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The neglected status of the vermetid reefs in the Mediterranean Sea: A systematic map

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ABSTRACT

Studied since late 1800, vermetid reefs are marine bioconstructions of well-acknowledged importance in the Mediterranean Sea. Despite their persistence being jeopardized in the whole basin, recent studies have referred to this bioconstruction as a neglected habitat. In this study, we assessed the neglected status of the Mediterranean vermetid reefs in the scientific literature producing a systematic map through a multi-method bibliometric protocol. Scopus and Web of Science databases were jointly used for data collection. Vermetid reefs publication rate (i.e., number of publications per year) was investigated compared to the other Mediterranean bioconstructions using ANOVA analysis and Zero-Inflated Poisson regression. Later, VOSviewer software was used to perform a bibliometric network analysis and for mapping visualization. The analysis aimed at investigating gaps, patterns, and trends of the vermetid reefs together with the other main Mediterranean bioconstructions (i.e., *Astroides calycularis*, *Cladocora caespitosa* and coralligenous formations, and sabellariid and *Lithophyllum* reefs). The ANOVA analysis of the number of publications from 1966 to 2020 found statistically significant differences between coralligenous and vermetid reefs publication rates in the 2006–2010, 2011–2015, and 2016–2020 timeframes and pointed out a clear before/after-2010 pattern in coralligenous publication rate, which was also confirmed by the Zero-Inflated Poisson regression model. The bibliometric network analysis of the bioconstructions literature revealed the same temporal pattern, with the vermetid reefs poorly investigated and weakly connected to newer research lines and conservation topics. Instead, coralligenous showed strong connections with biodiversity conservation and was indicated as a recent research hotspot. Overall, the results of this study confirm previous references of the vermetid reefs as a neglected habitat and, among others, show an increasing research interest in the coralligenous topic.

1. Introduction

Marine bioconstructions, or bioherms (Schuhmacher and Zibrowius, 1985), are elevated biogenic structures found from the sea surface to the deep sea, resulting from centuries or even millennia of biological activity. Organisms such as calcareous algae, sponges, corals, vermetids, oysters, mussels, polychaetes (serpulids and sabellariids), barnacles, and bryozoans can modify the geological substrate by creating a new one through diverse building processes including skeleton production, sand-binding and cementing activities, or the consolidation of calcareous sediments originated from shells or other skeletal debris (Ingrosso et al., 2018). The resulting bioconstructions increase the spatial complexity of the marine environment, providing settlement opportunities and habitats for many species. As a result, bioconstructions host a great diversity of marine life, playing a crucial role in supporting the biodiversity of the Earth's oceans and seas.

Bioconstructions have been extensively studied in the scientific literature over the past years, but research efforts have been unevenly distributed. Tropical coral reefs are among the most studied marine habitats, not only for their ecological importance but also due to the emerging concerns posed to their existence by climate change (Hoegh-Guldberg et al., 2007; Parmesan, 2006; Scheffer et al., 2001). Despite being analogously important, significantly less attention has been given to the bioconstructions of the temperate areas, whose health and persistence are also at risk. It is the case of the Mediterranean Sea, a basin characterized by high levels of anthropogenic pressure (Coll et al.,

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2010, Coll et al., 2012), where many different types of bioconstructions can be built by corals, red coralline algae, vermetid molluscs, and serpulid worms (Relini, 2009). Among these, the two endemic scleractinian corals *Astroides calycularis* (Pallas, 1766) and *Cladocora caespitosa* (Linnaeus, 1767), both included in the International Union for Conservation of Nature (IUCN) Red List of Threatened Species, can form reefs in the shallow infralittoral waters (Casado de Amezua et al., 2015; Ocaña et al., 2015). Many other threatened species inhabit the coralligenous reefs, peculiar formations in the lower infralittoral and the circalittoral zones in dim light conditions. These formations originate from the activity of encrusting algae that accumulate carbonate structures to which many organisms such as gorgonians, sponges, and bryozoans associate (Ballesteros, 2006). Coralligenous formations are acknowledged as one of the Mediterranean's most diverse and complex marine habitats, and great emphasis is put on their conservation and protection (Çinar et al., 2020; Giakoumi et al., 2013). Other important bioconstructions of the Mediterranean Sea are the sabellariid reefs, made by the two polychaete species, *Sabellaria alveolata* (Linnaeus, 1767) and *Sabellaria spinulosa* (Leuckart, 1849), found along the mid littoral-upper infralittoral zone on sandy seafloors. In the intertidal zone of rocky shores, the coralline red alga *Lithophyllum byssoides* (Lamarck) Foslie, 1900 can generate structures called "trottoirs" and the gregarious vermetid gastropods belonging to the genus *Dendropoma* can build up reefs - called "trottoirs à vermets" by Pérès and Picard (1952) and by Molinier and Picard (1953) - in combination with the encrusting red alga *Neogoniolithon brassica-florida* (Harvey) Setchell & L.R.Mason, 1943 (Safriel, 1966).

Considering their ecological value, all bioconstructions should be considered priority targets in conservation plans. Currently, different directives and conventions recognize, classify, and target Mediterranean bioconstructions as habitats to be protected. As comprehensively reported by Ingrosso et al. (2018), the Barcelona Convention (1975), the Bern Convention (1979), the EU Habitat Directive 92/43/EEC (European Community, 1992; European Commission, 2007, 2013), the European Red List of Habitats (Gubbay et al., 2016), and the IUCN Red List of Threatened Species (IUCN, 2021) directly target Mediterranean bioconstructions or call for the protection of species that build or inhabit them. In addition, the European Nature Information System (EUNIS) (Tunesi et al., 2006) and the EU Marine Strategy Framework Directive (MSFD) 2008/56/EC (European Community, 2008) offer unambiguous classification systems for these habitats. Despite their relevance as hotspots of marine biodiversity and the conservation drivers in place, not all Mediterranean bioconstructions have been drawing the same degree of attention from the scientific community.

In particular, some bioconstructions could be considered *neglected habitats*, here defined as habitats that do not receive the proper attention they deserve in the scientific landscape regardless of their recognized ecological importance in terms of contribution to biodiversity, performance of ecosystem functions, and/or provisioning of ecosystem services. Such lack of regard could be caused by multiple factors such as difficulties in identification, description and mapping, a restricted or patchy distribution, and/or lack of monetary funds for research. All these factors lead to knowledge gaps that impede the effective conservation of habitats and species, especially in the face of emerging pressures and threats in a fast-changing biosphere.

Among the Mediterranean bioconstructions, the vermetid reefs are often referred to as a neglected habitat (Chemello et al., 2014; Milazzo et al., 2016). According to Chemello (2009), the scientific research on *Dendropoma* bioconstructions dates around the half of the nineteenth century, when the French naturalist de Quatrefages (1854) first described these peculiar formations in the intertidal zone of the rocky coasts near Palermo (NW Sicily, Italy). Fundamentals were then the scientific works of Monterosato (1892), Molinier and Picard (1953), and Pérès and Picard (1964) that paved the way for more recent research in the Western (e.g., Chemello, 1989; Pandolfo et al., 1992; Laborel and Laborel-Deguen, 1994) and Eastern Mediterranean (e.g., Safriel, 1974, 1975; Safriel and Ben-Eliahu, 1991). Despite the long research history, the knowledge on this reef-building species is still poor (Milazzo et al., 2016). Just recently, Templado et al. (2015) disentangled the cryptic species complex previously under the name *Dendropoma petraeum* (Monterosato, 1884) in the four different species *D. cristatum* (Biondi, 1859), *D. anguliferum* (Monterosato, 1878), *D. lebeche* (Templado et al., 2015) and a new undescribed species in the Ionian Sea (Calvo et al., 2009). The ecological role and importance of the vermetid reefs are well-acknowledged in the literature. Providing an additional horizontal surface in the intertidal zone, these bioconstructions support high biodiversity and, in addition, offer coastal protection against erosion (Chemello and Silenzi, 2011; Milazzo et al., 2016). Considering their relevance for the rocky coastal environment and the existence of international conventions and directives promoting their protection, it is alarming that no coherent conservation measure is in place to support the persistence of this habitat at the Mediterranean scale, leaving its protection instead to chance occurrences in Marine Protected Areas (MPAs) and to a few Sites of Community Importance (SCIs). It has to be remarked indeed that no MPA has been established for or explicitly targets the protection of vermetid reefs, which furthermore mostly fall in low to medium protection zones (Chemello et al., 2014). Since 1990, vermetid reefs have been listed as threatened bioconstructions in the "Livre rouge "Gérard Vuignier" des végétaux, peuplements et paysages menacés de Méditerranée" (UNEP/IUCN/GIS POSIDONIE, 1990), the first draft of a Mediterranean Red Data Book, but their conservation status has not been assessed yet. Only recently, a dramatic decrease in the live cover of vermetid reefs in the Eastern and Central Mediterranean has been recorded (Badreddine et al., 2019; Galil, 2013; Küstner et al., 2015; Rilov, 2016).

Assessing the neglected status of the Mediterranean vermetid reefs would represent an important step to fostering the knowledge of this bioconstruction, which is fundamental to supporting its conservation at the Mediterranean scale. In this study, we aim to quantitatively assess the scientific literature on the vermetid reefs compared to the other main bioconstructions of the Mediterranean Sea, evaluating their neglected status and identifying research gaps.

2. Materials and methods

The objectives of the study were addressed by creating a systematic map following the Collaboration for Environmental Evidence Guidelines and Standards for Evidence Synthesis in Environmental Management (CEE, 2018) as well as conforming to the RepOrting standards for Systematic Evidence Synthesis (Haddaway et al, 2017; file S1). The main objective of the study was firstly formulated as the broad research question "are Mediterranean vermetid reefs a neglected habitat?", which was further refined into more specific ones (Table 1).

According to these questions, the review consisted of two complementary bibliometric approaches. First, the publication trend on the vermetid reefs topic was analyzed and compared to the overall bioconstructions trend to quantitatively investigate the research interest on

Table 1
Starting and refined questions for the systematic map.

Starting question	Refined question(s)	Further refined question(s)
1. Are vermetid reefs a neglected habitat?	2.1 Compared to the publication rate of the scientific literature on the other Mediterranean bioconstructions, are vermetid reefs a neglected habitat? 2.2 Based on the scientific landscape of the Mediterranean marine bioconstructions, are vermetid reefs a neglected habitat?	3.1 Compared to the publication rate of the scientific literature on the most studied Mediterranean bioconstruction, are vermetid reefs a neglected habitat? 3.2 Compared to the patterns and trends of the scientific research on the most studied Mediterranean bioconstruction, are vermetid reefs a neglected habitat?

the topic in the bioconstructions literature. Further, the most studied Mediterranean bioconstruction was chosen as the trend comparator to assess the neglected status of the vermetid reefs. Finally, a bibliometric network analysis of the scientific literature on the main Mediterranean bioconstructions was performed to explore and visualize the relative scientific landscape and identify patterns and trends of the vermetid reef research compared to the other bioconstructions with a focus on the most studied one. The key elements of the systematic map were identified according to the PICO structure (Population, Intervention, Comparator, Outcome) (Table 2).

2.1. Data collection, coding, and screening

The two bibliographic databases Scopus and Web of Science Core Collection (WOS) were used to collect literature data on the main Mediterranean bioconstructions and their habitat-forming species, i.e., *Astroides calycularis*, *Cladocora caespitosa*, coralligenous formations, sabellariid reefs (*Sabellaria alveolata* and *Sabellaria spinulosa*), and vermetid reefs (*Dendropoma* spp.). To do so, a search string was built and tested in Scopus to include the highest number of documents of the test list in the search results (files S2 and S3). The early production on the bioconstructions topic, including milestone papers, was written in the native languages of the Mediterranean countries that contributed to the research on it. Italian, French, and Spanish terms were therefore selected and included in the search string.

The search was performed selecting the search fields "article title, abstract, and keywords" in Scopus and "topic" in WOS. No year restriction was applied. Literature data were collected on June 23rd 2022, and the output of the research was exported in ".ris" format. The two databases were accessed using the subscription of the University of Palermo. The results from both searches were imported in the reference management tool Zotero (https://www.zotero.org) and merged. Duplicates were then manually identified and deleted (files S4 and S5).

To select and include all the relevant literature, the following eligibility criteria were identified and applied in the screening process: 1) the document had to address a marine bioconstruction or habitat-forming species; and 2) the document had to refer to bioconstructions of the Mediterranean Sea. The screening was performed on documents titles and abstracts. Metadata on the type of bioconstruction, year of publication, and language were then extracted from the selected documents. The topic of each document was assigned according to which bioconstruction or habitat-forming species was stated as the object of the study. For this purpose, documents titles and abstracts were thoroughly checked (file S4).

2.2. Publication trend analysis

To assess the neglected status of the vermetid reefs in the Mediterranean bioconstructions literature, statistical analyses on the publication rate (i.e., number of publications per year) were carried out. Following the screening process, the coralligenous bioconstruction was chosen as the comparator. The publication rate on the vermetid reefs was therefore compared to the publication rates on the coralligenous and the overall bioconstructions topics.

First, the number of publications on the three topics (i.e., total bioconstructions, vermetid reefs, and coralligenous) were plotted by year from 1966 (i.e., the first year recording a publication on the vermetid reefs in the database) to 2020. Vermetid reefs and coralligenous publication rates were later relativized to the total number of publications produced by year on the bioconstructions topic to investigate their contributions to the overall research on the subject. To statistically compare these contributions, analysis of variance (ANOVA) was performed on the relativized values considering six time windows, i.e., $\leq$1995, 1996–2000, 2001–2005, 2006–2010, 2011–2015, 2016–2020. In particular, two-way ANOVA was performed to examine the influence of time (i.e., years) and topic (i.e., coralligenous and vermetid reefs) on the number of relativized publications by year. Normality of data distribution and homogeneity of variance were tested before performing the analysis using Shapiro-Wilk ($p > 0.05$) and Levene tests ($p > 0.05$), respectively. Later, Tukey's HSD test was used to identify significant differences in all pairs of the considered time intervals.

Finally, a Zero-Inflated Poisson regression model with a log link was used to estimate the publication rates of coralligenous and vermetid reefs. The model was chosen due to the high scarcity of documents on these two bioconstructions occurring in the first decades of the database. Only 48 % and 65 % of the years between 1966 and 1996 recorded a publication on vermetid reefs and coralligenous, respectively. The rates of coralligenous and vermetid reefs were normalized using the logarithm of the overall bioconstructions publications as an offset.

2.3. Bibliometric network analysis

The analysis of bibliometric networks is a quantitative method to investigate the scientific literature, allowing for the creation and visualization of citation, keyword co-occurrence, and co-authorship networks (Van Eck and Waltman, 2014). Such analysis has been widely applied in recent years, and it has proven to be a valuable tool to detect patterns and emerging trends on a wide range of scientific topics as well as to identify their research gaps or needs (Pauna et al., 2019; Picone et al., 2021; Saggiomo et al., 2020; Skaf et al., 2020).

To explore the scientific literature on the Mediterranean bioconstructions, a term co-occurrence analysis was performed using VOSviewer software (Van Eck and Waltman, 2010), version 1.6.18 (Van Eck and Waltman, 2022). A total of 32,976 terms were extracted from document titles and abstracts through VOSviewer's text mining feature, ignoring structured abstract labels and copyright statements. To count the occurrences of the terms in the documents, the binary counting method was selected. A thesaurus file listing 8857 among erroneous/meaningless terms to be eliminated and synonyms to be merged was created based on the extracted terms. Synonyms were identified based upon meaning, singular/plural forms, and acronyms. In addition, logical synonyms were identified as terms that provided the same information according to the scope of the analysis (e.g., "late Messinian" and "Messinian"). The complete list of synonyms and removed terms is provided in the Online Supplementary Material (file S6). After its application, the 32,976 extracted terms decreased to 24,995. Finally, terms to be visualized in the map were reduced to 191 by setting a threshold of at least 34 occurrences.

Overall, three different maps were produced using the network, the overlay, and the density visualizations featured by VOSviewer. In the network visualization, terms are represented by a circle whose size is directly proportional to their occurrences in the publications dataset. The distance between two terms approximately indicates their relatedness. Closely related terms are grouped into clusters to which unique colours are assigned. In the case of a co-occurrence network map, two terms are linked if they co-occur together in the same document. The number of co-occurrences between two terms is referred to as their "link

Table 2
The key elements (components) of the systematic map.

PICO structure	Key elements	Explanation
Population	Mediterranean vermetid reefs	The bioconstruction for which the neglected status will be assessed
Intervention	Scientific interest	The research efforts made by the scientific community on the topic
Comparator	Mediterranean marine bioconstructions	All other main bioconstructions of the Mediterranean Sea. The most studied bioconstruction is chosen as the comparator
Outcomes	Publication rate and importance in the bibliometric network	The number of publications per year and their weight in the scientific landscape

strength". The "total link strength" measures instead the importance of a term in the network, calculated as the sum of all its link strengths. The co-occurrence network map of terms provides information on how and to which extent topics in the bioconstructions literature are jointly investigated, highlighting patterns through their links and clusterization.

The overlay visualization is the same as the network visualization, except for the meaning carried by the item colours. In this visualization, item circles are coloured based on one of the item scores calculated by VOSviewer. By selecting the "average publication year" score, the overlay map graphically provides a temporal perspective on the occurrence of its items in the time window of the analysis using a colour gradient. The "average publication year" of terms is calculated as the average of the publication years of the documents in which the terms occur. This type of overlay network map allows for the visualization of the literature evolution over time, showing past and emerging lines of research.

In the item density map, the areas of the map are coloured according to the density of their items. Density is calculated based on the number of items in a point and the weights - i.e., importance measures (Van Eck and Waltman, 2010) - of the items in the neighbouring areas. In this analysis, we used the number of occurrences as the weight for calculating the density value. The higher these values, the higher the density at that point of the map. Opposite to the network and overlay maps, the density map does not show the links between items. The item density map of terms points out the most investigated research areas of the literature based on both the number of topics and their importance.

To generate the three maps, the layout parameters "attraction" and "repulsion" were set to 1 and 0, respectively, and the advanced layout parameter "random starts" was set to 100. The clustering parameter resolution was set to 1.05 and the minimum cluster size to 5. The main terminology used in the co-occurrence analysis is explained in Table 3. The main steps of the protocol for the systematic map are synthetized in Fig. 1.

3. Results

The search on the Scopus and WOS databases produced 3,876 and 3,112 results, respectively. The document years of publication ranged from 1862 to 2022 for Scopus, and from 1985 to 2022 for WOS. After merging the two datasets and removing the duplicates, the overall number of documents decreased from 6,988 to 4,394. The application of the eligibility criteria restricted the results to a total of 1,177 documents to be included in the analysis. Of the 1,177 documents on Mediterranean bioconstructions, 308 dealt with the coralligenous and 135 with the vermetid reefs. Overall, about 94 % of all documents were in English, with only around 5 % represented by Italian, French, or Spanish ones (file S5). As regards the vermetid reefs, all works produced before 1966 were missing.

Table 3
Terminology used in the co-occurrence analysis of terms performed using VOSviewer.

Term	Description
Items	Objects of interest (i.e., terms)
Link	Co-occurrence of two terms in the same publication
Link strength	The number of co-occurrences of a term with the other terms of the network
Total link strength	The cumulative number of co-occurrences of a term with the other terms of the network
Cluster	Set of related terms included in the co-occurrence map. One item can belong to only one cluster
Average publication year	Average year of the publications in which a term occurred
Network visualization	Map of terms co-occurrence. Co-occurring terms are linked. Terms are colored according to their cluster
Overlay visualization	Map of terms co-occurrence. Co-occurring terms are linked. Terms are colored according to the average publication year
Density visualization	Map of terms co-occurrence. Areas of the map are colored according to the term density

The analysis of the number of articles published per year from 1966 to 2020 on all Mediterranean bioconstructions showed an overall increasing trend, reaching a maximum of 78 publications in 2019 (Fig. 2). In the same year, the highest number of publications was reached for the coralligenous topic with 30 articles (38.5 %), while the peak of publication rate on the vermetid reefs was achieved in 2018 with only 10 articles (14.0 %). The analysis of the relativized coralligenous and vermetid reef publication rates showed the contributions of the two topics to the bioconstructions research (Fig. 2c). Before 2010, the contributions were comparable and often overlapping. From 2010, coralligenous and vermetid reefs showed different contributions with values consistently above and under 0.2, respectively. In particular, after 2011, more than 30 % of the bioconstructions research was composed of publications on the coralligenous topic, while the vermetid reefs contributed only by 10 %. Overall, the coralligenous topic showed an increasing contribution trend, while it appeared to be declining in the case of vermetid reefs.

The two-way ANOVA performed on the coralligenous and vermetid reefs publication rates from 1966 to 2020 found a statistically significant difference in the average relativized number of publications by both years ($p < 0.001$) and topic ($p < 0.001$). The interaction between years and topic resulted significant too ($p < 0.001$) (Table S7). The Tukey post-hoc test (Table S8) revealed significant pairwise differences between coralligenous and vermetid reefs from 1966 to 1995 to each of the remaining five timeframes ($p < 0.001$). The analysis also found statistically significant differences between coralligenous and vermetid reefs contributions over each timeframe, particularly comparing the last two periods, 2011–2015 and 2016–2020. Moreover, the coralligenous contributions of 2011–2015 and 2016–2020 were significantly different between them and, at the same time, significantly higher than the coralligenous ones preceding 2010. Vermetid reefs contributions did not differ among any of the timeframes from 1996 to 2020 and showed a significant decrease overall ($p < 0.05$). On the contrary, coralligenous contributions significantly increased over time ($p < 0.05$) (Fig. 3). The Zero-Inflated Poisson regression model showed significant positive effects of the interaction between the last three periods and the coralligenous topic (2006–2010: $\beta_9 = 0.98$, SE = 0.46, $p < 0.05$; 2011–2015: $\beta_{10} = 1.72$, SE = 0.42, $p < 0.001$; 2016–2020: $\beta_{11} = 1.69$, SE = 0.38, $p < 0.001$) (Table S9).

As a result of the extraction and synonyms identification processes, 191 terms were produced for the bibliometric network analysis. The co-occurrence network analysis assigned a cluster number (CL) as well as the number of links (L), total link strength (TLS), and occurrences (O) values to each term included in the network map. In addition, the average link strength (ALS) was calculated as the total link strength/number of links ratio. The resulting values of the terms used to compose the search string are shown in Table 4. Results of all the terms composing the network are reported in the Online Supplementary Material (file S10). To include all searched terms, also those that did not meet the occurrences threshold (i.e., not shown in the map) were listed in Table 4. In this case, cluster, links, and total link strength values were not produced. Overall, "area", "bioconstruction", "biodiversity", and "coralligenous" were the most occurring terms (416, 406, 312, and 282 occurrences, respectively). Among all bioconstructions, coralligenous resulted to be the most studied, followed by *Cladocora caespitosa* (O = 141), vermetid reef (O = 68), *Astroides calycularis* (O = 39), sabellariid reef (O = 20), and *Lithophyllum* rim (O = 4). Sabellariid and *Lithophyllum* bioconstructions did not meet the occurrences threshold and therefore were not shown in the network map. All bioconstructions included in the network map were highly connected, with links ranging from 190 (coralligenous) to 154 (*Astroides calycularis*). Despite their high connectivity, these terms differed greatly by total link strength. According to this measure, coralligenous was the strongest bioconstruction and, at

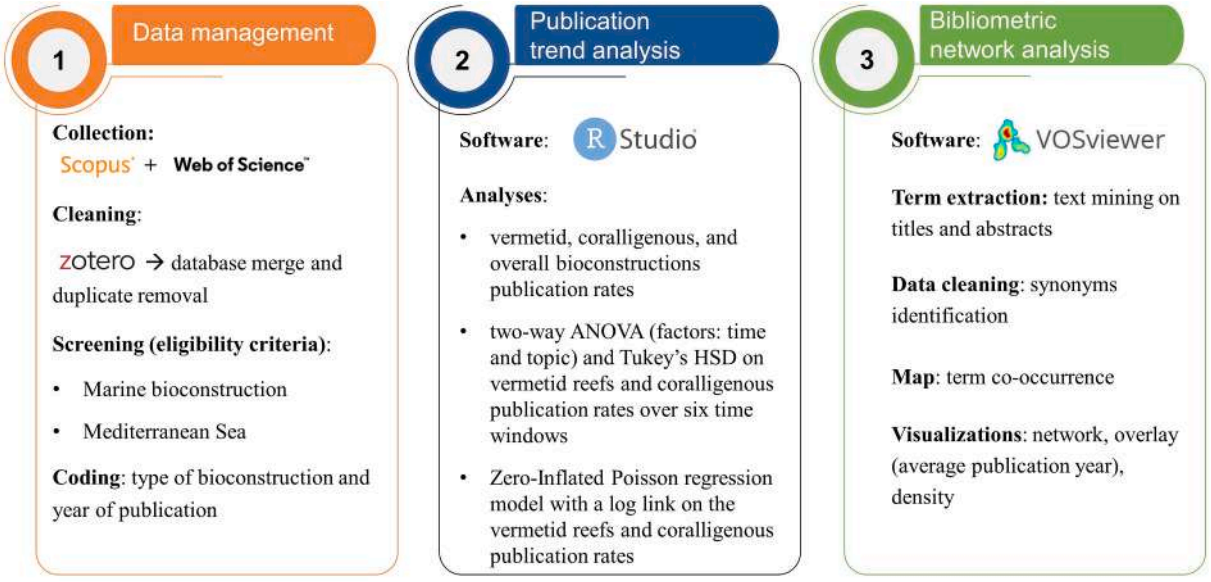

Fig. 1. Representation of the three steps composing the methodology applied in this study. For each step, the main details are provided.

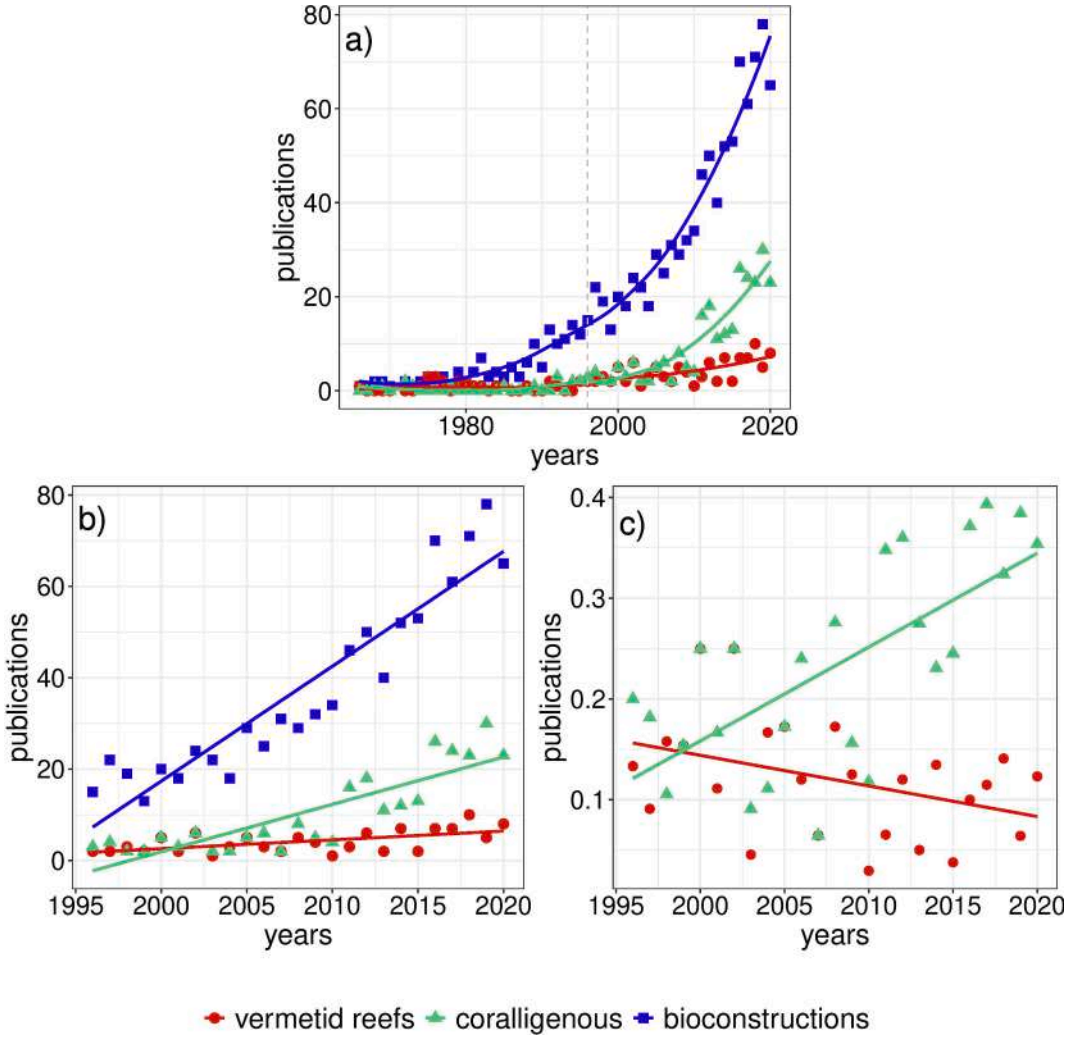

Fig. 2. (a) Number of publications on bioconstructions (blue), coralligenous (green), and vermetid reefs (red) from 1966 to 2020; the grey dashed line highlights the two periods of interest. (b) Number of publications on bioconstructions (blue), coralligenous (green), and vermetid reefs (red) from 1996 to 2020. (c) Number of publications on coralligenous (green) and vermetid reefs (red) relativized to the total number of publications on bioconstructions from 1996 to 2020. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

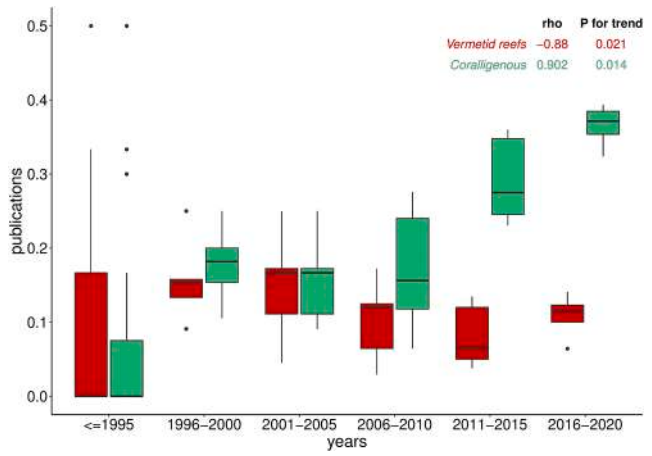

Fig. 3. Average number of publications by six time windows (from 1966 to 2020) on coralligenous (green) and vermetid reefs (red) relativized to the number of publications on bioconstructions. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

the same time, the fourth strongest term overall (TLS = 5,070). The other bioconstructions "*Cladocora caespitosa*", "vermetid reef', and "*Astroides calycularis*" were, respectively, around 60 %, 80 %, and 90 % weaker (TLS = 2,035; 1,038; 603). The average link strength of bioconstructions mirrored the same pattern of the total link strength, with the highest value reached by the "coralligenous" term (ALS = 26.7), followed by "*Cladocora caespitosa*" (ALS = 10.8), "vermetid reef" (ALS = 5.8), and "*Astroides calycularis*" (ALS = 3.9).

In the co-occurrence network map, the 191 terms were grouped in 4 clusters (Fig. 4). Cluster 1 was the largest with 65 items, followed by cluster 2 (58), cluster 3 (40), and cluster 4 (28). Each cluster included at least one of the bioconstructions (and/or their building or composing species) searched in the search string. Cluster 1 (green) included among the most important terms in the whole network, i.e., "biodiversity", "area", "habitat", and "coralligenous". The cluster developed around "biodiversity", closely surrounded by the strongly connected terms "coralligenous" (LS = 130), "habitat" (LS = 134), "area" (LS = 120), and "benthos" (LS = 86). The cluster showed also the presence of the term "conservation", linked to terms such as "biodiversity" (LS = 76), "habitat" (LS = 75), "coralligenous" (LS = 66), and "importance" (LS = 29). Overall, cluster 1 mainly focused on two connected research lines: 1) biodiversity conservation and management topics and 2) the coralligenous bioconstruction, as shown by the terms "biodiversity", "conservation", "protection", "management", "MPA", "anthropogenic pressure", "disturbance", and "impact", "coralligenous", and "Alcyonacea".

Cluster 2 (blue) was centered around "bioconstruction", the strongest and most occurring term of the network. Other relevant terms were "time", "reef", "environment", "formation", "deposit", and "sediment". Along with these terms, the presence of "paleoecology", "paleoenvironment", "fossil", "stratigraphy", "sea level", "sea level change", "Miocene", and "Holocene", point out to a clear focus on paleogeological and paleoecological topics. As regards bioconstructions and/or their forming species, "corallinales" and "*Lithophyllum* spp" were included in this cluster.

Cluster 3 (yellow) focused on corals research and on the effects of climate change on their reproduction. The term "corals", placed at the center of the cluster, was the most occurring (O = 223), followed by "condition" (O = 215), "growth" (O = 201), "change" (O = 196), and "temperature" (O = 170). All these terms were connected among them and to the term "climate change". In this cluster, both *Cladocora caespitosa* and *Astroides calycularis* bioconstructions were found. Compared to *Cladocora caespitosa*, *Astroides calycularis* resulted as less important in the network, showing lower values of occurrences (39 versus 141), links (154 versus 188), and total link strength (603 versus 2,035) (Table 2).

"Vermetid reef" and "Vermetidae" were included in cluster 4 (red), the smallest one. Placed close to strictly connected terms such as "Mollusca", "Gastropoda", "intertidal zone", "Israel", and "Sicily", they were among the least occurring terms in their cluster (O = 68 and 66, respectively). The most occurring terms were instead "coast" (O = 260), "algae" (O = 162), "presence" (O = 144), and "record" (O = 128). It is worth noticing that cluster 4 also included the term "habitat former" (O = 72; TLS = 1,428), placed at the center of and connected to "bioconstruction" (LS = 39), "biodiversity" (LS = 37), and "coralligenous" (LS = 27). From a configurational point of view, clusters 1, 2, and 3 bordered the network map with few overlapping areas. On the contrary, cluster 4 was placed at the center of the map, overlapping mainly with clusters 1 and 2.

The average publication year of the elements included in the search string ranged from 1998.6 (*Dendropoma* spp.) to 2018 (*Dendropoma cristatum*) (Table 2). According to this measure, cluster 1 was the most recent (APY = 2013), followed by cluster 3 (APY = 2011.1), cluster 4 (APY = 2008.4), and cluster 2 (APY = 2007.8) (Fig. 5). As regards the bioconstructions, "*Astroides calycularis*" had the most recent average publication year (APY = 2013), followed by "sabellariid reef" (APY = 2012.6), "coralligenous" (APY = 2012.5), "*Cladocora caespitosa*" (APY = 2009.6), "*Lithophyllum* rim" (APY = 2011.5), and "vermetid reef" (APY = 2007.3). Given the low number of occurrences of the terms "sabellariid reef" (O = 20) and "*Lithophyllum* rim" (O = 4), and their consequent exclusion from the map, *A. calycularis* and coralligenous

Table 4
Co-occurrence network analysis results of the terms used to compose the search string, including average publication year (APY), occurrences (O), cluster (CL), number of links (L), total link strength (TLS), and average link strength (ALS) values.

Term	Avg. Pub. Year (APY)	Occurrences (O)	Cluster (CL)	Links (L)	Total Link Strength (TLS)	Avg. Link Strength (ALS)
bioconstruction	2008.3	406	2	190	6954	36.6
coralligenous	2012.5	282	1	190	5070	26.7
Cladocora caespitosa	2009.6	141	3	188	2035	10.8
Lithophyllum spp	2008.8	74	2	184	1254	6.8
vermetid reef	2007.3	68	4	180	1038	5.8
vermetidae	2006.3	66	4	174	997	5.7
Astroides calycularis	2013	39	3	154	603	3.9
Sabellaria alveolata	2010.9	34				
Sabellaria spp	2010.2	33				
Dendropoma spp	1998.6	28				
Dendropoma petraeum	2008.3	25				
sabellariid reef	2012.6	20				
Lithophyllum byssoides	2003.6	12				
Sabellaria spinulosa	2012	10				
Dendropoma cristatum	2018	7				
Lithophyllum rim	2011.5	4				

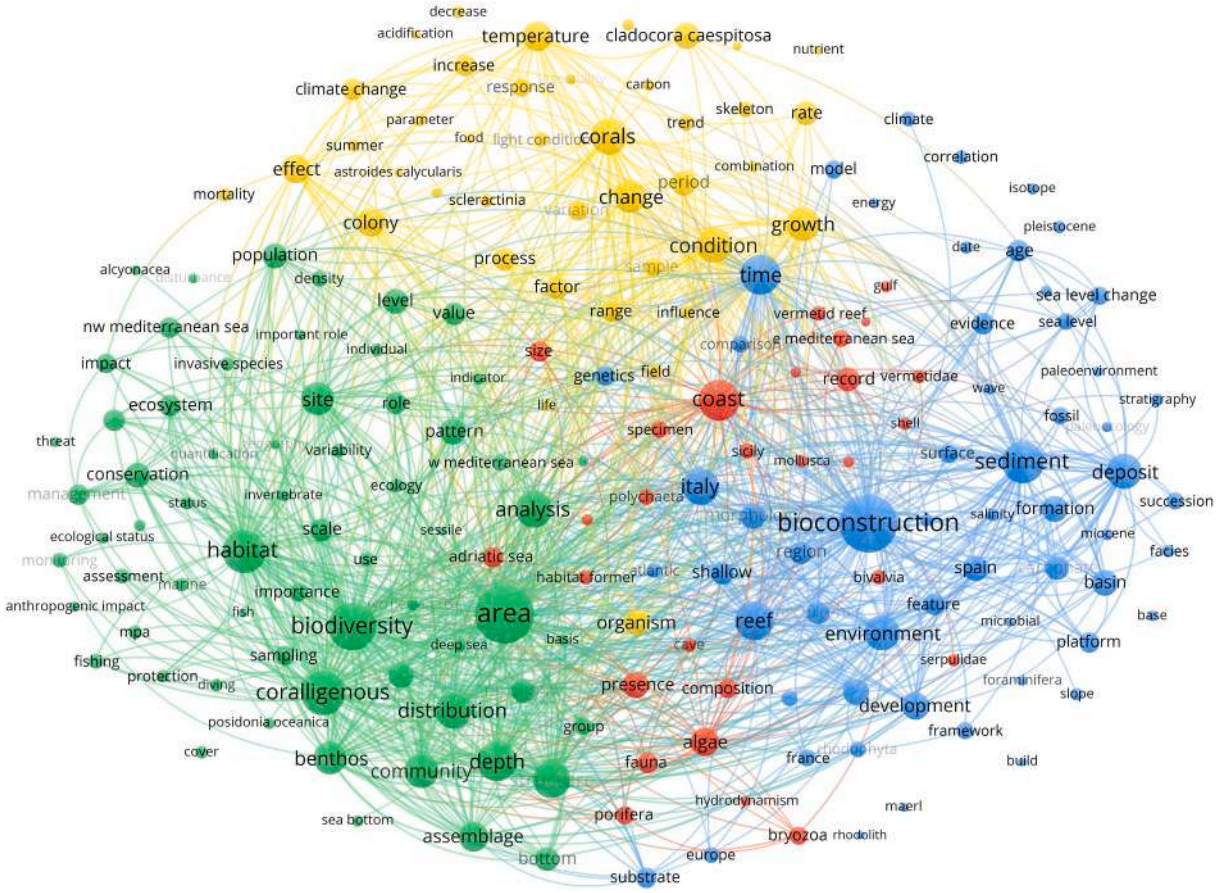

Fig. 4. Co-occurrence network map of terms extracted from the scientific literature on Mediterranean bioconstructions. Colors represent clusters of related terms.

were the bioconstructions with the most recent average publication years in the network, while *C. caespitosa* and vermetid reef were the oldest (Fig. 5).

As regards map density (i.e., number of terms in a point and occurrences of the neighboring terms), it was possible to identify different major hotspots in the map (Fig. 6). The densest hotspot was situated in the cluster 1 area and it included the terms "habitat", "coralligenous", "biodiversity", "benthos" and "importance". Close to it, in the border area between clusters 2 and 4, another hotspot included the terms "area", "distribution", and "community". Another hotspot developed around the "bioconstruction" term of cluster 2, close to "coast", "reef", "morphology", and "environment". Furthermore, in the same cluster, a less dense hotspot comprised terms related to geological research, i.e., "sediment", "deposit", "formation", "carbon", "basin", and "platform". The last of the major hotspots was found in the cluster 3 area and was composed of "corals", "change", "condition", "growth" and "time". Minor hotspots could also be found throughout the map, such as "conservation - management - ecosystem - impact", "temperature - increase - response", and "age - sea level change". Of all the bioconstructions displayed in the map, coralligenous was the only one in a high density hotspot. Vermetid reefs were instead placed in a low density area, between a major and a minor hotspot.

4. Discussions

The assessment of the neglected status of vermetid reefs in the Mediterranean Sea was performed using coralligenous formations as a comparator. Coralligenous was the most studied bioconstruction in the analyzed scientific literature, and its publication productivity set a reference value for measuring the scientific interest on the other Mediterranean bioconstructions. The comparison between vermetid reefs and coralligenous was also supported by the fact that both bioconstructions are well-acknowledged in the scientific literature for supporting high biodiversity levels and have a Mediterranean scale distribution (Gordó-Vilaseca et al., 2022; Martin et al., 2014), potentially drawing the scientific interest of researchers from different Mediterranean countries.

Scientific databases are biased towards English-language journals, whose overrepresentation disadvantages the research published in other languages (Mongeon and Paul-Hus, 2016). The results of the bibliographic search on the Mediterranean bioconstructions lacked the pioneering work written and published in the native language of the authors that contributed to establishing the research on the topic, i.e., mainly French, Italian, and Spanish. This includes the early productions on both the vermetid reefs (among others, de Quatrefages, 1854; Monterosato, 1892; Molinier and Picard, 1953; Pérès and Picard, 1952, 1964) and the coralligenous (among others, Bacci, 1947; Feldmann, 1937; Giaccone, 1965; Giaccone and de Leo, 1966; Gili and Ros, 1984; Laborel, 1960, 1961; Laubier, 1966; Marion, 1883; Pruvot 1894, 1895; Pérès and Picard, 1951; Rossi, 1958; Tortonese, 1958) that were not present in Scopus and WOS databases. Such gap underlines an important limit of bibliographic searches performed on English-oriented scientific databases, as it indeed was found in the case of the Mediterranean bioconstructions literature.

The positive trend of the scientific publication rate on the Mediterranean bioconstructions suggests an overall increased interest in the topic over time (Fig. 2a). The temporal analyses pointed out the leading role of coralligenous research, which became the main contribution to the scientific literature on Mediterranean bioconstructions in the last decade (Fig. 2; Fig. 3). Even though the analysis of the scientific publication rate on *Astroides calycularis* and *Cladocora caespitosa* formations as well as *Sabellaria* spp. and *Lithophyllum* reefs was not performed in this study (despite being included in the search string), a measure of their

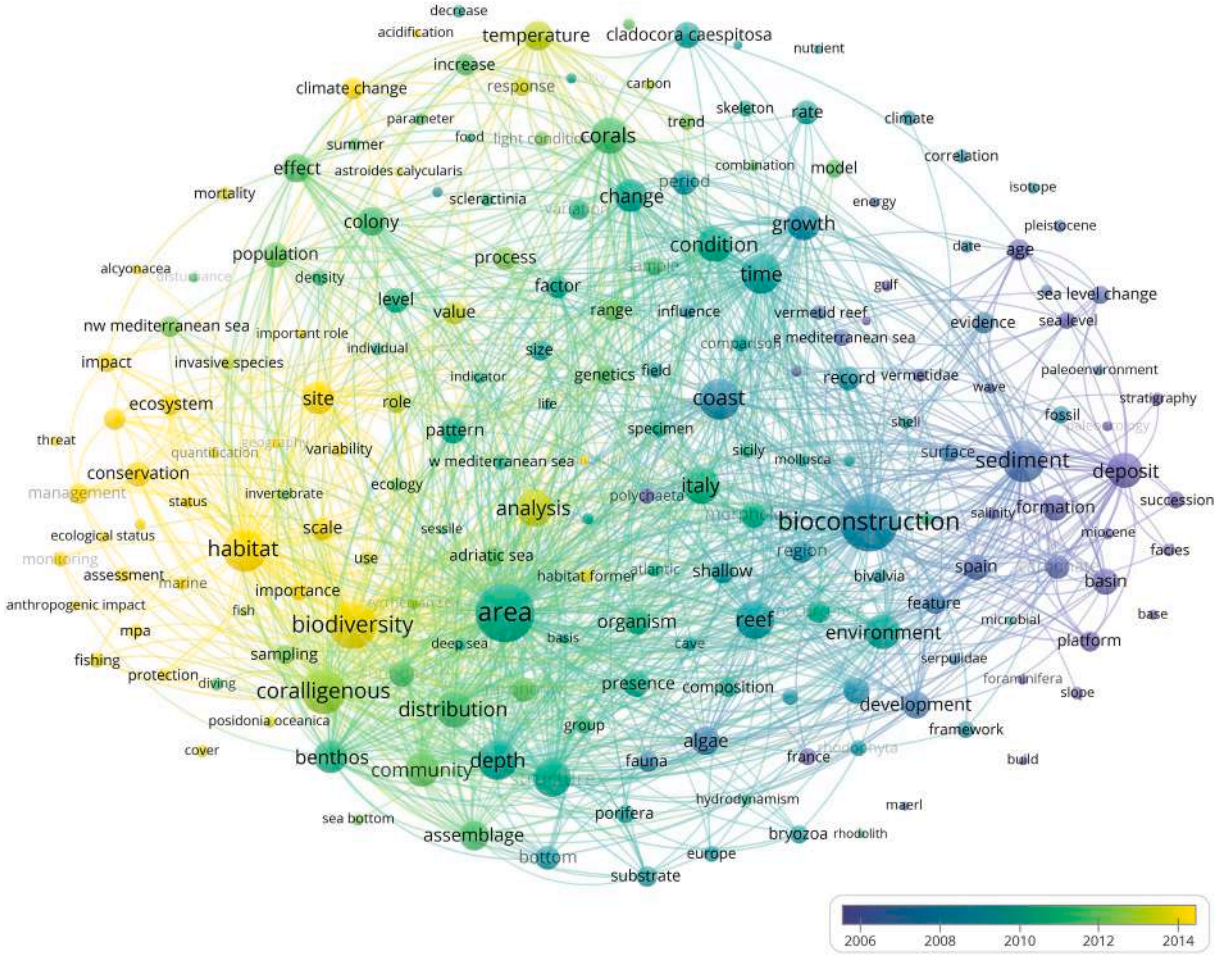

Fig. 5. Overlay visualization of the co-occurrence network map of terms extracted from the scientific literature on Mediterranean bioconstructions. The color gradient shows the average publication year of the publications in which the terms occurred.

cumulative publication rate could be inferred by the temporal trends shown in Fig. 2a and their number of occurrences in Table 4. Compared to the coralligenous, these bioconstructions appear to be understudied as well as the vermetid reefs, especially sabellariid and *Lithophyllum* reefs, but ad hoc analyses would be needed to define them as neglected.

All the temporal analyses performed on coralligenous and vermetid reefs publication rates showed statistically significant differences between them. The ANOVA results revealed that the two relativized publication rates differed by both topic (i.e., coralligenous, vermetid reefs) and time (i.e., years), as well as by their interaction. Therefore, not only the two topics contributed differently to the overall bioconstructions research, but also their evolution over the years was different. The Tukey post-hoc test allowed identifying between which of the investigated time windows such differences occurred, resulting in a clear before/after-2010 pattern. The significant increase of coralligenous contributions in the 2011–2015 and 2016–2020 windows pointed out a manifest focus of the scientific community on coralligenous research after 2010. At the same time, the only pairwise difference found for the vermetid reefs was the significant increase between 1966-995 and the remaining five timeframes (Fig. 3).

The before/after-2010 pattern emerged from the Zero-Inflated Poisson regression model too. The strong and significant positive effects of the interaction between the last two time windows (i.e., 2011–2015 and 2016–2020) and the coralligenous topic (Table S9) highlight that, in those years, the coralligenous production was significantly higher than the vermetid reefs one. In particular, the 2011–2015 window showed a more significant interaction, identifying that period as key for the change of pace experienced by the coralligenous research. Moreover, the significant interaction of 2016–2020 suggests that the publication rate gap between coralligenous and vermetid reefs research is still ongoing and increasing. The analysis of the average publication years of the most occurring terms in the bioconstructions literature provided a temporal perspective not only on the investigated bioconstructions, but also on the research lines connected to them (Fig. 5). In line with the temporal statistical analyses, the overlay network map showed that the scientific interest progressively shifted to the study of corals formations and coralligenous assemblages, neglecting the vermetid reefs. The term "vermetid reef" (APY = 2007.3) fell in the second oldest cluster of the network (cluster 4, APY = 2008.4), far from the more recent terms of clusters 1 and 3 to which, respectively, "coralligenous" (APY = 2012.5) and the two corals "*Astroides calycularis*" (APY = 2013) and "*Cladocora caespitosa*" (APY = 2009.6) belong.

The reasons behind the recently increasing interest on coralligenous assemblages and the concurrent progressive neglect of vermetid reefs could be sought in the European and international conservation directives that were adopted around the beginning of the last decade that eventually shaped the scientific research on the topic of Mediterranean bioconstructions. The first directives, the Barcelona Convention (1975), Bern Convention (1979), and the EU Habitats Directive (1992) included both vermetid reefs and coralligenous formations, and their building species, in their protection lists. In particular, the Barcelona and Bern Conventions did not explicitly target the two bioconstructions, but included *Dendropoma petraeum* (later updated to *Dendropoma petraeum* complex of species) and many species composing coralligenous

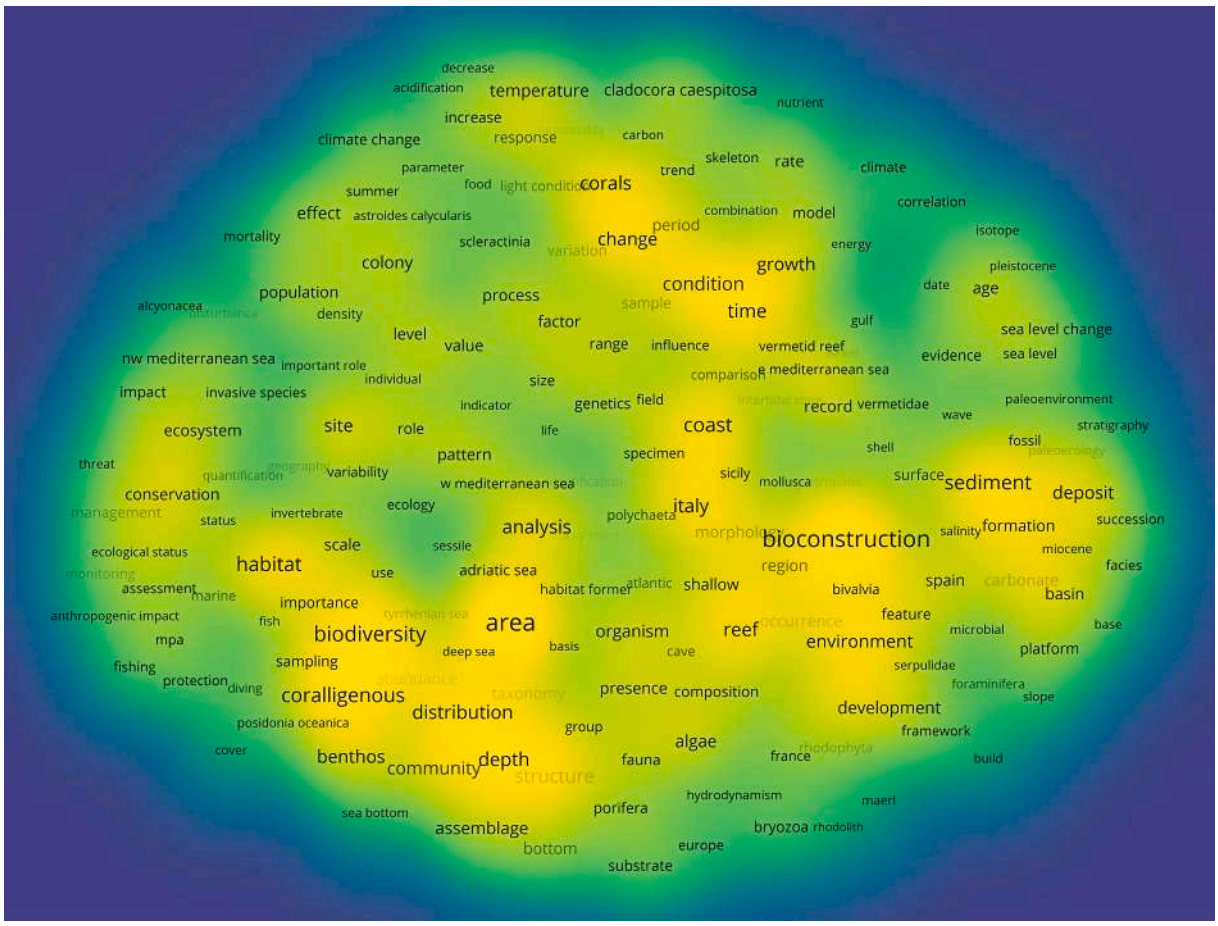

Fig. 6. Density visualization of the co-occurrence map of terms extracted from the scientific literature on Mediterranean bioconstructions. Areas of the map are colored on a color gradient from blue (min. density) to green to yellow (max. density). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

assemblages - e.g., *Corallium rubrum* (Linnaeus, 1758), *Axinella polypoides* (Schmidt, 1862), *Lithophaga lithophaga* (Linnaeus, 1758) - in their lists of species to be protected. The EU Habitats Directive instead included *Dendropoma petraeum* reefs and coralligenous communities such as gorgonians and madreporarians under the generic habitat type 1170 "Reefs" (92/43/EEC). These directives could have influenced the research on bioconstructions in the period identified as "before 2010", in which coralligenous and vermetid reefs publication rates in the context of bioconstructions research were comparable. Coralligenous formations began to be explicitly included when, under the Protocol Concerning Specially Protected Areas and Biological Diversity in the Mediterranean (SPA/BD) of the Barcelona Convention, the Action Plan for the conservation of the "Coralligenous and Other Calcareous Bio-concretions" was developed and adopted in 2008. Following, three symposia called "Symposium on the Conservation of the Coralligenous and other calcareous bio-concretions" took place in 2009, 2014, and 2019. In the same period (2008–2010), the EU Marine Strategy Framework Directive (MSFD) defined the criteria and methodological standards to achieve Good Environmental Status (GES) of EU marine waters by 2020 based on eleven qualitative descriptors (2010/477/EU). Descriptor 1 addressed the identification, mapping, and assessment of the condition of "special habitat types, especially those recognized or identified under Community legislation (the Habitats Directive and the Birds Directive) or international conventions as being of special scientific or biodiversity interest" (2008/56/EC). While this descriptor would potentially promote studies on all bioconstructions of the Mediterranean Sea, including vermetid reefs, descriptor 6 fostered the scientific research on the structure and function of benthic ecosystems such as coralligenous, deep corals, mäerl, and *Posidonia oceanica* to account for the sea-floor integrity. The identification of the coralligenous bioconstruction as an indicator/descriptor of Good Environmental Status likely entailed the convergence of funds, and consequentially of scientific interest, into coralligenous studies promoting its rise in the bioconstructions literature. The translation of these directives into practice would explain the presence of terms such as "conservation", "protection", "management", and "MPA", together with "ecological status", "anthropogenic pressure", "index", "benthos", and "monitoring" in the coralligenous cluster (Fig. 4). All these terms have more recent average publication years (APY $>$ 2014) indeed.

Despite their inclusion in the abovementioned conservation directives, vermetid reefs are weakly linked to "conservation" (LS = 6) and "protection" (LS = 3) (Fig. 4). Such weak connections imply that only few studies involving vermetid reefs explicitly address the issue of protecting and conserving this bioconstruction. The international directives that boosted the research on coralligenous (in terms of both publication rate and variety of investigated topics) did not have the same impact on the vermetid reefs. After decades from the Barcelona Convention, the first to have addressed the importance of preserving the reef-forming species *Dendropoma petraeum*, the conservation of vermetid reefs is still an understudied matter. The concerning lack of studies on the subject points out a severe gap between the aims of directives and their translation into practice. The research on vermetid reefs needs to be enhanced to fill the gap of information required to assess their conservation status, as is the case of most taxonomic groups, especially in high-endemism regions such as the Mediterranean Sea (Hochkirch et al., 2021). No *Dendropoma* species has been assessed in IUCN Red Lists to

this day (https://www.iucnredlist.org/) as well as other understudied reef-forming species such as *Sabellaria alveolata* and *Sabellaria spinulosa*. On the contrary, the well-studied *Astroides calycularis*, *Cladocora caespitosa*, and many species of coralligenous assemblages - e.g., the red gorgonian *Paramuricea clavata* (Risso, 1826), *Corallium rubrum*, or the dusky grouper *Epinephelus marginatus* (Lowe, 1834) - have been assessed and included.

Information on the distribution of the vermetid reefs is also deficient. Although their presence in the intertidal zone would make them more accessible to spot and report compared to other bioconstructions, their actual distribution in the Mediterranean Sea is poorly known. Over the years, vermetid reefs have been studied in many areas of the basin, but a comprehensive and updated map is far from being produced – even though some efforts have been made in the past (Chemello et al., 2014). On the contrary, the coralligenous distribution was recently mapped for the Mediterranean Sea (Giakoumi et al., 2013; Martin et al., 2014) despite being less accessible than intertidal habitats. Due to the high amount of data and money required for the mapping process, comprehensive Mediterranean-scale maps were produced only for other few marine habitats explicitly mentioned in the Marine Strategy Framework Directive (e.g., *Posidonia oceanica* (Linnaeus) Delile, 1813, and mäerl). The convergence of funds to the coralligenous research in the past decade is indicative of the importance attributed to this bioconstruction. This is evidenced by the presence of the terms “importance”, “important role”, and “role” in the coralligenous cluster (Fig. 4) as well as by the fact that the term “importance” was positioned in the densest hotspot of the density map among and connected to the terms “coralligenous” (LS = 34), “biodiversity” (LS = 46), “habitat” (LS = 46), and “conservation” (LS = 29) (Fig. 6). Such acknowledged importance recently drew the attention on the identification and assessment of the ecosystem services provided by the coralligenous habitat (Thierry de Ville d’Avray et al., 2019; Zunino et al., 2019; Zunino et al., 2020). Regardless of the analogous major functional role played in the intertidal zone by the vermetid reefs and the consequent importance attributed to them in the scientific literature, their ecosystem services have not been comprehensively explored and accounted for, with only few of them hypothesized and/or valued (Chemello et al., 2014; Milazzo et al., 2016). As well as ecosystem services, climate change is another research area in which vermetid reefs are not as studied as other bioconstructions. Climate change is a hot research topic in environmental sciences and, of course, also in the marine bioconstructions literature (O = 112, APY = 2014.3). Changes in temperature, sea-level, and acidification of oceans and seas impact reef-building species threatening their persistence. Such phenomena resulted to be mostly investigated for coralligenous and corals bioconstructions (clusters 1 and 3, respectively; Fig. 4), as shown by the co-occurrences of “climate change” with “coralligenous” (LS = 35), and with “*Astroides calycularis*” (LS = 11), “*Cladocora caespitosa*” (LS = 17), and “corals” (LS = 38). As regards the vermetid reefs, the issue remains overall underexplored and their responses to climate change pressures poorly investigated (Milazzo et al., 2016). Only recently, an experimental study on the impacts of acidification and temperature rise was conducted on these bioconstructions showing negative effects on the early life stages of *D. cristatum* and consequently on the vermetid reefs it builds (Alessi et al., 2019).

To our knowledge, this is the first study to assess the neglected status of a marine habitat by analysing literature data through a quantitative and multi-method bibliometric approach. Such methodological protocol could be applied to any habitat, marine or terrestrial, to indicate and assess its neglected status in the scientific literature. Overall, the results confirm previous identifications of vermetid reefs as a neglected habitat (Chemello et al., 2014; Milazzo et al., 2016), showing a lack of attention in the scientific landscape of Mediterranean bioconstructions in terms of both publications and investigated topics. Vermetid reefs match the definition of neglected habitat provided in this study, presenting all the elements that contribute to it, i.e., ecological importance, complex taxonomical identification, lack of distribution maps, and deficiency of economic funds for research. Such factors occur in the face of the explicit inclusion of *Dendropoma* spp. and vermetid reefs in international directives and conventions that aim at their protection and conservation, which, moreover, would need to be updated to the new nomenclature produced after the recent taxonomical disentanglement of the *Dendropoma* species complex (Templado et al., 2015).

The worrying general lack of protection of vermetid reefs at the Mediterranean scale and the local and global threats to their persistence call for the filling of the knowledge gaps from which the scientific literature on the subject poorly suffers. Like other underrepresented or neglected habitats, vermetid reefs require proper data acquisition and monitoring programs, and efficient management actions and plans from the local to the Mediterranean scale. At the current rate, information and conservation gaps are not going to be filled any time soon, which may be too late considering the fast pace and intensity at which climate change pressures impact marine and coastal ecosystems. The scientific research needs to enhance the knowledge and support the effective conservation of all the important bioconstructions of the Mediterranean Sea, including the neglected vermetid reefs.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.ecolind.2022.109358.

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