pinpointing gaps and opportunities for future work.

Acknowledgement

This work was funded by Malaysian Ministry of Higher Learning for the Higher Education Center of Excellence (HICoE) grant (Vot No: 56061) (grant number: 56061).

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Coordinating Editor: Jose de Jesus Adolfo Tortolero-Langarica

Received: 6 November, 2023; First decision: 29 February, 2024; Revised: 17 June, 2024; Accepted: 18 June, 2024

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