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Review article

Knowledge mapping analysis of the global seaweed research using CiteSpace

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ABSTRACT

Seaweed research has gained substantial momentum in recent years, attracting the attention of researchers, academic institutions, industries, policymakers, and philanthropists to explore its potential applications and benefits. Despite the growing body of literature, there is a paucity of comprehensive scientometric analyses, highlighting the need for an in-depth investigation. In this study, we utilized CiteSpace to examine the global seaweed research landscape through the Web of Science Core Collection database, assessing publication trends, collaboration patterns, network structures, and co-citation analyses across 48,278 original works published since 1975. Our results demonstrate a diverse and active research community, with a multitude of authors and journals contributing to the advancement of seaweed science. Thematic co-citation cluster analysis identified three primary research areas: "Coral reef," "Solar radiation," and "Mycosporine-like amino acid," emphasizing the multidisciplinary nature of seaweed research. The increasing prominence of "Chemical composition" and "Antioxidant" keywords indicates a burgeoning interest in characterizing the nutritional value and health-promoting properties of seaweed. Timeline co-citation analysis unveils that recent research priorities have emerged around the themes of coral reefs, ocean acidification, and antioxidants, underlining the evolving focus and interdisciplinary approach of the field. Moreover, our analysis highlights the potential of seaweed as a functional food product, poised to contribute significantly to addressing global food security

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and sustainability challenges. This study underscores the importance of bibliometric analysis in elucidating the global seaweed research landscape and emphasizes the need for sustained knowledge exchange and collaboration to drive the field forward. By revealing key findings and emerging trends, our research offers valuable insights for academics and stakeholders, fostering a more profound understanding of seaweed's potential and informing future research endeavors in this promising domain.

1. Introduction

The cultivation of marine macroalgae, also known as seaweed, accounts for only 1.05% of the globe's 275 billion USD seafood trade [1]. With an estimated worth of 2.65 billion USD, there has been an exponential growth in seaweed farming, which saw a thousand-fold surge from 34.7 thousand tonnes in 1950 to an astounding 34.7 million tonnes in 2019 [2]. The Asia-Pacific region is the powerhouse of global seaweed aquaculture, delivering 97% of the total output. China is the largest contributor with 56%, followed by Indonesia with 27%, and South Korea with 5%. Around 35.8 million tonnes of this yield are shared by 49 different nations or territories. The farmed varieties are predominantly Japanese Kelp (*Laminaria japonica*), Eucheuma seaweed nei (*Eucheuma* spp.), Gracilaria seaweed (*Gracilaria* spp.), Wakame (*Undaria pinnatifida*), and Nori nei (*Porphyra* spp.) [2,3].

The category of seaweeds, comprising naturally occurring and cultivated macroalgae, excludes phytoplanktonic algae and microalgae. The utilization of seaweed-derived products has evolved over time, expanding from basic culinary applications to sophisticated, advanced uses. With its status as a multi-billion-dollar sector, seaweed has found its role in various segments, from human and animal nutrition to medicine, biofuel, and even as a key component in fertilizers. Historically, seaweed consumption by humans can be traced to the early fourth century in Japan [4]. Recent F.A.O. data also indicated that Japan, China, and the Republic of Korea are the largest consumers of seaweed as a supplement or condiment in their daily life [5].

Seaweeds gained attention because of their versatility in usage. Previous research includes reviews of seaweed applications in various industries. For example, in livestock diet [6,7], in a few applications as antioxidant agents of commercial products [8,9] as carriers in pharmaceutics (e.g., agars, alginates and carrageenan's) [10,11] and as agriculture production bio-stimulants [12,13].

Previous scientometric analyses have provided valuable insights into the field of seaweed research [14,15]; however, they have not

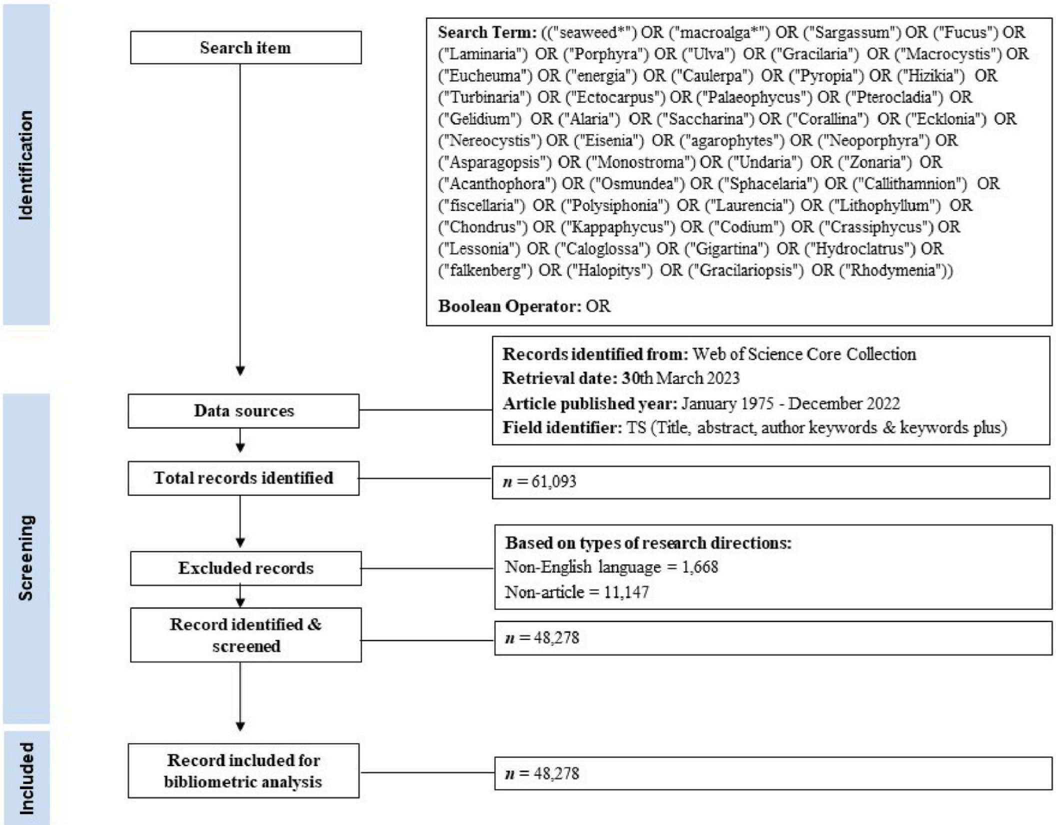

Fig. 1. Flowchart for research structure on global seaweed study.

comprehensively assessed the literature landscape using co-citation analysis. In order to bridge this knowledge gap and enhance our grasp of the current status and progression of macroalgae studies, supplementary analyses are crucial to elucidate global tendencies, academic trajectories, and possible areas of insufficient knowledge. In light of this context, the primary objectives of this investigation have been streamlined as follows:

1. To investigate the key participants within the field of seaweed research. This includes the analysis of leading authors, institutions, and countries. This comprehensive review will illuminate the key contributors and their significant contributions to the field, as well as the structure, and interconnections within the global seaweed research community. In essence, we aim to construct a knowledge map of the seaweed research landscape.
2. To explore the evolution of major themes and interdisciplinary connections in seaweed research by examining the research clusters and identifying emerging trends. An extensive analysis of the utilized keywords in the publications of seaweed research will be carried out, as they serve as markers of significant trends and potential future research directions.
3. To understand the historical and temporal context of the field through a timeline co-citation analysis. By examining the temporal relationships between seminal publications, we seek to grasp their influence on the trajectory of seaweed research.

The intention of this study is to present an all-inclusive perspective on the prevailing trends and budding research themes in the field of seaweed investigation. Using the Web of Science Core Collection (WOSCC) database as the fundamental reservoir of scholarly articles, this probe aspires to impart valuable implications that can steer upcoming scholarly pursuits and shape policy-making in the domain of macroalgae exploration. Such a bibliometric scrutiny will not just aid in ascertaining the avant-garde in the discipline but also foster a deeper understanding of the scientific discourse, unexplored areas, and evolving scholarly pathways. By showcasing a thorough and methodical literature review, this study seeks to captivate the attention of peers and offer a valuable compendium for the scholarly fraternity, ultimately propelling the development of seaweed research and its prospective applications across a range of sectors, such as food, bioenergy, and environmental stewardship.

2. Materials and methods

2.1. Data sources and methodology

To comprehensively explore the evolution of seaweed-related literature, we employed a systematic and rigorous search strategy using the Web of Science Core Collection (WOSCC) database. The study's flowchart is depicted in Fig. 1. We analyzed data derived from publications spanning 1975 to 2022, ensuring an extensive coverage of historical and contemporary research.

For text processing, we utilized the.txt format to extract information from manuscript titles, research abstracts, author keywords, and Keywords Plus, which enabled us to construct a robust descriptive dataset. The WOSCC database also supplied co-citation references for each paper or article, providing valuable metadata for our scientometric analysis.

Considering the vast number of approximately 12,000 seaweed species described globally [16], we opted for a focused approach by using Genus name of the seaweed and two major keywords for our search string; ("seaweed*") OR ("macroalga*") OR ("Sargassum") OR ("Fucus") OR ("Laminaria") OR ("Porphyra") OR ("Ulva") OR ("Gracilaria") OR ("Macrocystis") OR ("Eucheuma") OR ("energia") OR ("Caulerpa") OR ("Pyropia") OR ("Hizikia") OR ("Turbinaria") OR ("Ectocarpus") OR ("Palaeophycus") OR ("Pterocladia") OR ("Gelidium") OR ("Alaria") OR ("Saccharina") OR ("Corallina") OR ("Ecklonia") OR ("Nereocystis") OR ("Eisenia") OR ("agarophytes") OR ("Neoporphyra") OR ("Asparagopsis") OR ("Monostroma") OR ("Undaria") OR ("Zonaria") OR ("Acanthophora") OR ("Osmundea") OR ("Sphacelaria") OR ("Callithamnion") OR ("fiscellaria") OR ("Polysiphonia") OR ("Laurencia") OR ("Lithophyllum") OR ("Chondrus") OR ("Kappaphycus") OR ("Codium") OR ("Crassiphycus") OR ("Lessonia") OR ("Caloglossa") OR ("Gigartina") OR ("Hydroclatrus") OR ("falkenberg") OR ("Halopitys") OR ("Gracilariopsis") OR ("Rhodymenia"). This decision ensured comprehensive yet manageable search results, preventing the overwhelming complexity that would arise from including all scientific names. Additionally, it eliminated potential confusion stemming from other species' names unrelated to seaweeds. To enhance the validity of our analysis, we excluded non-English articles, mitigating potential biases among reviewers with limited language proficiency. By appending an asterisk (*) to "seaweed," we ensured the inclusion of variations such as "seaweeds."

Due to database constraints, our search was limited to titles, keywords, and abstracts, as the WOSCC did not provide access to full-text articles. Nonetheless, this scope allowed us to accurately identify and analyze relevant literature while avoiding duplicate terms referring to the same article title, keywords, or abstract in the downloaded metadata. Our methodological approach, grounded in scientometric analysis and a carefully designed search strategy, provides a solid foundation for mapping the evolution of seaweed literature, while demonstrating the strength and comprehensiveness of the techniques employed in this study.

2.2. Data visualization

Scientometrics has recently been reconceptualized as a systematic, continuous, and comprehensive evaluation of quantitative studies across various scientific and technological fields [17–19]. This approach employs diverse tools such as CiteSpace, VOSviewer, and SciTools to identify knowledge domains and thematic issues in large datasets, allowing for a thorough examination of complex research areas.

For our qualitative dataset, we utilized Microsoft Excel 2019 and its associated statistical analysis tools to perform descriptive analyses. These analyses generated insights into the evolution and trends of (i) publication volume, (ii) author contributions, (iii) institutional participation, (iv) journal titles, and (v) country involvement in seaweed research.

We employed CiteSpace software (v. 6.2.R2) for a comprehensive co-citation analysis, as this tool seamlessly integrates with co-cited data from the Web of Science (W.O.S.). Developed by Chaomei Chen at Drexel University, U.S.A. (https://citespace.podia.com/), CiteSpace provides a robust visualization map based on relationships between co-cited authors, documents, and journals. The software evaluates these connections using various metrics, including degree, centrality, sigma, silhouette, Latent Semantic Indexing (LSI), Log-Likelihood Ratio (LLR), and Mutual Information (MI) [20]. We assessed the quality of variables for our study by focusing on degree, centrality, and sigma [21].

However, due to search strategy limitations, our scientometric analysis using the WOSCC database encountered an "artefact" effect [22]. Specifically, the WOSCC database restricted searches to titles only for studies between 1990 and 1991, whereas searches for all other years encompassed "titles, abstracts, and keywords." Despite this constraint, our methodological approach, rooted in scientometrics and comprehensive data analysis tools, offers a solid foundation for mapping the evolution of seaweed literature and showcases the strength of the techniques employed in this study.

3. Results

3.1. Publication trends

The global annual publications on seaweed have revealed an interesting and dynamic trend in the publication landscape (Fig. 2). The data spans over 48 years, from 1975 to 2022, encompassing 48,286 records. The initial years (1975–1990) were characterized by a relatively modest publication output, with an average annual count of 213 records, amounting to merely 1.43% of the entire record count. The period from 1991 to 2010 witnessed a steady ascent in annual publications, averaging 1051 records each year, constituting 3.14% of the full record count. Between 2010 and 2011, there was an abrupt rise in publication, with an increase of 19.96% in the yearly record tally. In the most contemporary phase (2011–2022), there has been a considerable upsurge in the number of publications, with an average annual record count of 2387, corresponding to 5.88% of the complete records. The pinnacle was reached in 2021, with 3629 publications, accounting for 7.52% of the full records.

3.2. Geographical distribution of contributions

The knowledge mapping investigation performed using CiteSpace revealed informative patterns concerning the global distribution of macroalgae research (Fig. 3). The five primary contributing nations, namely the United States, People's Republic of China, Japan, South Korea, and Australia, account for almost half of the 48,286 scholarly publications in this field.

The United States emerges as the leader with 15.79% of the scholarly publications, making it a substantial contributor to macroalgae research. The People's Republic of China follows closely, providing 13.04% of the scholarly output. Japan, South Korea, and Australia contribute 7.36%, 6.39%, and 6.31% of the scholarly publications respectively, highlighting their significant roles within the global macroalgae research community.

In addition, European nations such as Spain, France, and Germany, along with Canada, India, and Brazil, also contribute notably to the global corpus of macroalgae research, indicating the international span of research efforts in this field.

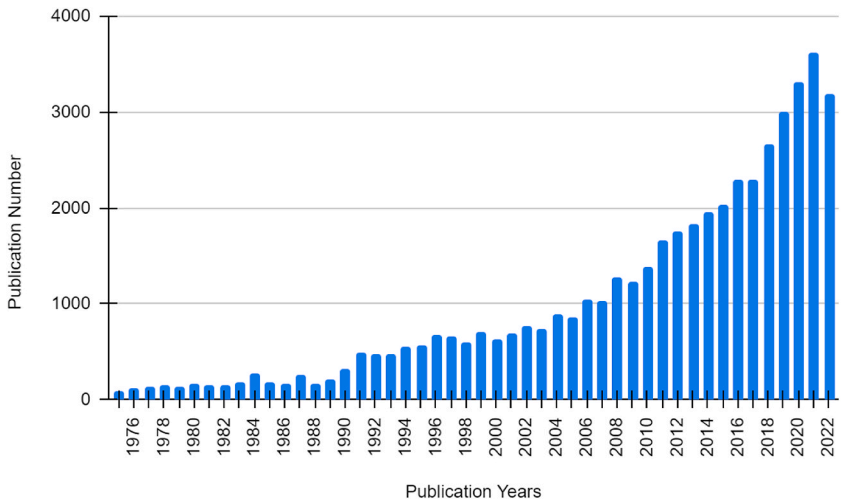

Fig. 2. The annual number of published articles on seaweed research in the Web of Science Core Collection from 1975 to 2022.

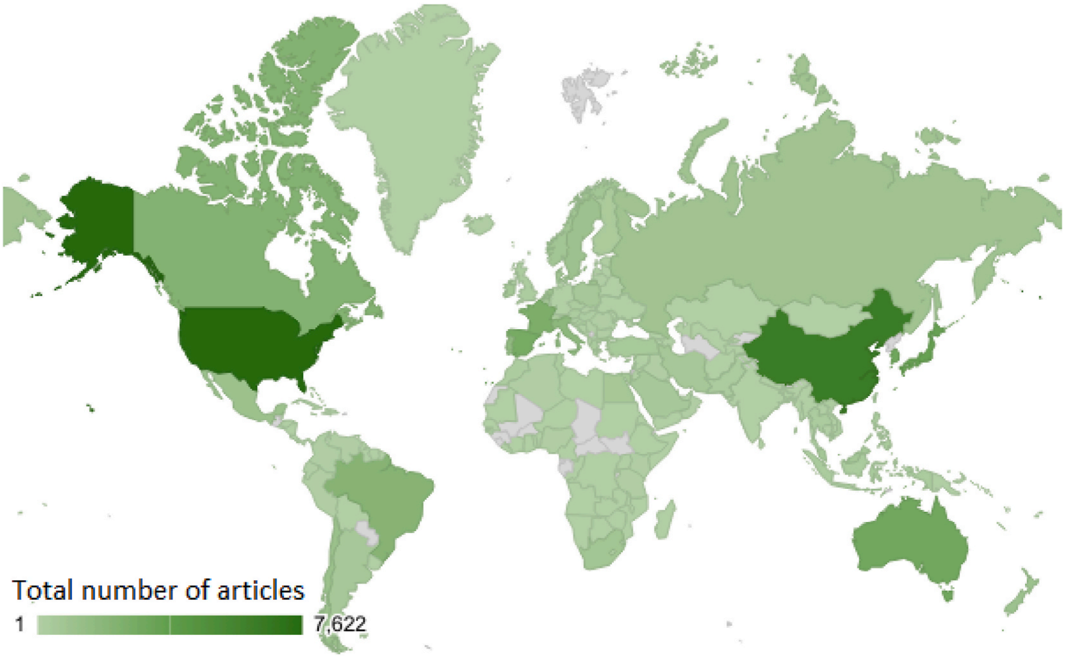

Fig. 3. Total publications per nation for seaweed research; dark green represents the highest total number of publications, lighter green represents fewer publications, and grey shows no publication records. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

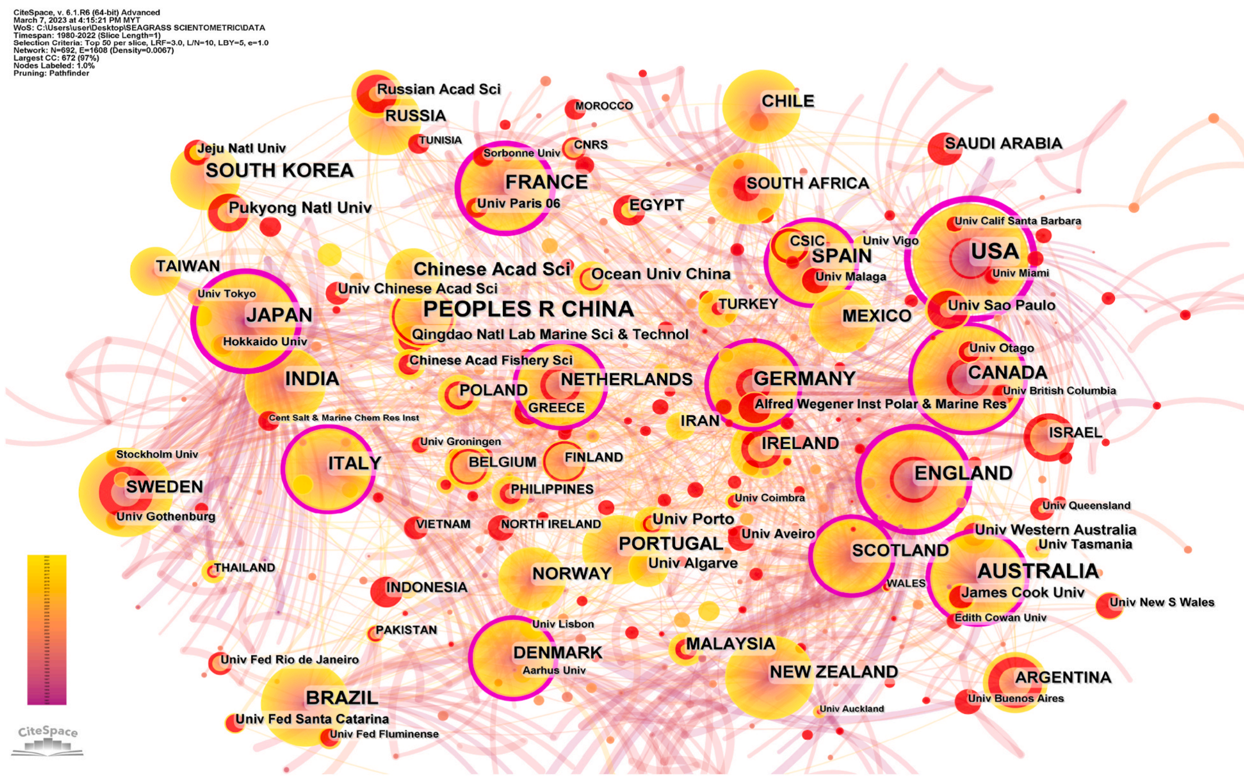

Fig. 4. Cooperation network among the countries and organizations in seaweed-related research between 1975 and 2022. Node size represents the number of publications from each country or organization; line thickness indicates the extent of research cooperation between entities.

3.3. In-depth analysis of the key contributors

Seaweed research, characterized by its multidisciplinary scope and complexity, demands synergistic efforts across various scientific fields, academic institutions, and funding bodies. A meticulous examination of the principal entities in this domain is critical for an in-depth comprehension of the current research milieu and for identifying potential avenues for further investigation. Fig. 4 showcases a network clustering visualization map, intricately constructed using the CiteSpace tool. This map elucidates the intricate web of collaborations and interactions among pivotal organizations and individuals in seaweed research. Complementing this visual representation, Table 1 methodically enumerates the foremost 10 research disciplines, the leading organizations in terms of publication volume, and the key funding agencies instrumental in seaweed research from 1975 to 2022. This tabulation and visualization collectively illuminate the inherently interdisciplinary nature of seaweed research, as well as the significant academic and financial contributors driving advancements in this field.

Marine Freshwater Biology leads the research disciplines with 14,906 publications, demonstrating the strong connection between seaweed studies and aquatic ecosystems. This is followed by Plant Sciences (7036), Environmental Sciences (6692) and Ecology (5054), emphasizing the importance of seaweed research in understanding ecological processes, environmental interactions, and plant biology. Other vital disciplines include Biotechnology Applied Microbiology, Oceanography, Food Science Technology, Biochemistry Molecular Biology, Fisheries, and Chemistry Applied, highlighting the diverse range of scientific fields that have contributed to the advancement of seaweed research.

Chinese Academy of Sciences is the most published organization, with 1586 publications reflecting its strong commitment to exploring and understanding seaweeds. Other prominent organizations include the Centre National De La Recherche Scientifique (CNRS) (1443 publications), UDICE French Research Universities (1265 publications), University of California (1228 publications), and Helmholtz Association (757 publications). These organizations represent a diverse range of academic and research institutions from around the world, showcasing global interest and collaborative efforts in seaweed research.

Institutions based in France, encompassing the Centre National De La Recherche Scientifique (CNRS) and the union of UDICE French Research Universities, have been instrumental in propelling macroalgae research forward. France's preeminence in this field is chiefly due to its expansive coastal stretch along the Atlantic Ocean, the English Channel, and the Mediterranean Sea, which boasts a wealth of coastal biodiversity. This diversity offers a plethora of marine habitats and abundant seaweed species, serving as a natural laboratory for scientific exploration and investigation. For instance, the French National Inventory of Natural Heritage (INPN) has documented almost all seaweed species along the French coast, showcasing the nation's vast marine resources [23]. Furthermore, French governmental and non-governmental organizations, recognizing the potential of seaweed research in addressing ecological, economic, and industrial challenges, have invested substantially in research and development. Funding from organizations such as CNRS and the European Commission has facilitated the advancement of innovative research projects, technology development, and dissemination of findings, exemplified by the initiation of projects like TASCMAR and GENIALG [24], which focus on sustainable biotechnological applications of marine resources, including seaweeds.

The National Natural Science Foundation of China (NSFC) emerges as the leading funding agency, supporting 3387 publications. This is followed by the National Science Foundation (N.S.F.) with 1234 publications and the Conselho Nacional De Desenvolvimento Cientifico E Tecnologico Cnpq with 1087 publications. Other significant grant providers include the European Commission, U.K. Research Innovation (UKRI), Fundacao para a Ciencia e a Tecnologia, the Japanese, Spanish Government, and the Australian Research Council. The diverse array of funding agencies underscores the recognition of seaweed research's importance and its potential applications across various sectors.

The evolution of global seaweed research, as depicted in these; Table 2 (1975–1990), Table 3 (1991–2010) and Table 4 (2011–2022), displays a rich timeline of investigations, demonstrating shifts in focus areas and the diversification of journals publishing on this topic.

Table 1
Main contributors in research disciplines, organization and funding agencies related to seaweed between 1975 and 2022.

Important Research Disciplines		Most Published Organization		Major Funding Agencies	
Research Disciplines	No.	Affiliation	No.	Grant Providers	No.
Marine Freshwater Biology	14,906	Chinese Academy of Sciences	1586	National Natural Science Foundation of China NSFC	3387
Plant Sciences	7036	Centre National De La Recherche Scientifique	1443	National Science Foundation NSF	1234
Environmental Sciences	6692	UDICE French Research Universities	1265	Conselho Nacional De Desenvolvimento Cientifico E Tecnologico Cnpq	1087
Ecology	5054	University Of California System	1228	European Commission	1037
Biotechnology Applied Microbiology	4629	Helmholtz Association	757	Fundacao para a Ciencia e a Tecnologia	911
Oceanography	3635	Institute of Oceanology CAS	736	Ministry Of Education Culture Sports Science and Technology Japan MEXT	853
Biochemistry Molecular Biology	3261	Ocean University of China	721	Coordenação de Aperfeiçoamento de Pessoal de Nível Superior	799
Food Science Technology	2453	Sorbonne Universite	711	Japan Society for The Promotion of Science	735
Fisheries	2063	Russian Academy of Sciences	682	Spanish Government	663
Chemistry Applied	1997	Egyptian Knowledge Bank Ekb	400	UK Research Innovation UKRI	639

Table 2
Top 10 highly cited articles in the studies related to seaweed on the Web of Science Core Collection database, from 1975 to 1990.

Highly cited articles			
Reference	Journal	Total WOS Citation (June 2023)	Publication title
Litler and Litler [25]	The American Naturalist	687	The evolution of thallus form and survival strategies in benthic marine macroalgae: field and laboratory tests of a functional form model
Chapman and Craigie [27]	Marine Biology	417	Seasonal growth in *Saccharina latissima* (formerly *Laminaria longicruris*): relations with dissolved inorganic nutrients and internal reserves of nitrogen
Lubchenco [26]	Ecology	362	*Littornia* and *Fucus*: effects of herbivores, substratum heterogeneity, and plant escapes during succession
Cardellina et al. [29]	Science	297	Seaweed dermatitis: structure of lyngbyatoxin A
Hay [42]	Ecology	292	The functional morphology of turf-forming seaweeds: persistence in stressful marine habitats
Percival [28]	British Phycological Journal	281	The polysaccharides of green, red and brown seaweeds: their basic structure, biosynthesis and function
Gschwend et al. [43]	Science	274	Volatile halogenated organic compounds released to seawater from temperate marine macroalgae
Underwood [44]	Oecologia	247	The effects of grazing by gastropods and physical factors on the upper limits of distribution of intertidal macroalgae.
Zieman et al. [45]	Bulletin of Marine Science	245	Distribution, abundance and productivity of seagrasses and macroalgae in Florida Bay
Edmonds and Francesconi [46]	Nature	245	Arseno-sugars from brown kelp (*Ecklonia radiata*) as intermediates in cycling of arsenic in a marine ecosystem

Table 3
Top 10 highly cited articles in the studies related to seaweed on the Web of Science Core Collection database, from 1991 to 2010.

Highly cited articles			
Reference	Journal	Total WOS Citation (June 2023)	Publication title
Hughes [30]	Science	2150	Catastrophes, phase shifts, and large-scale degradation of a Caribbean coral reef.
Hughes et al. [31]	Current Biology	1042	Phase shifts, herbivory, and the resilience of coral reefs to climate change
Riebesell et al. [32]	Nature	1013	Reduced calcification of marine plankton in response to increased atmospheric CO_2.
Valiela et al. [47]	Limnology and Oceanography	986	Macroalgal blooms in shallow estuaries: controls and ecophysiological and ecosystem consequences.
Sheng et al. [33]	Journal of Colloid and Interface Science	884	Sorption of lead, copper, cadmium, zinc, and nickel by marine algal biomass: characterization of biosorptive capacity and investigation of mechanisms.
Croft et al. [34]	Nature	864	Algae acquire vitamin B_{12} through a symbiotic relationship with bacteria.
Kinlan and Gaines [48]	Ecology	753	Propagule dispersal in marine and terrestrial environments: a community perspective.
Hentzer et al. [49]	Microbiology	744	Inhibition of quorum sensing in *Pseudomonas aeruginosa* biofilm bacteria by a halogenated furanone compound.
Cumashi et al. [35]	Glycobiology	708	A comparative study of the anti-inflammatory, anticoagulant, antiangiogenic, and antiadhesive activities of nine different fucoidans from brown seaweeds.
Raymundo-Piñero et al. [50]	Advanced Material	708	A high-performance carbon for supercapacitors obtained by carbonization of a seaweed biopolymer.

In the initial phase (1975–1990), a majority of the high-impact research was published in journals such as The American Naturalist, Ecology, and Science. The research of this period was predominantly centered around the physiological and ecological aspects of seaweed. The works of Litler and Litler [25], Lubchenco [26], and Chapman and Craigie [27] exemplify this focus, emphasizing seaweed evolution, succession, and nutrient relations. Further, studies investigating the biochemistry of seaweeds like the work of Percival [28] on polysaccharides or Cardellina et al. [29] on lyngbyatoxin, were also of notable influence.

The following period (1991–2010) revealed a remarkable change, both in terms of the journals involved, and the thematic focus. Publications from this era appeared in a wider array of journals like Current Biology, Limnology and Oceanography, and Journal of Colloid and Interface Science. Research topics ranged from broad ecological shifts (as demonstrated in the works of Hughes [30]; Hughes et al. [31]) to marine responses to climate variations [32]. Noteworthy is the perceptible transition towards the applicability of seaweed, as mirrored in the research by Sheng et al. [33] (2004) concerning the absorption of heavy metals, Croft et al. [34] (2005) focusing on algal symbiosis with bacteria, and Cumashi et al. [35] investigating fucoidans' biological activities.

The most recent period (2011–2022) revealed a further diversification of research topics and a clear emphasis on the application of seaweeds in multiple sectors. This period saw a spread of impactful research across journals like Journal of Applied Phycology, Bioresource Technology, and Nature Climate Change. Studies such as Holdt and Kraan [36], Wells et al. [37], and John et al. [38] underscore the potential of seaweed in functional foods and bioenergy sectors. The papers also hint at a rising concern for climate change impacts on marine ecosystems as highlighted by the works of Wernberg et al. [39,40], and a continued interest in algae's ecological roles and microbial interactions [41].

Table 4
Top 10 highly cited articles in the studies related to seaweed on the Web of Science Core Collection database, from 2011 to 2022.

Highly cited articles			
Reference	Journal	Total WOS Citation (June 2023)	Publication title
Holdt and Kraan [36]	Journal of Applied Phycology	1105	Bioactive compounds in seaweed: functional food applications and legislation.
Wernberg et al. [40]	Science	743	Climate-driven regime shift of a temperate marine ecosystem.
Wells et al. [37]	Journal of Applied Phycology	696	Algae as nutritional and functional food sources: revisiting our understanding.
John et al. [38]	Bioresource Technology	673	Micro and macroalgal biomass: a renewable source for bioethanol.
Wernberg et al. [39]	Nature Climate Change	646	An extreme climatic event alters marine ecosystem structure in a global biodiversity hotspot.
Fomina and Gadd [51]	Bioresource Technology	629	Biosorption: current perspectives on concept, definition and application.
Tyberghein et al. [52]	Global Ecology and Biogeography	515	Bio-ORACLE: a global environmental dataset for marine species distribution modelling.
Burke et al. [41]	PNAS	506	Bacterial community assembly based on functional genes rather than species.
Smetacek and Zingone [53]	Nature	501	Green and golden seaweed tides on the rise.
Craigie [54]	Journal of Applied Phycology	497	Seaweed extract stimuli in plant science and agriculture.

3.4. *Thematic cluster analysis of research*

Our research employed scientometric techniques to analyze a large dataset and identify co-citation clusters within the seaweed literature. CiteSpace's algorithms, specifically Latent Semantic Indexing (LSI), Log-Likelihood Ratio (LLR), and Mutual Information (MI), facilitated the extraction of meaningful patterns and relationships from the data. These algorithms are integral to the visualization and interpretation of complex research clusters, allowing for a comprehensive understanding of the knowledge landscape in seaweed research [20].

Our comprehensive analysis has identified 31 co-citation clusters, with the top 10 depicted in Table 5. These primary clusters embody the critical research areas within the seaweed literature, reflecting the evolution of the field and delineating the key trends and themes. Furthermore, the cluster labels, as generated by CiteSpace and depicted in Fig. 5, offer a lens into the intricate network of clusters. This visual tool assists in understanding the interrelated nature of seaweed studies, deepening our comprehension of the connections between various research topics, and facilitating the identification of potential future research directions [19].

Our analysis of global seaweed research led to the identification of ten distinctive co-citation clusters, each embodying unique research themes. A summarized account of these clusters and their key findings is given below:

a. Cluster 0: Coral Reef - Focused on the interactions between coral reef ecosystems and *Sargassum muticum*, a brown seaweed species. The studies within this cluster largely examine the potential benefits and detriments of seaweed to coral health, diversity, and ecosystem functionality [55–57].
b. Cluster 1: Solar Irradiation - Revolves around the impacts of sunlight on macroalgae physiology, specifically how differing light conditions affect photosynthesis, growth, and productivity [58–60].
c. Cluster 2: Ultraviolet Exposure - Explores the effects of UV on macroalgae, particularly the role of mycosporine-like amino acids (MAAs) in UV protection and their potential application in biotechnology and cosmeceuticals [61].
d. Cluster 3: Sea Acidification - Examines how kelp forests and macroalgae respond physiologically to increased CO_2 concentrations, alongside assessing the wider implications for community composition and ecosystem functionality [62,63].
e. Cluster 4: Antioxidative Activity - Emphasizes the antioxidative properties of *Ecklonia cava*, probing the bioactive compounds responsible and their potential health benefits [64,65].

Table 5
Top 10 cluster I.D.s in Seaweed research: A CiteSpace analysis.

ClusterID	Size	Silhouette Score	Label (LSI)	Label (LLR)	Label (MI)
#0	258	0.942	coral reef	coral reef	brown seaweed
#1	184	0.922	solar radiation	solar radiation	brown seaweed
#2	182	0.938	mycosporine-like amino acid	ultraviolet radiation	brown seaweed
#3	156	0.993	ocean acidification	kelp forest	brown seaweed
#4	149	0.968	antioxidant activity	*Ecklonia cava*	brown seaweed
#5	139	0.882	intertidal seaweed	embryonic sporophyte	brown seaweed
#6	124	0.927	nuclear gene	nuclear gene	mitochondrial genome
#7	110	0.927	marine macroalgae	inorganic carbon	different biogeographic group
#8	97	0.95	morphological mutant	morphological mutant	ocean acidification
#9	93	0.94	shade species	shade species	ocean acidification

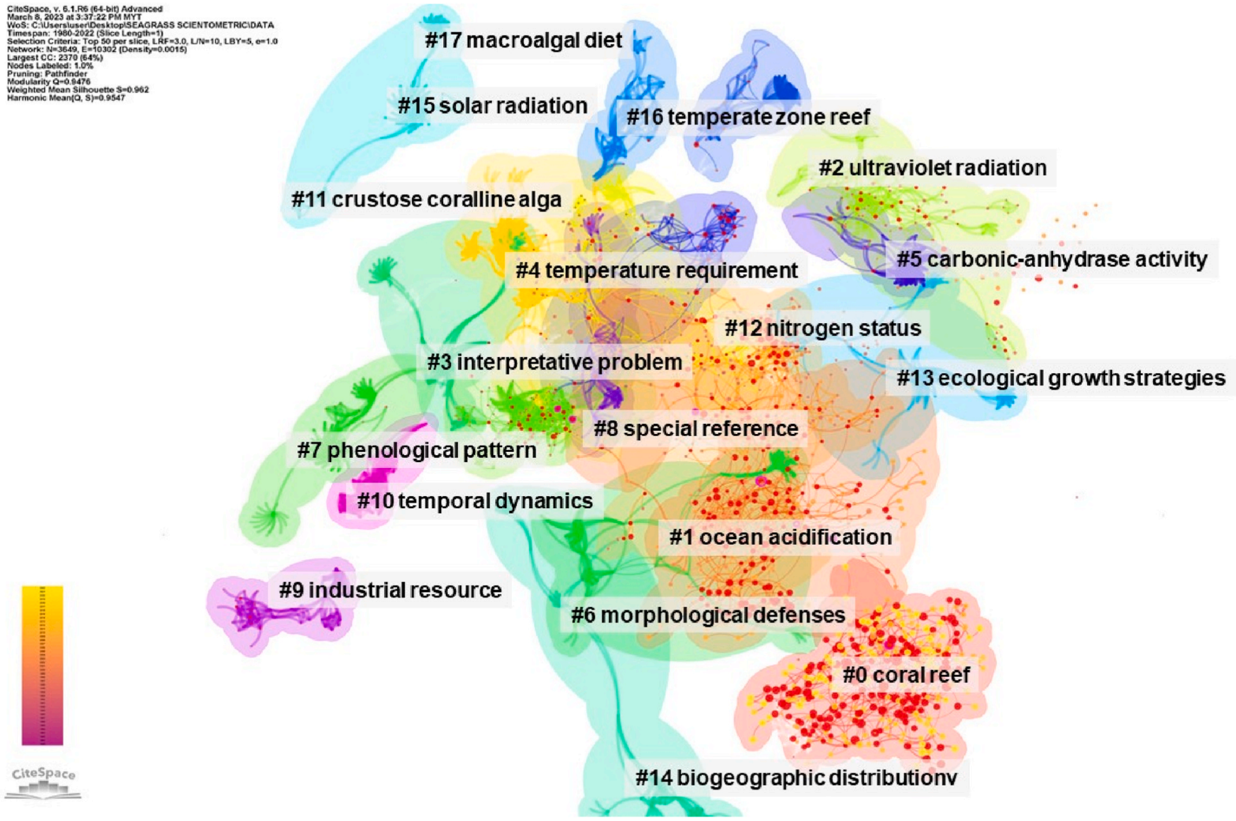

Fig. 5. The reference co-citation network of publications on seaweeds from 1975 to 2022 was analyzed. The size of the nodes in the network reflects the frequency of citation, while the colors of the nodes, ranging from magenta (1975) to yellow (2022), indicate the progression of research over time. The colored connections between the nodes illustrate the co-citation relationships, highlighting the interconnectivity and collaborative nature of research within the seaweed study community. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

f. Cluster 5: Intertidal Seaweed - Investigates the ecology of littoral macroalgae, focusing on variables affecting their distribution, reproduction, and population dynamics [66].
g. Cluster 6: Nuclear Gene - Delves into the genetic makeup of macroalgae, scrutinizing the nuclear genes' relationship with the mitochondrial genome and their contribution to genetic diversity and evolution [67].
h. Cluster 7: Marine Macroalgae - Investigates the role of aquatic plants in biogeochemical cycling, particularly the mechanisms of carbon intake and their potential contribution to global carbon sequestration [68].
i. Cluster 8: Morphological Mutants - Explores morphologic variation in macroalgae in relation to environmental changes, analyzing the genetic and environmental influences on this variation [69,70].
j. Cluster 9: Shade Species - Centers on low-light tolerant macroalgae species, examining their adaptations and contributions to the overall diversity and productivity of marine ecosystems [71,72].

Our parallel scientometric keyword clustering analysis identified 423 high-frequency keywords (Fig. 6), offering a complementary perspective. This keyword-based analysis illuminates the multi-dimensional evolution of seaweed-related studies, with clusters underscoring various research aspects, such as ecology, environmental impacts, and potential applications across diverse sectors.

This study uncovered ten primary keywords co-citation clusters within global seaweed research, each offering unique insights. The major descriptors and notable findings are given below:

a. Cluster #0: Coral Reef (Major descriptors: "community," "patterns," "diversity") - Centralized around coral reef ecosystems, with key research from Hughes et al. [73] elucidating seaweeds' vital role in coral reef health and resilience.
b. Cluster #1: Antioxidant Activity (Major descriptors: "algae," "seaweed," "antioxidant activity") - Investigates the antioxidant potential of seaweed-derived compounds.
c. Cluster #2: Solar Radiation & Acidification (Major descriptors: "photosynthesis," "marine macroalgae," "light") - Explores the impact of solar radiation and ocean acidification on macroalgae. Notably, Duarte et al. [74] probed the resilience of macroalgae under increased CO_2 concentrations.

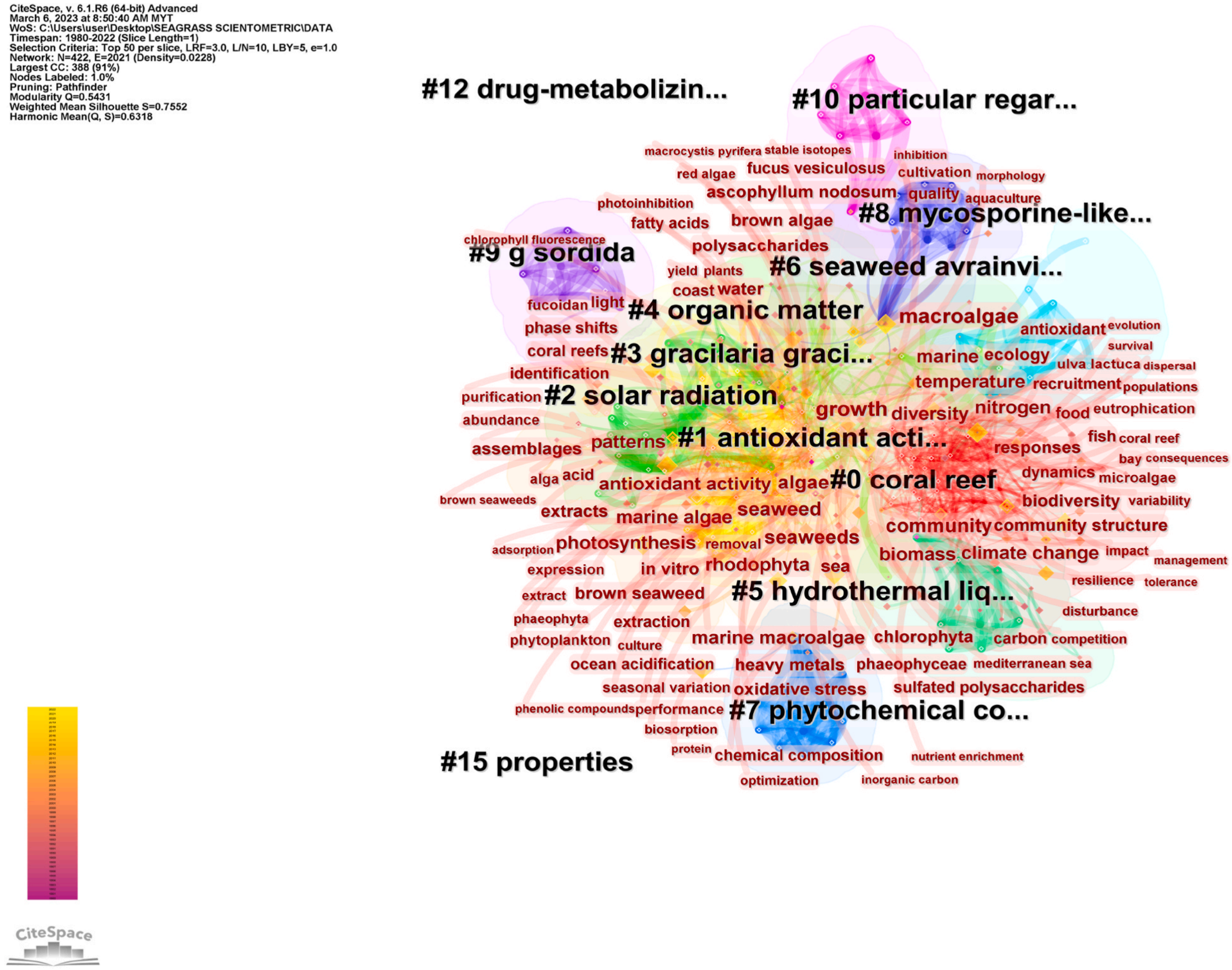

Fig. 6. Scientometric clustering of 423 key keywords into 13 thematic groups in Seaweed research publications (1975–2022) via CiteSpace analysis.

d. Cluster #3: *Gracilaria gracilis* (Major descriptors: "growth," "seaweeds," "Rhodophyta") - Focuses on the growth and taxonomy of the red alga, *Gracilaria gracilis.* Spanò et al. [75] provides insights into its cultivation strategies.
e. Cluster #4: Organic Matter & Stable Isotopes (Major descriptors: "water," "carbon," "plants") - Examines the relationship between water, carbon, and seaweed plants. Carvalho et al. [76] contributed to understanding seaweeds' role in coastal carbon cycling.
f. Cluster #5: Hydrothermal Liquefaction (Major descriptors: "biomass," "microalgae," "competition") - Explores the potential of seaweed biomass in bioenergy production, with Wang et al. [77] demonstrating the feasibility of converting seaweed biomass into bio-oil.
g. Cluster #6: *Avrainvillea longicaulis* (Major descriptors: "evolution," "resistance," "chemical defenses") - Investigates the seaweed species *Avrainvillea longicaulis*' chemical defenses and antioxidant activity, with Hay et al. [78] and Zubia et al. [79], examining its ability to produce secondary metabolites deterring herbivory.
h. Cluster #7: Phytochemical Composition (Major descriptors: "chemical composition," "protein," "limitation") - Examines the chemical and protein composition of seaweeds. Notably, Wong and Cheung [80] emphasized seaweeds as potential alternative protein sources.
i. Cluster #8: Mycosporine-like Amino Acids (M.A.A.s) & Nutrient Enrichment (Major descriptors: "macroalgae," "morphology," "sp nov") - Focuses on the protective role of M.A.A.s in macroalgae against harmful U.V. radiation, with Sun et al. [81] providing critical research.
j. Cluster #9: *Gracilaria chilensis* (formerly *Gracilaria sordida*) (Major descriptors: "red alga," "leaves," "alpha-galactosidase") - Investigates the interactions between *Gracilaria chilensis*, amphipod grazers, and the alpha-galactosidase enzyme. Notable contributions from Freile-Pelegrín et al. [82] and Ho et al. [83] studied alpha-galactosidase content in *Gracilaria chilensis* and its complex interactions with other species.

Comparing the two analyses—co-citation and keyword clustering-provides us with a more comprehensive view of the seaweed research landscape. While co-citation clusters emphasize the connectivity and co-occurrence of cited references, they provide a broader understanding of the overarching themes in seaweed research. Conversely, the keyword clusters provide more specific and nuanced insights, highlighting emerging trends and underexplored domains in the field.

For instance, the co-citation Cluster #3, 'ocean acidification,' mirrors keyword Cluster #2, which also explores ocean acidification's impact on macroalgae growth. While the former gives us an overview of the broader research area, the latter dives into specifics, such as photosynthesis and light, offering granular insights. Similarly, co-citation Cluster #4, 'antioxidant activity,' and keyword Cluster #1, centered around antioxidant activity, both discuss the antioxidant potential of seaweed-derived compounds. However, the keyword cluster provides additional context, focusing on specific types of seaweed that exhibit high antioxidant activity.

By concurrently analyzing both co-citation and keyword clustering results, we can identify broader research areas and their specific focal points. This dual analysis approach also helps us pinpoint common themes, divergences, and underexplored areas in seaweed research, thus providing a thorough understanding of the historical development, current state, and potential future directions of this field.

In summary, the knowledge mapping analysis, through both co-citation and keyword clustering, reveals the diverse and evolving landscape of seaweed research. These analyses highlight the crucial role of seaweeds in ecological processes, potential industrial applications, and responses to environmental stressors, offering valuable insights for future exploration and research in this dynamic field.

3.5. Keyword citation burst analysis

Keyword citation burst analysis is a critical tool for identifying evolving trends, influential research areas, and the dynamic landscape of a scientific field. The intellectual milestones shaping seaweed research over time are illuminated by examining the duration, strength, and temporal dynamics of keyword citation bursts [19].

Table 6 presents a comprehensive analysis of the top 15 keywords with the strongest citation bursts in global seaweed research from 1975 to 2022. A strong citation burst signifies a sudden increase in the number of citations within a particular time frame, highlighting the importance and relevance of a specific topic or concept during that period.

Among the top keywords, "light" exhibited the longest citation burst, spanning 18 years from 1990 to 2008. This finding underlines the significance of understanding light's role in seaweed photosynthesis, growth, and distribution. "Extraction," with a citation burst between 2016 and 2022, implies a growing interest in developing efficient extraction techniques for seaweed-derived compounds in various industries, including food, cosmetics, and biofuel.

The keyword "quality" has seen a recent increase in its citation burst from 2018 to 2022, reflecting the growing concern for maintaining the quality of seaweed products and understanding the factors affecting it. "Removal" and "reproduction" have citation bursts spanning 11 and 13 years, respectively, indicating the importance of understanding seaweed removal and reproductive strategies in managing their populations and their impact on marine ecosystems.

"Chemical composition" and "antioxidant" keywords suggest a recent surge in interest in understanding seaweed's nutritional value and potential health benefits. The keyword "populations" and its citation burst from 1994 to 2006 indicate the significance of understanding the dynamics of seaweed populations in the context of biodiversity, ecology, and conservation.

The presence of "assemblages" and "plants" as keywords with substantial citation bursts highlights the importance of studying seaweed communities and their interactions with other marine organisms, such as coral reefs. "Degradation," "abundance," "protein," and "chlorophyll fluorescence" all emphasize different aspects of seaweed biology and ecology, including decomposition, biomass, protein content, and photosynthetic efficiency.

Finally, "ocean acidification" emerged as a critical keyword between 2014 and 2019, reflecting the growing concerns about the impacts of climate change on marine ecosystems and seaweed populations. This keyword signifies the importance of investigating seaweed's response and adaptation to ocean acidification in the context of global environmental change.

Table 6
Top keywords with the strongest citation burst for seaweed-related publications (1975–2022).

Keywords	Year	Strength	Begin	End
light	1990	**121.72**	1990	2008
extraction	2016	**119.56**	2016	2022
quality	1992	**109.51**	2018	2022
removal	2006	**67.69**	2006	2017
reproduction	1990	**63.22**	1996	2009
chemical composition	1976	**55.49**	2016	2022
populations	1990	**53.03**	1994	2006
assemblages	2001	**52.08**	1998	2016
plants	1990	**49.72**	1991	2009
degradation	1991	**49.02**	1991	2010
antioxidant	2012	**45.81**	2012	2016
abundance	1991	**44.01**	1991	2006
protein	1991	**43.78**	2006	2011
chlorophyll fluorescence	1992	**43.02**	1997	2004
ocean acidification	2014	**42.24**	2014	2019

3.6. Timeline Co-citation analysis

The document co-citation timeline serves as a valuable instrument for highlighting the chronological progression and global researcher interest in the distinct areas of seaweed science. In the span from 2010 to 2022, notable peaks in citation bursts were observed, signaling heightened research attention in three main clusters of global seaweed study (Fig. 7).

Cluster #0: "Coral Reefs" exhibited marked citation bursts, indicating an intensified interest in exploring seaweed's role within coral reef ecosystems and its impact on their health and resilience. Meanwhile, Cluster #3: "Ocean Acidification" also saw a rise in citations during this period, reflecting the growing global concern on the impact of increased CO_2 levels on marine ecosystems, particularly on macroalgae physiology and productivity. Additionally, the study of Cluster #4: "Antioxidant Activity" witnessed a surge in research interest. This demonstrates the keen scientific curiosity to understand and exploit the potential antioxidant properties of seaweed-derived compounds, spurred by their promising applications in health, nutrition, and cosmeceuticals.

4. Discussion

Our timeline co-citation analysis unveiled the prominence of coral reefs, ocean acidification, and antioxidant activity as key focal points in current seaweed research. These findings illuminate the importance of deciphering seaweed's multifarious roles in varied marine ecosystems, essential for predicting and attenuating environmental shifts, inclusive of climate change and ocean acidification.

The conspicuous coral reef cluster indicates a growing recognition of seaweed's impact on coral reefs and its potential as a mitigation measure against coral reef degradation. This shift places seaweed restoration research at the forefront, especially in the face of climate change and other anthropogenic impacts. It also suggests an increasing interest in exploring the ecological and environmental factors influencing seaweed communities.

Ocean acidification, a rapidly developing research area, underlines the necessity to investigate seaweed's potential in mitigating the detrimental effects of increased ocean acidity. Preliminary research signifies that some seaweed species can absorb and utilize dissolved inorganic carbon, which might alleviate local acidification, offering sanctuary to susceptible organisms.

Lastly, the emergence of antioxidant activity as a hotspot mirrors an escalating interest in the exploitation of seaweed-derived antioxidants across several sectors. The unearthing of novel antioxidant compounds in seaweed underscores the prospective benefits of these entities in mitigating oxidative stress and inflammation, marking a promising avenue for interdisciplinary research.

In essence, these three focal areas intersect to offer a comprehensive understanding of seaweed research. Future sections will delve

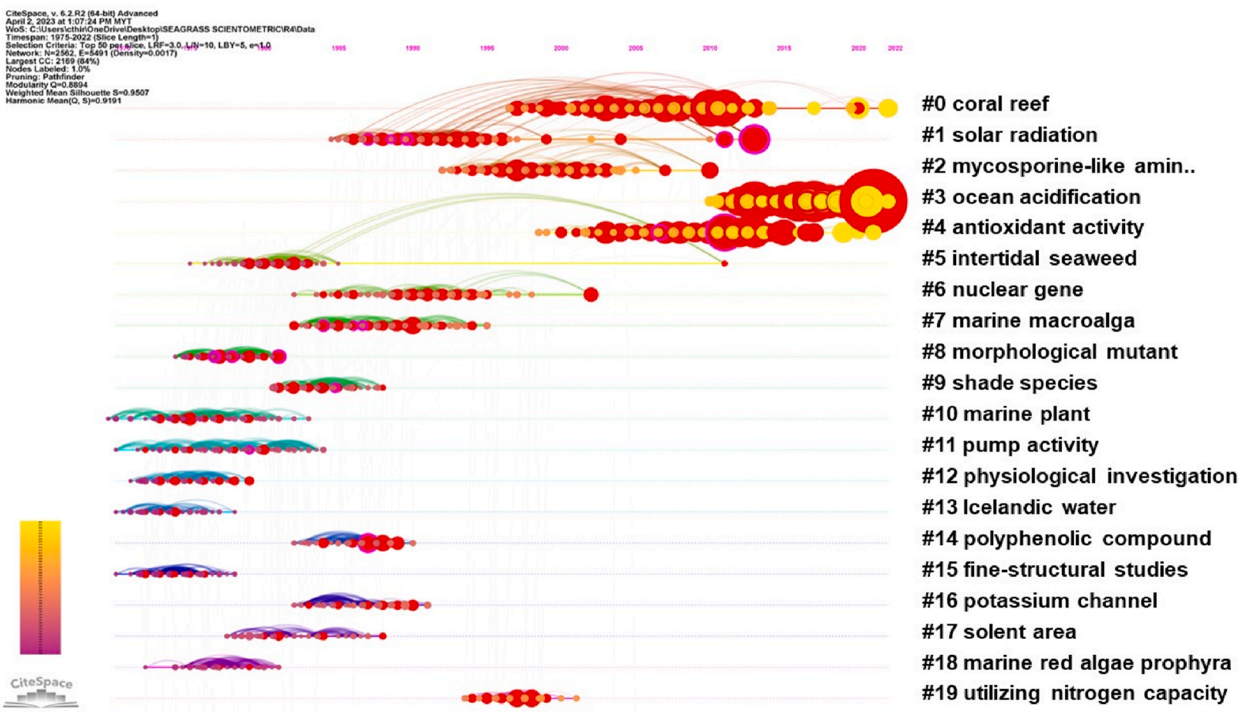

Fig. 7. A timeline co-citation analysis in the research related to seaweed between 1975 and 2022. The node represents the reference name, whereas the lines represent the connections between those references. Larger nodes indicate higher frequencies of citations. References with strong citation bursts are shown with red rings, whereas references with high centrality are shown with yellow rings. The longer the colored line segment in the figure, the larger the time span of the citation. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

deeper into each of these areas, urging a collaborative approach among scholars to address looming environmental and human health challenges.

4.1. Coral reefs and Seaweed: A balancing act in marine ecosystems

The increasing prevalence of seaweed-coral competition in coral reefs globally, particularly in regions where key herbivores have been overfished, has raised concerns about the potential threat of large seaweeds to coral reef biodiversity [84–87]. Seaweed biomass fluctuations are influenced by a variety of biotic (competition, herbivory) and abiotic (light, temperature, wave action, nutrients) factors, with the importance of these factors varying depending on the regional context [86]. In some cases, nutrient inputs and other bottom-up factors emerge as primary drivers of fleshy seaweed biomass [86,88]. Following the pattern of ecosystem shifts witnessed globally, the Akumal Reef in the Mexican Caribbean presents an illustrative case. The reef has undergone a drastic transition over a 25-year period due to multiple stressors, with a hard coral cover loss of 84% and an opposing algae cover increase of 74%. Factors such as urban expansion, climate change markers, and precipitation patterns have been linked to these shifts [89]. This data further supports the assertion that bottom-up factors, including nutrient inputs, can indeed serve as significant drivers in the increase of fleshy seaweed biomass.

While the role of seaweed-coral interactions in reef ecosystems remains uncertain, with some researchers questioning whether seaweeds are a cause or consequence of coral decline [90–93], allelopathy has been identified as a common mechanism of competition between numerous coral-seaweed pairings, often resulting in coral stress, bleaching, or tissue death upon contact [94,95]. The focus of numerous studies on lipid-soluble secondary metabolites as allelopathic agents, functioning through contact rather than water dissolution, highlights the ecological importance of these compounds in marine environments, where rapid advection of water-soluble elements in high-flow conditions can occur [91,96]. For example, the study by Nieder et al. [97] investigated the role of the seaweed *Galaxaura*, particularly *Galaxaura divaricata*, in competitive interactions within marine ecosystems, focusing on the Dongsha Atoll's lagoon. The research underscores Galaxaura's ability to compete with corals and offer substrate for other macroalgae. It further elucidates how lipid-soluble secondary metabolites from *G. filamentosa* can lead to coral tissue bleaching and death, thereby posing a potential barrier to coral recovery in regions affected by mass coral bleaching events.

Bioactive secondary metabolites have also been associated with specific roles within the seaweed's ecological interactions. Stored within specialized gland cells in the seaweed thallus, these metabolites are transported to the seaweed surfaces through existing pores [98]. They often perform a dual ecological function acting as both anti-herbivore and antifouling agents. However, depending on the environmental context, they may also assume unique functional roles, necessitating their differential distribution within and on the seaweeds [87,98]. Seaweeds employing allelopathic chemicals to damage corals may compromise their anti-herbivore defenses and render them more vulnerable to herbivores [87,96]. Seaweed-coral competition can suppress seaweed chemical defense against herbivores, but this may come at little cost to seaweeds in severely degraded, and overfished reefs where seaweed browsers are scarce and induced allelopathy may be most prevalent [99]. Bromophenols serve as illustrative examples of secondary metabolites that embody multi-faceted ecological roles, including chemical protection and deterrence. These compounds, initially extracted from the red algae *Neorhodomela larix*, have been subsequently identified and isolated from a diverse array of marine macroalgae groups, demonstrating their widespread beneficial ecological actions [100].

In contrast, some studies have reported that seaweeds can impact corals via physical mechanisms such as shading or abrasion [101,102]. For instance, shading by the common Caribbean macroalgae *Lobophora variegata* has been shown to result in overall coral tissue loss and increased mortality rates, while *Dictyota pulchella* led to 99% growth inhibition [101]. However, Parakkasi et al. [102] found no significant correlation between the shading effect of seaweed farming and coral growth. Likewise, another field study investigating the outcomes and mechanisms of seaweed-coral competition in the Caribbean observed no apparent effects of abrasion and shading [103]. These contrasting results highlight the complex nature of seaweed-coral interactions and the need for further research to better understand the various factors and mechanisms at play.

The spread of macroalgae on coral reefs could also account for the elevated incidence of coral diseases [104]. A range of mechanisms underscores the influence of macroalgae on coral diseases. Primarily, direct contact between macroalgae and corals can cause abrasions on the coral surface, increasing susceptibility to infections by opportunistic pathogens and reducing light available for coral symbiotic algae (zooxanthellae) to photosynthesize [105–107]. De et al. [108], reported the detrimental effects of repeated thermal bleaching events during the 2014–2016 El Niño-Southern Oscillation period have significantly impacted marginal coral communities in the Eastern Arabian Sea. These communities experienced a significant shift from coral dominance to a regime ruled by macroalgae and algal turf, accompanied by increased prevalence of coral diseases and reduced coral recruitment. Algal cover grew from 21% to nearly 53% within a span of five years (2014–2019), and incidences of coral disease followed a similar upward trend. The compounded effects of these stressors led to a noticeable decrease in coral cover. Secondly, macroalgae varieties have been found to exude allelopathic substances that obstruct neighboring coral growth and survivability, thereby weakening their defensive mechanisms and rendering them more disease-prone [91,105,109]. In addition, through the process of decomposition, seaweed may contribute to nutrient enrichment in their local environments, resulting in increased nutrient levels which in turn could inhibit coral growth and augment their disease susceptibility [110,111]. Finally, seaweed possess the capacity to modify the microbial assemblages linked to the coral holobiont, thereby promoting potentially harmful microbes and enhancing the probability of coral diseases [112].

4.2. Ocean acidification and Seaweed: assessing macroalgae response to a changing world

Seaweeds, as photosynthetic organisms, have demonstrated varying degrees of tolerance and sensitivity to ocean acidification

[113,114]. In some cases, elevated CO_2 levels have been shown to stimulate growth rates in seaweed species. For instance, Britton et al. [115] reported that macroalgal assemblages, such as the kelp *Ecklonia radiata*, exhibited increased productivity under elevated CO_2 concentrations. This can be attributed to the enhanced availability of dissolved inorganic carbon (D.I.C.), which serves as a substrate for photosynthesis [114,116]. Gao et al. [117] explored the relationship between photosynthesis, aerobic respiration, and carbon sources in microalgae cultivation. They found that increasing the proportion of inorganic carbon (HCO^{3-}) in the green microalga *Chlorella vulgaris* improved its growth and carbon fixation by promoting the expression of an essential enzyme, RuBisCO. When the ratio of inorganic to organic carbon increased, energy for biomass production primarily came from photoreactions. Furthermore, CO_3^{2-} and glucose together resulted in optimal carbohydrate and lipid accumulation. This research provides crucial insights into the carbon metabolism of microalgae, possibly informing future studies on seaweed responses to CO_2 variations.

However, this protective effect is inherently dynamic, subjecting organisms to varying pH levels, and thus necessitating the ability to tolerate such changes [118,119]. Regardless, macroalgae habitats tend to offer consistent relief from ocean acidification stress due to their autotrophic activity, despite short-term pH fluctuations [120–122]. Particularly, photosynthetic macroalgae, especially species that form substantial aggregations, are generally tolerant to anticipated ocean acidification conditions, implying their sustained role as crucial ocean acidification refugia for numerous associated marine species [114].

However, seaweed's response to ocean acidification is species-specific and not universally beneficial. Some calcifying seaweed species, such as coralline algae, have exhibited negative responses to increased acidity [123]. In a study by Britton et al. [124], two types of red seaweeds, *Callophyllis lambertii* and *Plocamium dilatatum*, displayed distinct responses to varying pH conditions. Fluctuations in pH led to decreased growth and photosynthesis in *C. lambertii*, while *P. dilatatum* was not affected. Furthermore, increased photosynthesis in *C. lambertii* under future ocean conditions may be due to the plant's unique biochemical characteristics, such as its ability to enhance RuBisCO, the enzyme involved in carbon fixation. In contrast, *P. dilatatum*'s inability to boost photosynthesis under heightened CO_2 might be attributed to its biological limitations.

Seaweed may contribute to countering ocean acidification via carbon sequestration processes. Being photosynthetic life forms, macroalgae are capable of sequestering CO_2 from the nearby water column and converting it into biomass [125]. Research indicating that seaweed beds and forests could locally moderate ocean acidification by reducing the acidity of the adjacent water further backs the potential of macroalgae as a tool for mitigating ocean acidification [126,127]. Gao et al. [128], found that seaweed farming in China can significantly contribute to carbon neutrality goals, with *Gracilariopsis lemaneiformis* showing the highest carbon sequestration capacity. Additionally, seaweed cultivation can increase dissolved oxygen levels and help combat seawater deoxygenation. However, to offset the nutrient release from fish mariculture, seaweed cultivation needs to be expanded and the degree to which macroalgae can counteract ocean acidification globally remains ambiguous and calls for additional scrutiny.

The intricate relationships between macroalgae and ocean acidification possess widespread implications for marine ecosystems. Alterations in macroalgae community composition and prevalence may influence trophic relationships, nutrient flows, and habitat structure. For instance, the dwindling of calcifying macroalgae might affect the settlement and survival of calcifying invertebrates that are dependent on these algae as a base [129]. Furthermore, the potential disappearance of habitat-forming macroalgae species could trigger ripple effects on associated fauna, impacting biodiversity and ecosystem resilience [130]. Torn et al. [131] examined the effects of factors such as increasing temperature, wind speed, and storm intensity, as well as decreasing salinity on macroalgae species like *Fucus vesiculosus* and *Furcellaria lumbricalis* in the Baltic Sea. Their modeling suggests that climatic changes may lead to considerable contractions in the distributional ranges of *Zostera* and *Furcellaria*, further disrupting the marine ecosystem. In a similar vein, research by Des et al. [132] indicated potential geographical shifts in habitat-forming macroalgae in the Rías Baixas due to ocean warming. Their work forecasts that *Himanthalia elongata*, a cold-temperate species currently found in the Northwest Iberian Peninsula, is expected to go extinct by the end of this century. Interestingly, this study also suggests that the species *Bifurcaria bifurcata* is likely to persist and potentially expand into the spaces vacated by *H. elongata.*

4.3. Seaweed antioxidants: exploring health benefits and potential applications

The investigation into the antioxidant properties of marine algae has sparked considerable interest lately, as the capability of these marine entities to produce unique compounds with considerable health advantages has become more apparent [133,134].

Current research underscores the rich antioxidant capacity of seaweeds, largely due to the diversity of active compounds they contain [135,136]. These natural antioxidants include pigments like chlorophylls, xanthophylls, and carotenoids, various vitamins and their precursors, as well as a range of phenolic substances. Additionally, they contain flavonoids, phospholipids, terpenoids, peptides, and other substances, all contributing to their potent antioxidant activity, thereby making them potent sources for the development of new therapeutic products and food applications [134,136].

For example, exploring specific seaweed species, Rajauria et al. [137] focused on the brown Irish seaweed *Himanthalia elongata* as a source of antioxidant compounds. Their extraction and purification methods yielded eight phenolic compounds including hydroxybenzaldehyde, phloroglucinol, kaempferol, and gallic acid. Zhong et al. [138] investigated the phenolic compounds present in eight seaweeds, Chlorophyta, *Ulva* sp., *Caulerpa* sp. and *Codium* sp.; Rhodophyta, *Dasya* sp., *Grateloupia* sp. and *Centroceras* sp.; Ochrophyta (phaeophyceae), *Ecklonia* sp., *Sargassum* sp., and concluded that the largest number of phenolic compounds were present in *Centroceras* sp. followed by *Ecklonia* sp. and *Caulerpa* sp. similarly, in another study evaluating the phenolic content activities of five seaweeds from North Sulawesi, Indonesia reported that *Turbinaria decurens* had the highest radical DPPH scavenging activity.

In recent years, compounds such as fucoidans, phlorotannins, and carotenoids derived from algae have been the focus of extensive research due to their multitude of health advantages, particularly their antioxidant and anti-inflammatory capabilities [139]. Numerous investigations have sought to comprehend the molecular makeup of these compounds across a variety of algal species, particularly focusing on the *Sargassum* genus. Factors such as the species, size, maturity, reproductive status, and geographical location appear to impact the levels and composition of phlorotannins found in this genus of seaweeds [140,141]. Additionally, seaweeds encompass unique bioactive polyphenols, which are thought to modulate gene expression [142,143]. Consequently, the potential use of seaweed in preventing conditions like ageing, cancer, and cardiovascular diseases is a subject of considerable scientific curiosity [136,143,144].

The abundance of antioxidant compounds in marine algae has further broadened opportunities for their inclusion in functional foods, nutraceuticals, and cosmeceuticals [145–147]. These applications not only furnish consumers with additional health advantages but also bolster the sustainability of marine resources by advocating the use of marine algae.

5. Conclusions

The findings of this scientometric analysis using CiteSpace application provide a comprehensive overview of the current state of seaweed research, offering valuable insights into the dynamic interplay between seaweeds, coral reefs, and ocean acidification. These interactions have significant implications for marine ecosystems and global biogeochemical cycles. A critical observation from this study is the increasing frequency of seaweed-coral competition and the diverse effects of ocean acidification on seaweed ecology, highlighting the imperative need for an integrative understanding of these complex relationships.

In addition to underscoring the key focal points in seaweed research, this study also brings to light certain underexplored areas. The application of knowledge mapping analysis has revealed significant gaps in our current understanding, particularly in the areas of seaweed allelopathy, shadowing effects, and the impact of physical abrasion on coral-seaweed interactions. Furthermore, there is a need to delve deeper into the long-term effects of ocean acidification on seaweed communities, including species-specific responses and the potential for seaweeds to act as agents of carbon sequestration on a global scale.

One significant limitation is the reliance on a single database for literature sourcing. In this study, the Web of Science (WoS) was chosen due to its comprehensive coverage and esteemed reputation in the academic community. However, this selection may inadvertently exclude relevant research published in databases not indexed by WoS. Furthermore, the methodology of knowledge mapping analysis, while powerful in identifying trends and gaps, is inherently limited by its quantitative nature. It primarily captures the frequency and co-occurrence of keywords, authors, and citations, which may not fully represent the qualitative aspects of research developments and the complexity of interdisciplinary interactions in seaweed research. Therefore, the conclusions drawn from such an analysis should be considered within the context of these methodological constraints.

The conclusions drawn from this research emphasize the importance of adopting a more holistic approach in future studies. There is a pressing necessity to expand our research horizon to not only emphasize the strengths but also address the weaknesses in seaweed research. By doing so, we can gain a more nuanced understanding of the ecological roles of seaweeds, their interactions with other marine organisms, and their potential applications in mitigating environmental challenges.

The progression of seaweed research is essential for the scientific community as it endeavors to address the emerging challenges faced by marine ecosystems in our changing world. Continued research in this field will not only enhance our understanding of these complex marine interactions but also guide effective conservation strategies, manage coral reef ecosystems under increasing anthropogenic pressures, and evaluate the feasibility of using seaweeds as a mitigative tool against ocean acidification. This study's comprehensive assessment of the current literature in seaweed research serves as a call to action for researchers to fill these knowledge gaps and foster collaborations that will propel the field forward.

Data availability statement

The authors do not have permission to share data.

CRediT authorship contribution statement

Thirukanthan Chandra Segaran: Writing – review & editing, Writing – original draft, Visualization, Software, Methodology, Formal analysis, Data curation, Conceptualization. **Mohamad Nor Azra:** Writing – original draft, Visualization, Validation, Funding acquisition, Data curation, Conceptualization. **Mohd Iqbal Mohd Noor:** Writing – original draft, Resources, Project administration, Methodology, Investigation. **Muhd Danish-Daniel:** Visualization, Validation, Resources, Project administration, Methodology, Investigation. **Juris Burlakovs:** Writing – review & editing, Writing – original draft, Resources, Investigation, Formal analysis. **Fathurrahman Lananan:** Validation, Software, Resources, Methodology, Formal analysis, Data curation. **Juntian Xu:** Software, Resources, Project administration, Methodology, Investigation, Funding acquisition. **Zulhisyam Abdul Kari:** Writing – original draft, Software, Resources, Project administration, Methodology, Funding acquisition. **Lee Seong Wei:** Writing – review & editing, Writing – original draft, Supervision, Project administration, Funding acquisition.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests:Lee Seong Wei is the Associate Editor for Heliyon.

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