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The evolution of coral reef monitoring in eastern Arabia: trends, gaps, and opportunities for the ROPME Sea Area

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Coral reefs are the most biodiverse ecosystem in eastern Arabia, which includes the Arabian Gulf, Gulf of Oman, and Western Arabian Gulf, an area collectively known as the ROPME Sea Area under UN convention. However, regional reefs are under growing threat from global climate change to local population-related pressures. This systematic review provides the first region-wide assessment of coral reef monitoring efforts, identifying 105 publications spanning almost four decades. Findings highlight a variety of research motivators, a diverse and evolving range of methods, and the inclusion of both citizen science and governmental projects alongside conventional scientific research. However, large disparities in monitoring efforts are evident between the countries as well as a concerning lack of international collaboration despite the transboundary nature of many regional coral reef stressors. The prevalence of short-term 'snapshot' studies and one-off authors also indicate the absence of a strong, continuous local research presence, undermining long-term conservation efforts. Most concerning is the recent decline in the volume of monitoring-related studies, both within scientific institutions and across multi-party projects, with research instead diverted to more novel areas of coral reef research. Given the ongoing regional reef decline, it is essential that monitoring efforts continue to grow, incorporating large-scale, long-term studies in order to accurately assess reef status and trends and assist in conservation.

KEYWORDS

systematic review, citizen science, time series, conservation, management

1 Introduction

The ROPME Sea Area in eastern Arabia is comprised of three water bodies including the Persian/Arabian Gulf (hereafter referred to as 'the Gulf'), the Gulf of Oman, and the southern coast of Oman in the western Arabian Sea. The ROPME Sea Area was designated under UNEP in 1979 to coordinate the actions of eight member states to protect shared regional coastal and marine ecosystems (ROPME: Regional Organization for the Protection

of the Marine Environment), with ROPME comprised of the eight bordering nations: Bahrain, Iran, Iraq, Kuwait, Oman, Qatar, Saudi Arabia, and the United Arab Emirates (Burt et al., 2021). Coral communities occur in each of the regional nations and serve as the most biodiverse ecosystem in this arid region, providing productive habitats that support a fishing industry second only to oil as an economic regional resource sector (Vaughan et al., 2019; van Lavieren et al., 2011). Due to the unusually extreme environmental conditions of this region – where the southern Gulf of Oman portions are affected by intense monsoonal cold-water upwelling while the northern portions of the Gulf experience the hottest sea temperatures on earth each summer – regional coral communities are relatively depauperate compared with the wider Indo-Pacific (Coles, 2003; Sheppard, 2003). However, coral can be extremely dense and extensive even in areas characterized by extreme conditions (Sheppard, 1987; Shinn, 1976; Salm, 1993), and regional coral communities have become a focus for research on acclimatory and adaptive responses of reef fauna to the extreme temperature, given that such conditions are expected to affect reefs elsewhere across the tropics in the coming century under climate change (Burt et al., 2020; Al-Gergawi et al., 2024).

Coral reef communities of the ROPME Sea Area are unique in their abilities to withstand extreme environmental conditions, which vary across the region (Coles, 2003; Rezai et al., 2004). Most notable is the extreme temperature regime that occurs in the Gulf, with the highest sea temperature maxima in the world (≥37°C) and an annual fluctuation of up to 25°C (Coles and Fadlallah, 1991). In addition, reef organisms there are adapted to withstand highly saline waters, exceeding 50ppt in some southern Gulf embayments (John et al., 1990). As a result of these conditions, the Gulf has been deemed a 'natural laboratory' for studying the impact of elevated sea temperatures and other extremes on reef habitats (Vaughan and Burt, 2016). Elsewhere in the region, the reefs of southern Oman in the outer ROPME Sea Area are characterized by a pseudo-high-latitude effect, where summer monsoon upwelling results in unusually cool nutrient-enriched reefs (Claereboudt, 2019). The scientific community therefore has a vested interest in monitoring and preserving these important and unusual regional reefs.

The conservation of ROPME Sea Area reefs is also incentivised by their economic value. Globally, coral reefs are valued for their provision of a variety of goods and services including coastal protection, recreational value, and fisheries products (Spurgeon, 1992). In the ROPME Sea Area, the fishing and tourism industries are the most important reef-related economic sectors (Vaughan et al., 2019). Acting as important feeding, breeding, and nursery grounds, regional coral reefs also make important contributions to local food security and artisanal fisheries (Sheppard et al., 2010; van Lavieren et al., 2011). In the Gulf alone, the fisheries industry is worth >US$500 million annually, second only to oil as a resource sector (Burt et al., 2014; van Lavieren et al., 2011). The tourism industry is also highly valuable, attracting visitors to the region for reef-based activities such as snorkeling and diving and, in turn, supporting economic growth through indirect tourism expenditure on items such as on accommodation and food (Shokri and Mohammadi, 2021; Spurgeon, 1992). The level of regional tourism interest is directly linked to a reef's level of biodiversity, with healthier reefs attracting more visitors (Al Ismaili et al., 2024a). The reliance of ROPME Sea Area economics on local coral reefs is another motivation to ensure sufficient monitoring and conservation efforts.

The pressing need for enhanced reef management and conservation efforts has become more apparent in recent decades as dramatic degradation of coral reefs has been reported across the region (Burt et al., 2013; Burt, 2024; Sheppard et al., 2010). Climate change presents a severe threat to reefs, with specific drivers of decline including increasing storm/cyclone activity in Oman and eastern UAE (Lincoln et al., 2021) as well as recurrent marine heat waves, particularly in the Arabian Gulf but increasingly region-wide (Burt, 2024; ROPME, 2021). Analyses of past monitoring records have shown that live coral cover has declined by 40% between 1995 and 2019, primarily from heat-induced bleaching events, particularly in the past decade (Burt et al., 2019, 2021). Alongside global climate change threats, the ROPME Sea Area has experienced substantial coastal development in recent years as a corollary of rapid population growth (van Lavieren et al., 2011). Between 1995 and 2021 the population across the Gulf Cooperation Council (GCC) countries almost doubled reaching over 50 million (Al Flaiti, 2023). Additionally, Bahrain, Kuwait, Qatar, and the UAE, each have populations disproportionally concentrated on coasts, adding to the pressure on coastal marine ecosystems (van Lavieren et al., 2011). Associated threats to coral reef communities include marine pollution (Freije, 2015), unsustainable fishing pressure (Buchanan et al., 2019), and growing development that degrades coastal reef habitats (Burt, 2014). The repercussions on reef structure and community composition are evident, with region-wide increases in algal cover (Burt et al., 2019, 2021), declines in coral and reef-associated community biodiversity (Burt and Bauman, 2020; Bargahi et al., 2020), and a shift to *Porites* dominated reefs, away from the historical *Acropora* frameworks (Burt et al., 2019; Riegl et al., 2018). Both the increasing pressure and current condition of reefs underscore the need for enhanced monitoring in the ROPME Sea Area, continuously assessing status and trajectories of change in order to develop effective management and conservation interventions.

Earlier literature reviews have described spatio-temporal patterns of reef-related science in parts of the Arabian region (Burt, 2013; Vaughan and Burt, 2016). But, to date, none have investigated the larger ROPME Sea Area, despite this being the politically established area for marine management in eastern Arabia. In addition, none have specifically examined the topic of reef monitoring, despite its importance in informing policy and management decision-making. This gap is important, as recent assessments have suggested that regional monitoring efforts are fragmented and inconsistent, hampering the region-wide understanding necessary for broader management intervention (Burt et al., 2021).

The current study aims to address this knowledge gap by compiling a comprehensive inventory of all historic coral reef monitoring efforts across the entire ROPME Sea Area, with the goal of understanding the growing strengths in this sector, and to identify gaps to be addressed in developing a region-wide understanding of reef health. To this end, the geographic scope, the leading authors and publishing outlets, variety of methodologies, and the study aims driving these monitoring efforts will be mapped. In addition, this review will identify the efforts of government organizations and citizen science programs as well as scientific researchers, assessing their contribution to regional reef monitoring. Through this study, the historic growth of coral reef monitoring will be explored, the key drivers of this work revealed, and any geographic or topical areas of underrepresentation highlighted. The results of this study will help target future monitoring efforts to better inform management and conservation of these unique regional reefs.

2 Methods

2.1 Literature search

To assess regional coral reef monitoring efforts, a systematic literature review was conducted that identified monitoring related publication in each of the ROPME Sea Area nations, and those that were pan-regional/multinational. A database search was conducted using the PRISMA methodology (Preferred Reporting Items for Systematic Reviews) which includes four stages: identification, screening, eligibility, and inclusion (Moher et al., 2015). English-language peer-reviewed journal articles, book chapters, and conference proceedings reporting coral reef monitoring efforts in the ROPME Sea area were sought on Web of Science, Scopus, and Google Scholar search engines. The literature searches were conducted on 23/01/2024 and included all sources published prior to 31/12/2023. The search syntax remained consistent across the three search engines, employing a broad set of Boolean Operators including all eight countries in the ROPME Sea area, the various names of marine provinces (e.g. Persian Gulf, Arabian Gulf, etc.), and a range of reef monitoring terms (see Supplementary Materials, section 1).

Prior to conducting the search, the research scope was defined using pre-specified criteria. In total, seven critical criteria were utilized, which were used to both create the search syntax as well as the inclusion/exclusion criterion used within the PRISMA process. Selection criteria required studies to be:

1. Within the geographic extent of the ROPME Sea Area.
2. On natural coral reef ecosystems; studies focused on artificial reefs were excluded.
3. Only survey-based studies. Invasive studies such as those using extractive sampling or manipulative experimental studies interfering with natural conditions were excluded.
4. Included only benthic and fish surveys; megafauna studies were excluded as these species are not as closely associated with reef environments.
5. Focused on and included primary data collection; review studies were excluded.
6. Based on quantitative data; purely qualitative/descriptive studies were excluded.
7. Written in English, as this is the dominant language for scientific reporting worldwide (Montgomery, 2009).

2.2 PRISMA process

Visual representation of the process which was undertaken can be seen in Figure 1. In the first stage, publications were identified by running the search syntax in the three search engines: Web of Science, Scopus, and Google Scholar. Google Scholar was used as a supplementary search to account for grey literature, where the first 200 results were reviewed. After removing duplicated papers there were a total of 394 publications. A two-step screening process consolidated the publications, beginning with a review of the title followed by the abstract. Initial screening of titles, including publications mentioning coral reefs and/or surveys and/or an appropriate location, reduced the count to 291 publications. Studies were excluded if the location, method, or study system explicitly contradicted the review's research scope, outlined in the above selection criteria. Following this, publication abstracts were similarly screened, reducing the total publication count to 138. Post-screening, the entire article was read, and studies were excluded based on the previously defined criteria, reducing the total publication count to 83. Of the accepted publications, 48% (n=40) were identified using Scopus, 48% (n=40) were identified using Web of Science, and 39% (n=32) were found in the Google Scholar supplementary search. Furthermore, using a snowballing approach, in which all references cited within the included papers were also screened, an additional 22 sources were identified and added to make a total of 105 publications (see Supplementary Materials, section 3).

2.3 Data extraction and synthesis

Following article selection, all 105 selected publications were fully read, and data were extracted based on pre-determined guided questions (Table 1). Binary definitions of 'gender' and 'biological sex' were used in this article (i.e. male or female). An author's gender presentation was interpreted using a variety of methods including website profiles, digital images, pronoun references, and other related parameters. Although this method can contribute to investigation of gender balance in research, it is acknowledged that gender presentation is not synonymous with biological sex nor does this method account for non-binary people, potentially leading to mischaracterization of some individuals. The data for all 105 articles included in this study are provided as Supplementary Table 3. Following data extraction, all analyses took place using RStudio version 2021.09.0.351 (R Core Team, 2021).

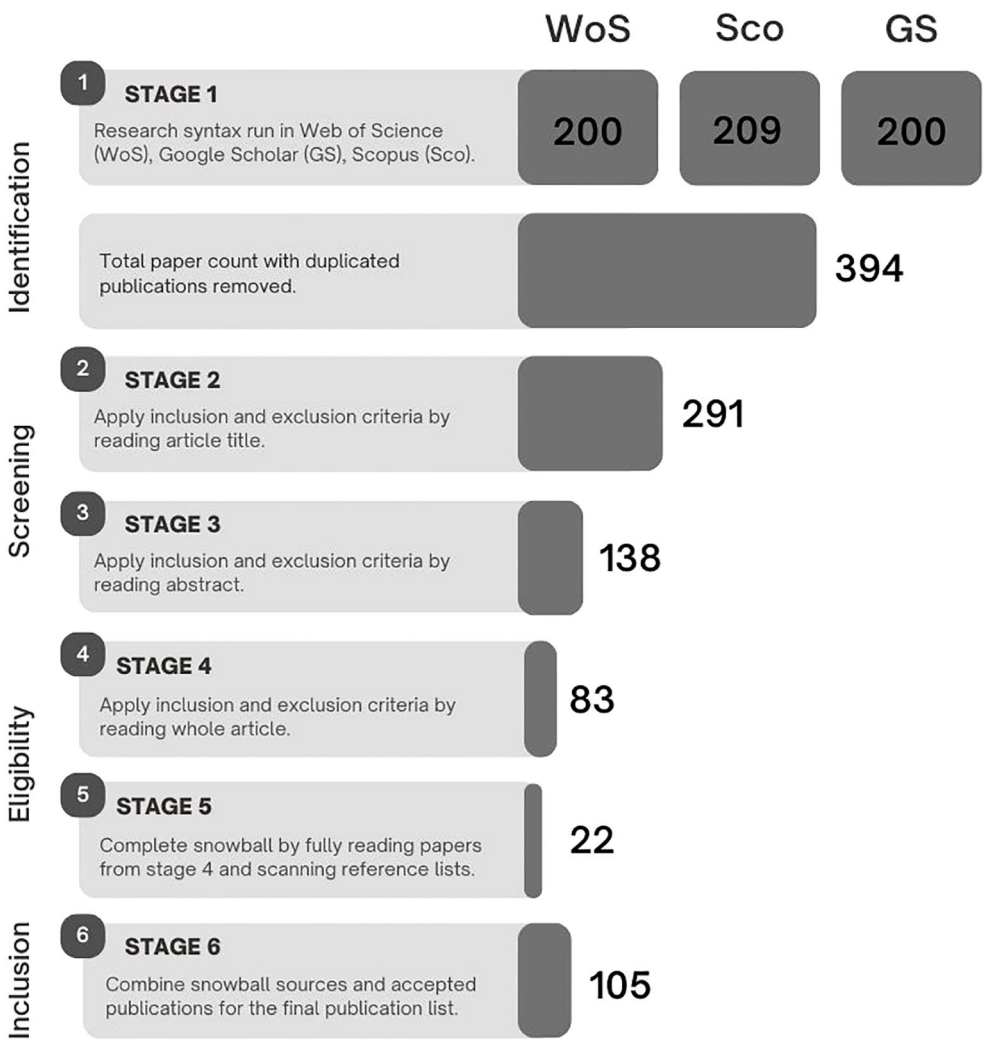

FIGURE 1
PRISMA diagram of the search process. Headings are shortened search engine names: WoS, Web of Science; GS, Google Scholar; Sco, Scopus.

2.4 Author network

The interconnected nature of authors in the review was investigated by creating a matrix of co-authorship using the Statnet package version 2019.6 (Handcock et al., 2008) in RStudio with nodes (or vertices) representing authors and the edges between them representing co-authorships.

2.5 Government and citizen science

Reporting of monitoring efforts in the Gulf is not restricted only to professional scientists and researchers, as citizen scientists and governments are also involved in reef monitoring. Citizen science, a rapidly growing field, involves individuals collecting and analyzing data who are not professionally trained, but who follow a prescribed simplified methodology to collect data (Bonney et al., 2014). For example, a common reef-related citizen science initiative used globally, including in the ROPME Sea Area, is Reef Check, a standardized protocol that allows recreational divers to collect and submit reef-related data (Hodgson, 2001; Uwate et al., 2000). Additionally, a number of government agencies have implemented reef monitoring programs to track the status of reefs within their jurisdiction [e.g. Environment Agent Abu Dhabi's coral reef monitoring programme (Al-Wasmi, 2015[1])]. Information on both groups was collected through Google searches, targeting government websites and summary documents of monitoring efforts in the region for inclusion.

3 Results

ROPME Sea Area coral reef monitoring publications spanned 40 years, from the first identified record in 1984 until the most recent full year of study, 2023. The frequency of publications has

1 Website source: https://www.thenationalnews.com/uae/environment/abu-dhabi-coral-reef-monitoring-stations-set-up-1.75506.

TABLE 1 Guided questions used to determine the data to be extracted from each source.

Guided question	Extracted data
What was the length of monitoring in this study?	Study duration.
When did the study occur – were there seasonal trends?	Period of study (year/season/month).
Where were monitoring efforts undertaken?	Site country and location.
Which organisms were monitored?	Organismal monitoring focus e.g. benthic, fishes, invertebrates.
Why was monitoring undertaken?	Additional phenomena/disturbances which motivated each study (e.g., temperature, disease, oil spill, etc.).
Who was involved in and who led monitoring efforts?	Author names, separating out first authors.
Was there a gender disparity in authorship?	Assumed gender (male or female) of authors.
What methods were used to monitor reefs?	Monitoring method eg. photo quadrat, belt transect, BRUVs.

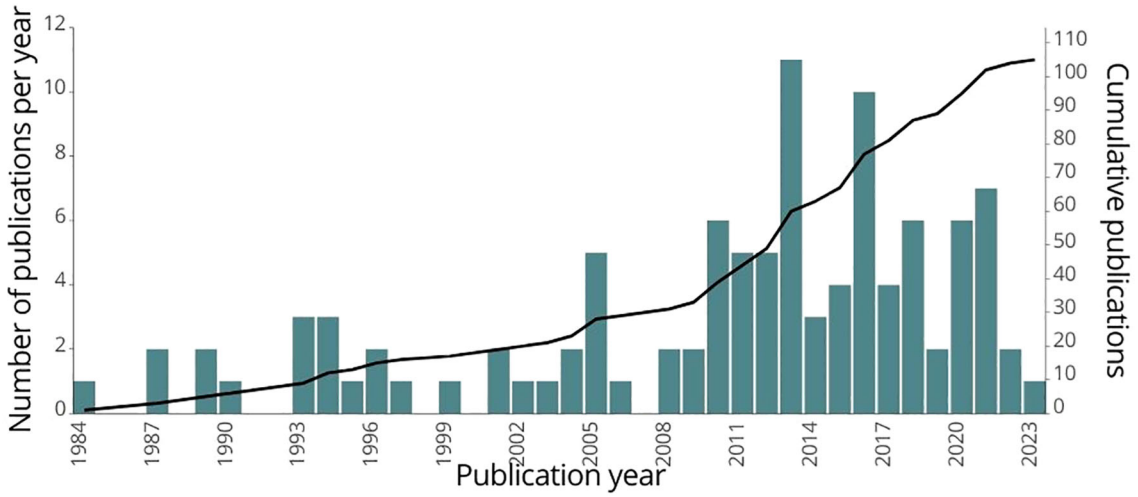

FIGURE 2
Frequency of publications monitoring coral reefs in the ROPME Sea Area by year.

increased considerably over time (Figure 2). Publications were initially sporadic in the 1980s and 1990s, with over a third of years without any monitoring-related publications, and all years never exceeding five publications. However, since 2008, there has been at least one publication related to reef monitoring in the ROPME Area each year. In particular, since the 2010s there has been a noticeable increase in the number of publications compared to previous decades. Monitoring-related studies peaked in 2013 with 11 publications followed by 2016 with 10 studies, the only two years to reach or exceed 10 publications per year. Overall, 45 of the 105 historic publications were produced in the most recent decade, between 2014 and 2023, which overall represents 42.8% of all historic reef monitoring records in the region.

3.1 Study location

The publications in this systematic review included monitoring efforts across all eight member states of the ROPME Sea Area. The largest number of studies were conducted in the UAE (n=39) followed by Iran (n=34) (Figure 3), together making up 59% of all regional reef monitoring records. The fewest publication records were identified for Iraq, Kuwait, and Bahrain, each with five or fewer reef monitoring studies published.

Overall, 90 publications involved monitoring efforts within a single country (Figure 3). However, there was some evidence of larger-scale multi-national monitoring operations with 12 studies spanning two nations, and a further three studies involving

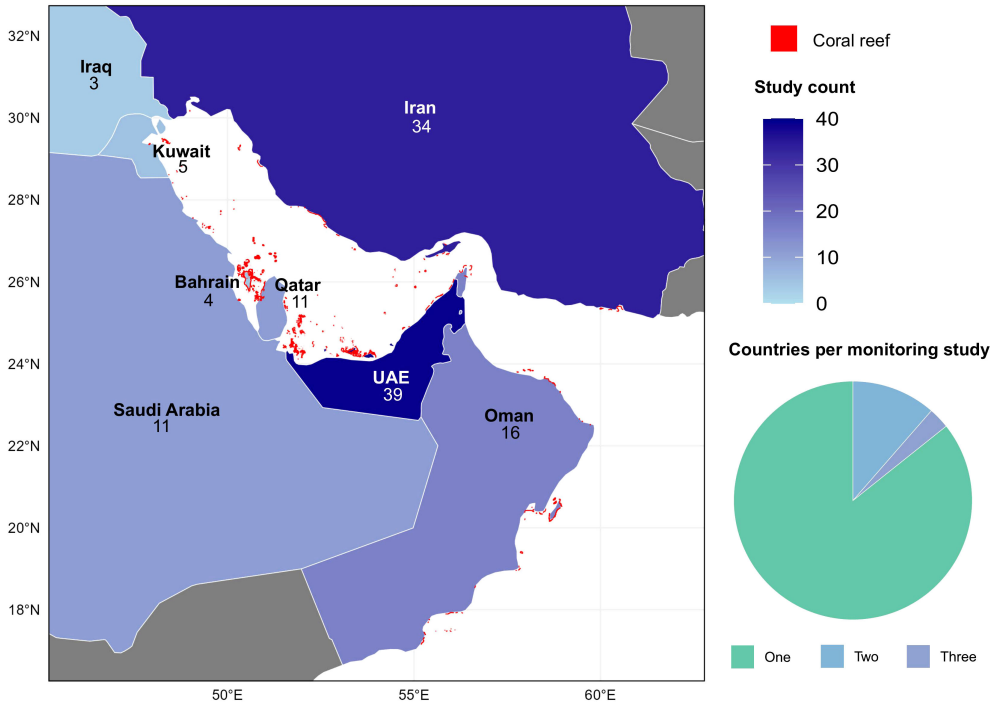

FIGURE 3
Map of the ROPME Sea Area. Coral reef extent is indicated in red, mapped using data from UNEP-WCMC et al., 2021 (www.unep-wcmc.org: updated May 2024). The surrounding eight member states are shaded according to the number of studies conducting within each country's territory. Monitoring study count in Saudi Arabia only includes work conducted in the Gulf, not the Red Sea. Labels indicate the exact study count. Studies are counted for each country, with those conducted in multiple countries considered an individual in each nation. The pie chart divides all studies by the number of countries in which monitoring was undertaken (One: 90; Two: 12; Three: 3).

monitoring across three regional nations. The UAE was included in most multinational studies, with all multinational publications including reefs the Emirates, except one. This was also common to studies including monitoring data from Oman and Qatar, where approximately half of their publications included data from other countries. In contrast, no regional-scale multinational studies involved Iraq, while Kuwait, Bahrain, and Iran data were each only included in only a single multi-national study, with remaining publications for these nations limited to data from within their borders.

3.2 Study motivation

The focus of each study was classified by the organismal groups being monitored: fishes, benthic (substrate including coral), and other invertebrates, or combinations of these (Table 1). Although 10 of the studies combined two organismal groups, the remaining 95 studies only investigated a single group; no studies investigated all three taxonomic groups. The majority of publications involved monitoring of benthic groups (85%, n=89), mainly surveys of coral communities and reef-related benthos, followed by fish-focused monitoring (21%, n=22), and only a small minority focused on invertebrates (4%, n=4).

Studies were further classified by the main aim(s) or topic(s) of focus in the study following a full reading of each publication. If no specific aim was explicitly described, the study was classified as 'monitoring'. Although publications within this review were all monitoring-focused, the majority had an additional aim or particular phenomena to investigate. These included disturbance events (e.g., oil spills), reef threats (e.g., disease), the discovery of new species or reefs, development of new survey methods or research towards new management and conservation programs. In total, 15 study foci were identified across 83 publications, in addition to broader monitoring descriptions (Figure 4). The majority focused on a single additional aim with only eight publications investigating multiple aims. The most common study focus was temperature (29 studies), which exceed even a general monitoring focus. Additionally, seven of the eight publications with multiple aims also included temperature as one of the focal areas of study. 'Method' studies, those focused on trialing and testing new methodologies, were also common in the region with 15 publications in this topic area (Figure 4).

3.3 Study methodology

Across the publications, 16 distinct quantitative methods were employed for monitoring reefs (see Supplementary Table 1 for the complete list). Out of the 16 methods, five were described as used only in a single publication. The three most common methods, each used 25 or more times included belt transects, photoquadrats, and

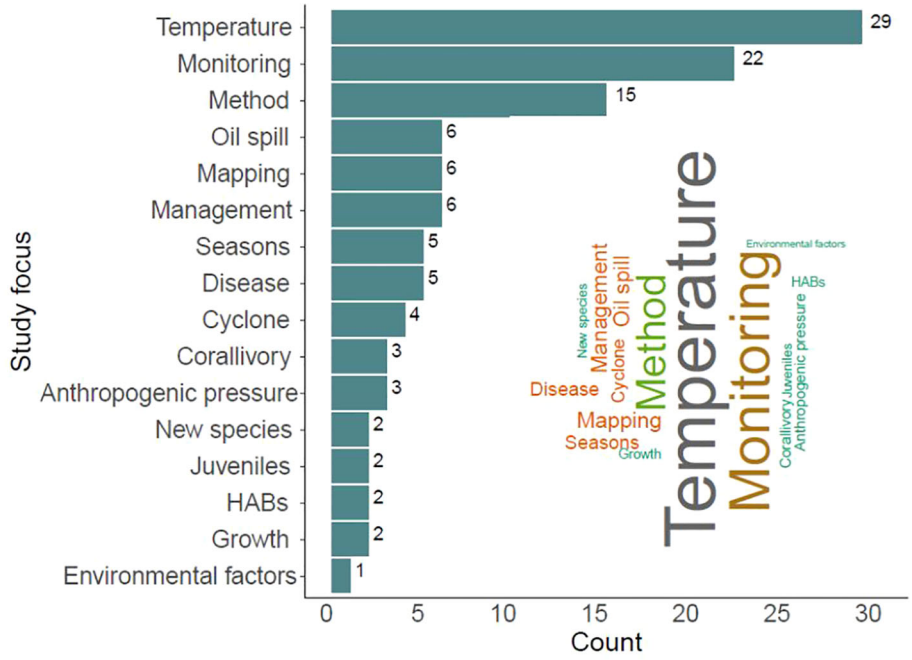

FIGURE 4
Studies were classified by a main study focus following a full reading. If no additional phenomenon was focused upon or aim evident, the study was labelled as merely 'Monitoring'. These are arranged into a bar plot and a keyword map, with word size relative to count.

line transects (Figure 5C), which together were included in 83 of the 105 publications included in this study (79% of total). Despite the majority of studies using a single method, employing a combination of techniques was relatively common with 34 studies using multiple methods (32% of total).

Study length was also considered when comparing monitoring methodology between publications. For this review, study length was calculated as the difference between the first and last year that monitoring efforts took place in a particular study; if monitoring efforts took place in a given year monitoring was considered active that year. Within the ROPME Sea Area, most studies were short in duration; although the duration of one single study reached 31 years, the median duration of a time series was just two years and the most common duration was a single year (Figure 5A). In addition, 83% (n=87) of studies were four years or less in duration, and only 6 studies (6% of total) were ten years or more in duration (Figure 5B). Study duration information was unavailable for three publications (Oladi and Shokri, 2021; Sheppard and Salm, 1988; Shojae et al., 2012).

3.4 Publication sources

The 105 publications included in this review were compiled from 68 distinct publication sources. The most frequent publication sources were scientific journal articles, with articles from 57 journals representing 84% of all publications. Additional sources included book chapters (n=4), conference and workshop proceedings (n=6), and institutional reports (n=1). Of the 68 sources, only 11 sources contained multiple reef-related publications, with the remaining 57 sources housing only a single publication each (see Supplementary Table 2 for full publication source list). The most common source was the journal *Marine Pollution Bulletin* with 17 publications, making it the only source to contain more than 10% of the total publication count (16.2%), and more than double the next most common source, the journal *Coral Reefs*, which contained eight publications (7.6% of total), which contained twice as many publications again as *Marine Environmental Research*, with four publications (3.8% of total). Many of these articles in *Coral Reefs* and *Marine Pollution Bulletin* were published as part of special issues focused on regional reefs, explaining the elevated publication count in these journals compared to other outlets. Together the top three journals made up over a quarter (28%) of the total reef monitoring publications identified in this study; all other sources contained three or fewer records.

3.5 Author network

In total, 237 individual authors contributed to the publications included in this systematic review. Among the authors, a gender disparity was apparent with only 24% (n=58) of authors being female and similarly only 24% (n=24) including female lead authors. Typically, each individual publication was attributed to four authors (median=4; mode=4) with a maximum author count of 12 (see Supplementary Figure 1). Across publications, there was a large disparity in the number of publications authored per author. Out of the 237 authors, 174 authors - approximately 75% of the

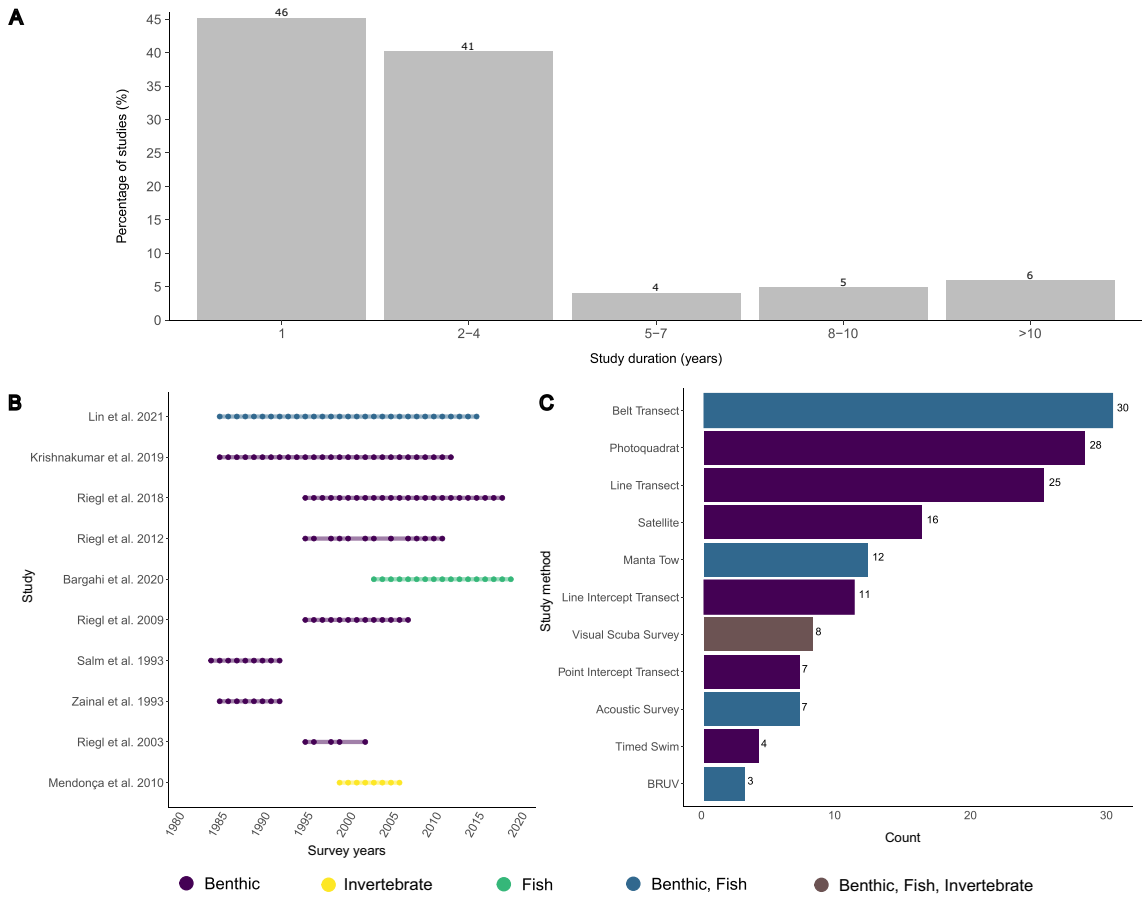

FIGURE 5
(A) The proportion of publications against monitoring effort duration (years). Duration data were unavailable for three studies (Oladi and Shokri, 2021; Sheppard and Salm, 1988; Shojae et al., 2012). **(B)** Study duration against year of study plotted for the ten longest duration studies included in this review. **(C)** Most common study methods employed across all of the publications. Only quantitative methods were included. Rare study methods (n=1) were not included in this plot. Color indicates the organism group, or groups, focused on within the study or using the method.

total - only had a single authorship credit on the publications included in this review. In contrast, the most productive author was included on 21 publications, on six of which they were first author, and seven of which they were the senior (last) author. The top five most productive authors were together lead or co-author on nearly half (46%) of all historic reef monitoring publications in the region. While there were a small number of recurrent authors who published frequently, the vast majority of authors published only a single item related to reef monitoring over the study period thus limiting the connectivity of individual authors.

To better understand the extent of interconnectedness in the author network, a matrix of co-authorship was created (Figure 6A). Overall, this reveals a sparse, fragmented network, with relatively few connections (edges) found between authors (nodes) compared to the number of possible connections. Author degree centrality, the number of co-authors each individual has across their publications in this review, ranged from 0 to 138 but, on average, remained relatively low (median=10; mode=10) (Figure 6B). The most well-connected authors, individuals in the top 5% of degree centrality, exceeded 22 co-authors across their publications and are indicated by their name labels in Figure 6A. As would be expected of the most productive author, Burt was the most well-connected author by peak degree centrality and eigenvector value (=0.491), a measure of influence of a single author on the network, followed by Bauman and Riegl (eigenvector>0.2). Despite these individuals, low network density, measuring close to 0 (gden=0.0255), highlights an overall lack of connections in the network and a research community that is not influenced by a single, central author. This is corroborated by the centralization measurements; high degree centrality indicates the presence of some well-connected authors (degree=0.27) but low betweenness suggests no sole author can be credited with holding the network together (betweenness=0.15).

3.6 Citizen and government science

3.6.1 Government-led monitoring

The UAE, Qatar, Oman, and Saudi Arabian governments have each contributed to coral reef monitoring efforts, each with multiple projects identified from the publicly available literature (Table 2). In contrast, Bahrain, Iraq, Iran, and Kuwait each had no publications identified through this review methodology indicating government-

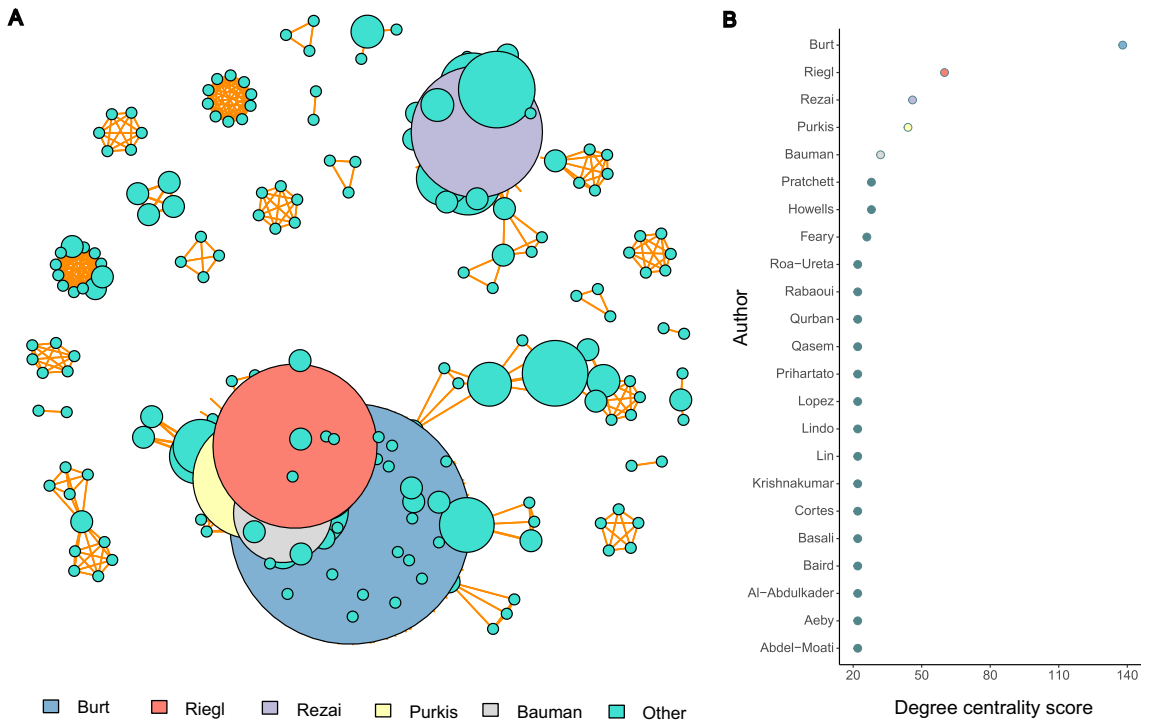

FIGURE 6
(A) Network diagram based on the list of authors on papers within the systematic review. Vertices (or nodes) represent authors and edges represent co-authorships (Nvertices = 237, Ntotal edges = 712). Vertex size indicates each author's publication count, with the five most productive authors highlighted by color. Line thickness indicates the strength of relationship, based on edge values from the adjacency matrix. **(B)** Degree centrality values for authors within the top 5% of degree centrality scores.

TABLE 2 A summary table of citizen science and governmental coral reef monitoring efforts within the eight member states of the ROPME Area.

Country	Citizen science	Government science
Bahrain	CoralWatch *(3 sites, 8 surveys, 2017-2023)* ReefCheck *(16 surveys, 1997-2020)*	No publications identified.
Iran	CoralWatch *(33 sites, 122 surveys, 2008-2022)* ReefCheck *(30 surveys, 1999-2020)*	No publications identified.
Iraq	No publications identified.	No publications identified.
Kuwait	CoralWatch *(65 surveys, 8 sites, 2009-2023)* ReefCheck *(5 surveys, 2006-2010)*	No publications identified.
Oman	CoralWatch *(1 site, 1 survey, 2010)* ReefCheck *(145 surveys, 2009-2017)*	National Coral Reef Management Plan by Ministry of Environment and Climate Affairs (Al-Jufaili et al., 1999). *Undertook surveys in 1996 to highlight major reef threats.* Oman Ministry of Environment and Climate Affairs partnered on Biosphere Expedition (Solandt and Hammer, 2015). *Monitoring study in Musandam Peninsula in 2014.* Joint GCC project for Arabian Gulf and Oman Gulf (Directorate-General of Nature Conservation, 2010). *Goal to estimate benthic resources and build marine species database through marine surveys.*
Qatar	Reef Life Survey has 4 sample sites off the Qatar Coast (Reef Life Survey, 2024a[2]). Citizens trained in visual survey techniques using belt transects and photography (Reef Life Survey, 2024b).	Monitoring by Ministry of Environment in collaboration with the Environment Agency of Abu Dhabi (Kloosterman, 2009). *4 permanent coral monitoring stations were installed.* Qatar Coral Monitoring Program run by Supreme Council for Environment and Natural Reserves (SCENR) (Abdel-Moati, 2006). *Baseline surveys were run in 2004*[3]. Coral reef investigations in the Gulf by Supreme Council for the Environment and Natural Resources, and Environment Agency Abu Dhabi (WWF, 2008[4]). *Further monitoring plans subsequently published in report* (Moati et al., 2008).

(Continued)

TABLE 2 Continued

Country	Citizen science	Government science
Saudi Arabia	CoralWatch *(1 site, 1 survey, 2017)* ReefCheck *(36 surveys, 1999-2009)*	Sustaining Research Project – a collaboration between Saudi Aramco, and King Fahd University of Petroleum and Minerals (Gray, 2023). *An ongoing project which has been running since 1984**. Coral Reef Survey in Support of the Marine and Coastal Damage Assessment (OSDA) in 2003 for the Presidency for Meteorology and Environment (Krishnakumar et al., 2014[5])
UAE	CoralWatch *(8 sites, 36 surveys, 2017-2022)* ReefCheck *(20 surveys, 2004-2022)*	Coral reef data is collected as part of the state of the environment reports produced by the EAD as part of the Abu Dhabi Global Environmental Data Initiative (AGEDI) (EAD, 2006). Coral reef investigations in the Gulf by Supreme Council for the Environment and Natural Resources, and Environment Agency Abu Dhabi (WWF, 2008[12]). *Further monitoring plans subsequently published in report (*Moati et al., 2008*).* Jebel Ali Marine Sanctuary monitoring program. *Maintained by Dubai Municipality since 1995* (Riegl, 2002). Marawah Marine Protected Area. Surveys undertaken off the coast of Abu Dhabi in order to establish high conservation value areas when designating an MPA (Al Cibahy and Al Abdesalaam, 2013). Marine Environment Research Centre (MERC) of the Environment Agency Abu Dhabi aerial surveys. *Whilst the surveys are designed to monitor marine macro-fauna, coral presence is also recorded* (Al Cibahy and Al Abdesalaam, 2013).

The monitoring schemes picked out all adhere to the same guidelines as those set in the systematic review. Beyond taking place in the ROPME area, they all involved primary science, were not extractive, were not exclusively focused on megafauna, and were set on natural coral reefs. Interactive map web pages were used to gather survey information for CoralWatch (CoralWatch, 2024) and Reef Check (Reef Check Foundation, 2024). Reef Check survey information for Bahrain was gathered from Uwate et al., 2000 *Saudi Aramco is largely a government owned company therefore their study is considered as government-led science in this study.

directed efforts towards coral reef monitoring (although there may be internal/non-public reports not represented due to the inclusion criteria used here). Of the four actively publishing countries, the UAE has produced the most reef monitoring publications, with five studies included in this review. In contrast, Saudi Arabia had the fewest publications, although their Sustaining Research Project is the longest monitoring effort, which has been running since 1984, and the first evidence of government-supported monitoring in the region. Government-led monitoring in the ROPME Sea Area has consisted of both short-term studies, such as those intending to designate MPAs (Al Cibahy and Al Abdesalaam, 2013[6]), as well as long-term monitoring programs, notably in Saudi Arabia and the UAE (Table 2). The spatial scale of projects also varies. Alongside work solely within their own territorial seas, collaborative projects between nations also exist such as recurring publications including monitoring data from both the UAE and Qatar.

3.6.2 Citizen science

Citizen science efforts are present in the ROPME Sea Area and, out of the eight member states, programs have been active in all but Iraq (Table 2). There were three citizen science projects of global standing that have been employed in the ROPME Sea Area: ReefCheck (Reef Check Foundation, 2024[7]), CoralWatch (CoralWatch, 2024[8]), and Reef Life Survey (Reef Life Survey, 2024a[9]).

The survey methods of ReefCheck and Reef Life Survey have some similarities, both using belt transects to monitor fishes and invertebrates, and surveying substrate using line transects and photoquadrats, respectively (Reef Check Foundation, 2020[10]; Reef Life Survey, 2024b[11]). However, while Reef Life Survey attempts to identify organisms at the species level, classifications for ReefCheck largely made at the family level, limiting the diversity assessment applications of the data. Another major discrepancy between the two organizations is the geographic scope of the monitoring. Reef Life Survey was only used in Qatar, including surveys of a total of four reefs, whilst ReefCheck has been active across six of the eight member states: Bahrain (Uwate et al., 2000), Iran, Kuwait, Oman, Saudi Arabia, and the UAE (Reef Check Foundation, 2024). With over 252 completed surveys since 1999, ReefCheck represents the largest quantitative citizen science monitoring program in the ROPME Area. However, ReefCheck efforts have been spatially inconsistent, varying dramatically between countries with just under 60% of surveys conducted in Oman, compared to just 0.02% in Kuwait, for example.

2 Website source: https://reeflifesurvey.com/species/.

3 Website source: https://wwfeu.awsassets.panda.org/downloads/coral_reefs_qatar___mohamed_alaa_abdel_moati.pdf.

4 Website source: https://wwf.panda.org/wwf_news/?135981/Coral-Reef-Investigations-in-Abu-Dhabi-and-Eastern-Qatar.

5 Website source: https://www.slideserve.com/cale/biodiversity-of-coral-reef-s-along-the-gulf-coast-of-saudi-arabia.

6 Website source: https://www.slideserve.com/daniel_millan/the-status-and-management-of-coral-reefs-in-the-united-arab-emirates-ashraf-al-cibahy-and-thabit-al-abdesalaam-e-mail.

7 Website source: https://www.reefcheck.org/tropical-program/coordinators-and-teams/.

8 Website source: https://coralwatch.org/maps/.

9 Website source: https://reeflifesurvey.com/species/.

10 Website source: https://www.reefcheck.org/tropical-program/tropical-monitoring-instruction/.

11 Website source: https://reeflifesurvey.com/methods/.

CoralWatch has been active in all regional nations except Kuwait and Qatar (Table 2). In total, 233 surveys have been conducted in the Gulf over the organization's history, peaking in Kuwait with 65 surveys (CoralWatch, 2024). However, in contrast to the other two programs which focus on quantitative date (e.g. percent cover and abundance), CoralWatch uses semi-quantitative methodology to assess reef health, for example employing a color chart and coding system to assess symbiotic algae concentration and indicate reef health (CoralWatch, 2018[12]).

4 Discussion

Since 1984, over 100 coral reef monitoring studies of the ROPME Sea Area have been published, notably increasing during the 2010s, reflecting a growing regional interest in the condition of reef ecosystems. The monitoring of these reefs is driven by their economic and ecological importance; local reefs support high-value fishing and tourism industries (Vaughan et al., 2019) as well as fauna uniquely adapted to the unusual regional environmental conditions (Coles, 2003; Rezai et al., 2004) and monitoring is thus necessary to understand reef status and trends. Regional research also makes valuable contributions to global coral reef assessment efforts as one of the ten regional nodes of the Global Coral Reef Monitoring Network (GCRMN) (Burt et al., 2021). Growing international interest in coral reef conservation is another strong impetus for increased regional monitoring, with data collected in the ROPME Sea Area helping inform a global community striving to rapidly develop our understanding and management of these declining ecosystems (Schaffelke et al., 2023).

However, at present, monitoring efforts do not reflect the importance of this region's reefs nor the threats they face. Almost half the studies undertook only a single fieldwork period (45%), failing to document long-term trends, and surveyed in only a single country (86%), with reefs in Iran and the UAE dominating studies. Effective monitoring of the region should increase study quantity, prioritizing long-term projects, and advocate for regional collaboration, particularly in the face of trans-boundary stressors such as climate change.

4.1 Disparities in national monitoring efforts

Across the ROPME Sea Area, there is uneven distribution of coral monitoring, where it is substantially higher in the UAE and Iran than the other six nations. The lack of Iraqi monitoring publications is presumably due to the limited reef extent, only recently discovered in 2014 (Pohl et al., 2014). However, the notable inequity in monitoring across the other nations can be linked to disparities in research capacity, largely driven by differences in national policies and funding availability. Both the UAE and Iran have invested substantially in higher-level education in recent decades, several with strong research focuses on marine sciences, improving their research infrastructure and the number of trained individuals (Ashour and Fatima, 2016; Burt et al., 2013). As a result, the UAE has one of the highest scientific publication counts among GCC nations, while Bahrain and Kuwait are considered less research intensive (Ajayan et al., 2022). Policies encouraging expatriate work also bolster a country's research capacity, bringing additional funding and expertise; international scientists based outside of the Emirates contribute significantly to research output for the UAE, for example, accounting for over two thirds of reef-related publications in an earlier assessment (Burt, 2013). In contrast, immigration policies, international embargoes, and periods of political instability have reduced international researcher access to some other regional countries and likely contributed to fewer publications.

The disparities between countries highlight a substantial problem - the limited amount of collaborative regional publications. Only 14% of studies were conducted in multiple countries, limiting the likelihood of successful policy and management improvements for what are often pan-regional issues. Uneven monitoring efforts leave some of the region's most rapidly declining reefs inadequately studied. For example, despite experiencing high rates of reef decline, only four monitoring studies have been published for Bahrain (Burt et al., 2013). Additionally, major stressors such as temperature, the greatest motivator of monitoring across this review, are trans-boundary in nature therefore the current isolated studies are insufficient for documenting its impact on reefs regionally. Instead, coordinated regional action, standardizing monitoring practices, and treating the ROPME Sea Area as a single interconnected ecosystem should be the goal. Work in the region should be undertaken to increase collaborative efforts, with wealthier or better equipped nations assisting in the formation of large-scale monitoring programs. Pooling resources and knowledge would both increase the scale and quantity of studies, drastically improving conservation prospects across the region.

4.2 The need for methodological standardization

Evaluation of coral monitoring methodology in the ROPME Sea Area also highlights the need for regional collaboration to modernize and standardize techniques. Photoquadrats, line transects, and belt transects have been employed most frequently and together were used in almost 80% of publications. Often considered 'traditional' reef monitoring techniques, these have allowed scientists to build large, long-term datasets at reefs worldwide for relatively low-cost over the last few decades, explaining their popularity (Aronson et al., 1994). However, global calls to automate and standardize reef monitoring have encouraged scientists to advance and modernize techniques in recent years (Apprill et al., 2023). In the ROPME Sea Area, methodology development is a key research focus, the second most common study aim in this review, accounting for 14% of

12 Website source: https://coralwatch.org/monitoring/using-the-chart/.

publications, including trialing new techniques (eg. parasailing: Kabiri et al., 2014) and upgrading existing methods (e.g. large-scale satellite mapping: Ben-Romdhane et al., 2016). Innovative new techniques can offer benefits such as greater accuracy in reef surveys and the potential to access more remote study sites. However, while experimentation should be encouraged, method diversification must primarily be motivated by the identification of widely applicable, accurate, and cost-effective techniques.

Researchers should use their studies to identify and advocate for consistent method use across the ROPME Sea Area, standardizing datasets and allowing for valid investigation of regional differences in reef condition. Switching between monitoring protocols can compromise data comparability (Vallès et al., 2019) meaning an excess of techniques may undermine collaborative monitoring efforts. Differences in data processing can also introduce variability with inconsistent and outdated labelsets on underwater transect data affecting large-scale monitoring efforts (Shao et al., 2024). Although immediate standardization of regional methodology may not be feasible, researchers should be encouraged and supported through this transition. In fish surveys, paired data collected simultaneously by different techniques can be used to develop reliable conversions for existing datasets (Caldwell et al., 2016). Likewise, the use of open-source software such as MERMAID for tagging and sorting data should become commonplace, standardizing labelsets and data outputs for transect analysis across the region (Madin et al., 2019). Irrespective of field methodology, adhering to global standards of data formatting such as Darwin Core post-fieldwork would support the development of common language, and therefore comparability, between studies despite the heterogeneous nature of biological datasets (Wieczorek et al., 2012). Similarly, regional monitoring efforts would benefit from the implementation of consistent data management protocols, with researchers encouraged to follow guidelines such as the FAIR data principles, ensuring the long-term availability of data repositories for the region (Wilkinson et al., 2016).

4.3 Resource limitations and prioritizing long-term studies

Alike much coral reef monitoring worldwide, the high demands of extended projects and resource limitations have restricted study duration in the ROPME Sea Area, resulting in a lack of long-term data to monitor reef health trends. In the region, short-term monitoring dominates, with only 6% of studies exceeding ten years in duration. Funding and training access are primary influencers; long-term projects are expensive and reliant on the extended dedication of highly trained scientists. Although regional tertiary-education capacity has grown substantially over the time span covered in this review, facilitating research through the availability of institutes and skilled individuals, this likely delayed the onset of long-term projects. The UAE demonstrates this shift with over 100 higher education institutes today compared to only five in 1990 (Ashour and Fatima, 2016). With only limited resources available, the prioritization of long-term monitoring is also restricted by the broadening scope of reef research. Molecular biology and physiology of regional coral populations made up a fifth of all reef publications in the Arabian region (also including the Red Sea) between 2005-2014 (Vaughan and Burt, 2016), potentially diverting focus and funding from monitoring projects.

However, despite an expanding field of research and the barriers in establishing extended studies, long-term datasets remain essential to inform conservation efforts and can be hugely influential in the designation of policy and management plans (Lin et al., 2021). In particular, they allow for more accurate research into reef threats, avoiding misleading results associated with studying an isolated event rather than the interaction of multiple stressors over time (Hughes and Connell, 1999). Researchers should prioritize the continuation of existing monitoring studies and focus on establishing a greater number of projects across the region in order to ensure reliable long-term conservation data is collected.

4.4 Limitations within the author network and regional capacity

At present, reef monitoring in the region has been undertaken by a fragmented author network which fails to represent the communities reliant on the reefs, limiting knowledge-building and long-term monitoring development. Although the geographical scale of the region should involve a variety of researchers and institutes, the limited number of repeat authors in this review suggests the majority do not contribute to the continuous monitoring necessary tp understand long-term trends. Instead, many studies are likely conducted either by short-term expatriate researchers based (temporarily) in the region or international researchers briefly visiting the region. The limited number of local citizen (*Khaleeji*) authors means that 'parachute science' and 'neo-colonial science' are a concern for the region (Vaughan and Burt, 2016). Likewise, the gender divide and dominance of male authors found in this review and seen more broadly across regional reef science (Al-Gergawi et al., 2024) also fails to represent the general public, further limiting local engagement in research. A lack of inclusivity and disconnection between society and research impedes public support for conservation efforts (Sanborn and Jung, 2021). To ensure long-term monitoring is undertaken, the ROPME Sea Area needs a base of local citizens invested in research, committing to the development of local marine science programs for future generations and supportive of collaboration across the region (Burt et al., 2014; van Lavieren et al., 2011). Initiatives such as training workshops and collaborative networks, bringing together and supporting local scientists should be used to bolster regional capacity.

4.5 The role of government and citizen science

While ROPME Sea Area governments do contribute to regional reef monitoring, their efforts have been inconsistent on both temporal and spatial scales. According to publicly available information, since 1984, there have been a total of 13 governmental projects, spanning only half of the eight countries: Saudi Arabia, Qatar, Oman, and the UAE. Although long-term monitoring is underway in the UAE and Saudi Arabia, the majority of regional work has been short-term, focused on MPA designation and mapping. Few projects have endeavored to collate long-term datasets or monitor temporal shifts in reef communities. While it is acknowledged that additional privately commissioned monitoring has likely been undertaken, data restrictions limit knowledge sharing and the overall impact these projects can have on regional reef research progress. Recent growth in artificial reef development as a conservation method, implemented by six of the ROPME Sea Area countries, has likely also reduced monitoring effort, diverting both interest and funding (Deb et al., 2014; Abu Dhabi Media Office, 2023[13]; Erftemeijer et al., 2004; Loughland et al., 2016; KOC, 2017; Al Ismaili et al., 2024b). Although these projects demonstrate an interest in marine ecosystems, the effectiveness of artificial reefs as a conservation solution is highly debated (Bartholomew et al., 2022; Burt et al., 2009). While artificial reefs may provide some benefits, more priority should be given by governments to monitoring natural reefs to develop data-driven management interventions to ensure the sustainability of these diverse and economically important ecosystems.

In contrast, public participation in reef monitoring is widespread across the ROPME Sea Area, with citizen science projects in all countries except Iraq, recording close to 500 surveys. Reef-based citizen science projects do typically garner significant local engagement with previous Mediterranean and Red Sea projects each boasting thousands of volunteers, covering a survey extent far beyond that achievable by conventional scientific projects (Goffredo et al., 2010; Branchini et al., 2014; Foster-Smith and Evans, 2003). However, the downfall of citizen science lies in a pervasive low opinion from the scientific community, with data often deemed unreliable for publication. Limited training, a lack of taxonomic expertise, and poorly designed scientific methods are commonly identified as concerns, leading to low quality data from the perspective of some scientists (Foster-Smith and Evans, 2003; Hunter et al., 2012). While the validity of these claims is debated, they both devalue the results of ongoing work and decrease the likelihood of further citizen science projects being implemented. Integrating citizen scientists into government or academic project frameworks could serve as a solution, maintaining public engagement while retaining confidence in data accuracy, benefitting both groups.

4.6 Recommendations for future monitoring and conservation efforts

There is a pressing need for enhanced reef management and conservation in the ROPME Sea Area as the scale and quantity of reef stressors dramatically increases. Driven by global climate change, the frequency of marine heatwaves has risen; during this review period, four global bleaching events have occurred (Reimer et al., 2024). Increased cyclone activity also threatens reef communities, particularly in the Gulf of Oman; physical damage from wave action leaves corals more susceptible to disease and reef framework vulnerable to bioerosion (Foster et al., 2008). The effects of these global stressors are then further exacerbated by local pressures on the region's reefs such as coastal development and pollution, attributed to the rapidly growing population (van Lavieren et al., 2011). Monitoring the impacts of both large-scale stressors and local pressures is essential to inform policymakers and advocate for regional and international collaboration to reduce these stressors. The rapid rate of change in regional reefs further reinforces this need for improved monitoring, supporting the timely implementation of management in response to rapidly changing conditions.

This review documents the past and current coral reef monitoring efforts in the ROPME Sea Area, identifying important contributions from conventional research institutes, governments, and citizen science projects. Continued involvement of all three sectors is advocated for, given both the geographical scale of the region and the growing pressures on reef ecosystems. Integrating citizen scientists into government monitoring frameworks is suggested as a novel method, using public enthusiasm to increase project quantity and momentum while maintaining data accuracy and confidence of the research community. Among researchers, greater inclusivity should also be prioritized, improving the gender balance and incorporating more regional citizens as authors, representing their local reefs and supporting the long-term viability of regional conservation efforts.

Across studies, an integrative approach to reef monitoring is advocated for, incorporating climatic and socioeconomic indicators of reef condition alongside common benthic and fish-based metrics. Increasing the spatial resolution of coral and reef-associated community baseline assessments should be prioritized, closing existing knowledge gaps associated with regional disparities in monitoring effort (Feary et al., 2013). However, effective monitoring practices should ensure reefs are considered at an ecosystem level, including abiotic factors such as temperature and nutrient concentrations in survey efforts. Increased monitoring of environmental conditions would help untangle the impact of the region's complex, spatially variable climatic conditions (Coles, 2003), from the myriad of localized stressors (van Lavieren et al., 2011), supporting the application of effective location-specific mitigation strategies. Likewise, integrating socioeconomic indicators into reef monitoring protocols would benefit reef

13 Website source: https://www.mediaoffice.abudhabi/en/environment/adq-environment-agency-abu-dhabi-and-archireef-successfully-deploy-innovative-marine-biodiversity-restoration-solution-off-the-shore-of-abu-dhabi/.

management, increasing public and stakeholder awareness of reef condition. Highlighted as a priority by regional environmental policymakers and academics (Feary et al., 2013), economic evaluation of coral reefs can help establish a balance between their protection and sustainable use, particularly relevant given the region's growing coastal populations (van Lavieren et al., 2011). Incorporating the Global Socioeconomic Monitoring Initiative for Coastal Management (SocMon) protocol into surveys, quantifying factors such as reef use patterns, community services provided, and traditional knowledge, would help highlight the value of reefs and further advocate for their conservation (Bunce et al., 2000).

The efficacy and impact of monitoring practices would be further improved by increased regional collaboration, tackling previous disparities in monitoring extent by pooling resources and prioritizing multi-national studies. Given the transboundary nature of many reef stressors, effective conservation action is reliant on monitoring data from across the eight countries, regarding the ROPME Sea Area as a single interconnected ecosystem. Following data collection, researchers should adhere to standardized data formatting and improved data sharing practices to create a centralized database for the region. Increased research partnerships across the eight nations should also be used to support the establishment and continuation of long-term monitoring projects, a priority given their capacity to influence policy designation (Lin et al., 2021). Ensuring the temporal continuity of datasets will help combat shifting baseline syndrome, ever prevalent in regional research (Sheppard et al., 2010), and support the implementation of effective management plans. With the support of regional and international stakeholders, these suggestions are possible, transforming monitoring practices to conserve the unique reefs of the ROPME Sea Area.

Data availability statement

The original contributions presented in the study are included in the article/Supplementary Material. Further inquiries can be directed to the corresponding author.

Author contributions

HG: Conceptualization, Formal analysis, Methodology, Writing – original draft. JH: Conceptualization, Writing – review & editing. JB: Conceptualization, Writing – review & editing.

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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.

Generative AI statement

The author(s) declare that no Generative AI was used in the creation of this manuscript.

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Supplementary material

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