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## Cyanobacteria and Marine Environmental Research: A Descriptive and Network Analysis of Global Publication Trends

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**Abstract:** Global studies on cyanobacteria and their link to marine ecology and pollution are thoroughly examined in this piece. Examining 620 Scopus database papers, the study looks at publication trends, top nations, major journals, and subject areas. The research notes a notable rise in studies since 2017, therefore underlining rising scientific interest in cyanobacterial blooms and marine environment pollution. Through keyword analysis, it also finds emerging themes, citations performance, and worldwide partnerships. The article seeks to lead future research, promote multidisciplinary collaborations, and advocate for legislation for marine environmental health.

**Keywords:** Cyanobacteria, Marine Ecology, Marine Pollution, Descriptive Analysis, Bibliometric Analysis

### I. INTRODUCTION

Cyanobacteria, frequently infer to as blue-green algae, are amongst one of the most primitive and phylogenetically varied lineages of photosynthetic prokaryotes on Earth, with a fossil record ranging over 2.5 billion years (Schirmeister et al., 2013). Their evolutionary adaptability of oxygenic photosynthesis was a key event in planetary history that led the Great Oxidation Event which primarily changed the atmosphere and facilitated the way for aerobic life (Lyons et al., 2014).

The ecological triumph of cyanobacteria is exhibited by their outstanding adaptability, letting them to colonize an enormous range of habitats. They are pervasive and flourishing in environments as diverse as hot springs, hypersaline lagoons, freshwater bodies, parched deserts, and terrestrial soils. This ecological flexibility is tuned by significant phylogenetic and metabolic multiplicity, empowering them to perform crucial ecosystem facilities (Whitton & Potts, 2012). A prime example of their ecological supremacy is found in the world's oceans. Marine cyanobacteria, particularly the picocyanobacteria *Prochlorococcus* and *Synechococcus*, are among the most abundant photosynthetic organisms on the planet. They form the foundation of numerous aquatic food webs, serving as vital primary producers and acting as powerful drivers of global biogeochemical cycles, including carbon and nitrogen (Flombaum et al., 2013).

Beyond their remarkable ecological impact, cyanobacteria hold enormous biotechnological potential. They are encouraging platforms for sustainable biotechnology because of their ability to transform solar energy and CO<sub>2</sub> into valuable compounds. They are being engineered for the production of biofuels, bioplastics, nutraceuticals, and pharmaceuticals which may offer a green and sustainable alternative to traditional industrial processes (Ducat et al., 2011). Moreover, their powerful metabolic pathways are being applied for bioremediation by breaking down environmental pollutants (Ahmad et al., 2020).

The molecular mechanisms encouraging these diverse ecological functions and biotechnological applications have become a major focal point in the contemporary cyanobacterial research domain. The cyanobacterial investigation ranges from genomic analyses of nitrogen fixation and photosynthesis to the metabolic engineering of biosynthetic pathways for product yield optimization.

However, this dual nature of cyanobacteria, both as an ecological benefactor as well as a potential threat poses significant challenges. Certain species, under conditions of nutrient enrichment (e.g., from agricultural runoff), can form harmful algal blooms (HABs). These blooms can deplete oxygen, block sunlight, and produce potent toxins that causes

disruption in aquatic ecosystems and significant threat to water security which leading an adverse impact on human health (Paerl & Otten, 2013). This interplay between their beneficial functions and detrimental potential highlights the complexity of managing cyanobacterial populations in a changing global environment.

In last decade there were significant progress in exploring the biological, ecological, and applied aspects of cyanobacteria, though the research terrain remains dispersed and seems unorganized. The range of studies encompassing evolutionary biology, ecosystem dynamics, toxin production, and bioengineering applications has generated a vast yet disjointed body of knowledge. Therefore, a systematic and quantitative analysis of the scientific literature is essential to integrate these dimensions and map the intellectual structure strengthening cyanobacterial research. A bibliometric review offers a vigorous methodological framework to objectively quantify research outputs, trace the temporal evolution of scientific themes, recognize influential contributors and institutions, and exhibit patterns of international collaboration. This approach would enable the portraying of research fronts and swings from basic ecological investigations to molecular and biotechnological innovations. By employing bibliometric analysis techniques, these studies pursue to synthesize and visualize the trajectory of cyanobacterial research, reveal obscured thematic areas, and create a data-driven roadmap to usher future research priorities. The assessment of current course of study aims to strengthen interdisciplinary linkages, support evidence-based policy formulation, and catalyze innovation activities in the sustainable application of cyanobacterial science.

## Background Study

Marine cyanobacteria, which are photosynthetic prokaryotes, are essential to biogeochemical cycles, oceanic primary production, and carbon fixation. Advances in molecular biology, genomics, and marine biotechnology have enhanced our knowledge of their ecological role, diversity, and possible uses over the past three decades. This part explores the contemporary advances in marine cyanobacterial diversity, ecological significance, production of secondary metabolites, and biotechnological applications.

In the 20th century, there were not a very significant number of studies that had been conducted to examine the taxonomic and genetic diversity of cyanobacteria, especially in marine systems. Nonetheless, the introduction of high-throughput sequencing has opened the door to unknown variation in marine cyanobacteria, especially in the genera *Prochlorococcus* and *Synechococcus* for scientists. These two genera are part of picophytoplankton communities, and along with the high genetic variability they possess, they can survive a wide range of different ocean conditions (Scanlan et al., 2009; Biller et al., 2015). Besides that, newly discovered clades and ecotypes with adapted light and nutrient requirements have been identified by metagenomic studies (Martiny et al., 2009).

Recently, understanding the role of cyanobacteria in marine ecosystems, has become a hot topic. The marine cyanobacteria are a major factor in the earth's nitrogen and carbon cycles. Nitrogen fixation of a biological nature in oligotrophic waters is aided by the diazotrophic cyanobacteria like *Trichodesmium* and *Crocospaera* (Capone et al., 2005; Zehr et al., 2016). Hence, they become the main source for the production in the areas of sea with low nitrogen content. What is more, relationships between marine microbial communities and viruses, and other organisms also matter for their dynamics period (Sullivan et al., 2003).

One of the main currents of research looks at marine cyanobacteria as a new source of secondary metabolites for pharmaceutical industry. The compounds *curacin*, *lyngbyatoxins*, and *apratoxins* are the kind of thing that may be effective simultaneously against bacteria, viruses, and cancer (Tan, 2007; Burja et al. 2001). The improved genome mining tool now enables us to discover biosynthetic gene clusters that produce these metabolites which signify the potential of these microorganisms for biotechnological applications (Jones et al., 2021).

Cyanobacteria are a major factor in the functionality of marine ecosystems. They associate with a wide variety of sea organisms such as corals, sponges, and diatoms. These relationships provide both parties access to nutrients and make the host species stronger (Wilkinson et al. 1988). Besides, the cyanobacteria contribute to the development of habitats by producing microbial mats and biofilms. These formations not only make marine sediments more secure but also provide shelters for a great number of different microbes (Stal, 2012). Taking into account their vital ecological roles, further research in this field could provide valuable insights and novel contributions to the study of marine ecology.

Marine cyanobacteria are being looked into to find new sources for biofuel, carbon capturing and bioremediation to help reduce the air pollution. One can see the species that are equipped with strong photosynthesis like *Synechococcus elongatus* become genetically modified for the production of bio-ethanol and hydrogen. Their abilities to make biodegradable plastics and biopigments are also in the spotlight of research (Ducat et al., 2011).

Cyanobacteria are necessary from the perspectives of nature but at the same time, they are not beneficial for marine ecosystems; they are also able to cause a variety of problems such as carbon-nitrogen cycle disruption and HABs. The negative effects that cyanobacteria may have on the environment are generally a result of changes in the surrounding milieu caused by pollution. The drop in water temperature, light, and nutrients availability is a few of the changes brought by pollution that affects cyanobacterial metabolism. These changes can cause alterations in the biogeochemical cycling that would then change the productivity and resilience of marine ecosystems (Karl et al., 2001). Ocean acidification due to high CO<sub>2</sub> emissions can also modify cyanobacterial physiology and favor species that cause blooms (Hutchins et al., 2007). Increasing reports of HABs with

toxic marine cyanobacteria are emerging threats to marine biodiversity and human health (Paerl & Paul, 2012). Anthropogenic nutrient enrichment especially from agricultural runoff and wastewater containing nitrogen and phosphorus is accelerating eutrophication in coastal areas and promoting cyanobacterial blooms (Paerl et al., 2011). Some cyanobacteria produce harmful toxins like *microcystins* and *nodularins* which further harm marine organisms and public health (Codd et al., 2005). Hence, this segment of research is also very popular and pragmatic in current scenario.

In order to conduct an exhaustive review of literature on cyanobacteria in marine ecology, including gaps in the research, trends, and future areas that require further study, what is needed is a systematic review and bibliometric analysis. Cyanobacteria are important members of the marine ecosystem by providing nitrogen fixation and primary production; however, blooms caused by climate change and eutrophication have large ecological effects such as oxygen depletion and toxin release (Paerl & Paul 2012). A systematic review guarantees a well-organized, objective synthesis of evidence while bibliometric analysis quantitatively tracks the evolution of research, key contributors, and thematic areas of focus (Donthu et al., 2021), which can guide future studies or policy interventions to minimize adverse effects on marine ecosystems and enhance sustainable management.

## II. MATERIALS AND METHODS

The Systematic Outline in the Methodology part aids as an analysis guide, making it easier for academicians and researchers to comprehend the complete research process. Each step that must be taken for this investigation is described in this section. This research purposes to perform descriptive and bibliometric analysis in the area of research work on the relationship and role of cyanobacteria on Marine Ecology and Marine Pollution. The research questions are enumerated in **Table 1** alongside the justifications and analysis methods. In order to give scholars a better understanding of the development *in* connected subjects, the descriptive analysis provides general information on the annual production of articles, top research journals, and performance of countries, Popular journals, Types of articles and so on. Apart from descriptive analysis, Bibliometric analysis has also been employed which is a quantitative method for assessing the bibliographic data in articles and journals. This method is frequently employed to look-into the references to scientific papers that are cited in a journal, to map the journal's scientific field, and to categorize research articles by research area, participation of countries, top keywords of the area of chosen research domain. To perform bibliometric analysis, a scientific computer-assisted review process has been employed to examine all the publications on a particular subject or area in order to find key authors or pieces of research, as well as their connections N. De Bellis (2009). Bibliometric analysis is applicable to various research domains across multiple subject matters by deploying various search approaches and data analysis algorithms. The bibliometric analysis's results are then provided, including the co-author, co-word, and bibliographic coupling analyses as well as general patterns in publication.

The bibliometric analysis method can alternatively be described as one that follow few recommendations Block, J.H.; Fisch, C. (2020). This procedure is used purposefully and adheres to predetermined stages, making it possible for other researchers to reproduce it. Bibliographic analysis emphasizes on quantitative methods to analyse books, journal articles, and other written materials, is frequently used across a wide range of fields Garza-Reyes, J. A. (2015). The bibliometric method comprises of the application of quantitative techniques on bibliometric data and gathers the bibliometric and intellectual structure of a topic by examining the relationships between several research components (Heersmink, et. al., 2011). With the use of such data, it is possible to shed-light the contributions of particular field of study, spot links and information silos, as well as trends and prospective gaps (Donthu, et. al., 2021).

Below is a thorough explanation of each subsection of the bibliographic analysis:

- i. **Publication analysis** Publication analysis is a systematic method that involves the examination and evaluation of the source materials, the area of study, and the research application of a given field. In order to measure research production, impact, and the emergence of themes, it is necessary to go through a range of bibliometric indicators such as publication count, citation counts, authorship, journals, and cooperative networks (Donthu et al., 2021). Identifying the most significant contributors, primary sources, and the absence of information, thus, leading research directions and allocation of resources becomes easier with the help of publication analysis (Aria and Cuccurullo, 2017). Ultimately, publication analysis through quantitatively depicting the organization and progression of scientific knowledge, becomes largely instrumental in the planning of studies and formulation of policies relying on evidence.
- ii. **Citation analysis** Shows an article's popularity by counting how often it is mentioned (Ding Y., Cronin B. (2011)).
- iii. **Co-authorship analysis** Evaluates the frequency of joint publications to track national cooperation efforts (Caviggioli F., Ughetto E. (2019)).
- iv. **Co-word / Co-occurrence analysis** Discover research hotspots via the degrees of keywords co-occurrence (Bui, et. al., 2020)
- v. **Bibliographic coupling** Find the bibliographic connections between two publications (Abdullah S., Naved Khan M. (2021)).

In this study, a procedure was established for choosing the search words, database to use, selection criteria for the search, software to use for analysis, and results analysis. **Figure 1**, below illustrates these steps, and the following paragraphs go into greater depth about them.

TABLE 1  
Overview of the Research Development in this Study

Descriptive / Bibliometric Analysis			
No.	Research Question(s)	Research Objective(s) and aims	Research Mythology
1	What is the publication trend of literature between Cyanobacteria on Marine Ecology or Marine pollution?	To understand how the development of Research between Cyanobacteria on Marine Ecology or Marine pollution has evolved over the years.	Descriptive analysis
2	Which countries contributed to the research development Cyanobacteria on Marine Ecology or Marine pollution?	To identify the countries that contributed the most and received the most citations for their work. To promote international research collaboration, it is essential to achieve this goal.	Descriptive analysis
3	Which journals led in the field of the Cyanobacteria on Marine Ecology or Marine pollution?	To identify the journals that published the most articles on the relationship between Cyanobacteria and Marine Ecology or Marine pollution. This goal is crucial in assisting researchers in selecting platforms for releasing and communicating their findings.	Descriptive analysis
4	Which are the research fronts of the development in the area of Cyanobacteria on Marine Ecology or Marine pollution research?	To identify the papers in the field that have a similar theme. This goal gives scholars a sense of the topics covered in the papers, which helps them when they are creating new research projects.	Descriptive Analysis (Subject area which covers chosen topic)
5	How is the countries collaboration structure in the field of the Cyanobacteria on Marine Ecology or Marine pollution?	This goal is directed to analyze the cooperation trend among different countries in the scientific research field of Cyanobacteria on Marine Ecology or Marine Pollution. Researchers working in this domain can use this objective to figure out the most appropriate country to co-author their research with.	Descriptive and Network Analysis (Co-authorship analysis: Collaboration of authors based on countries)
6	What is the conceptual structure of keywords in the area Cyanobacteria on Marine Ecology or Marine pollution?	To identify the research hotspots that evolved in the field. This objective helps researchers to understand the new research topics.	Descriptive and Network Analysis (Conceptual structure analysis: co-occurrence analysis of words)
7	What is the countries' coupling structure in the area Cyanobacteria on Marine Ecology or Marine pollution?	Presenting information on commonalities between the two countries. This goal helps to assess the degree to which these countries' ideas and literary works are alike.	Intellectual structure analysis (bibliographic coupling)

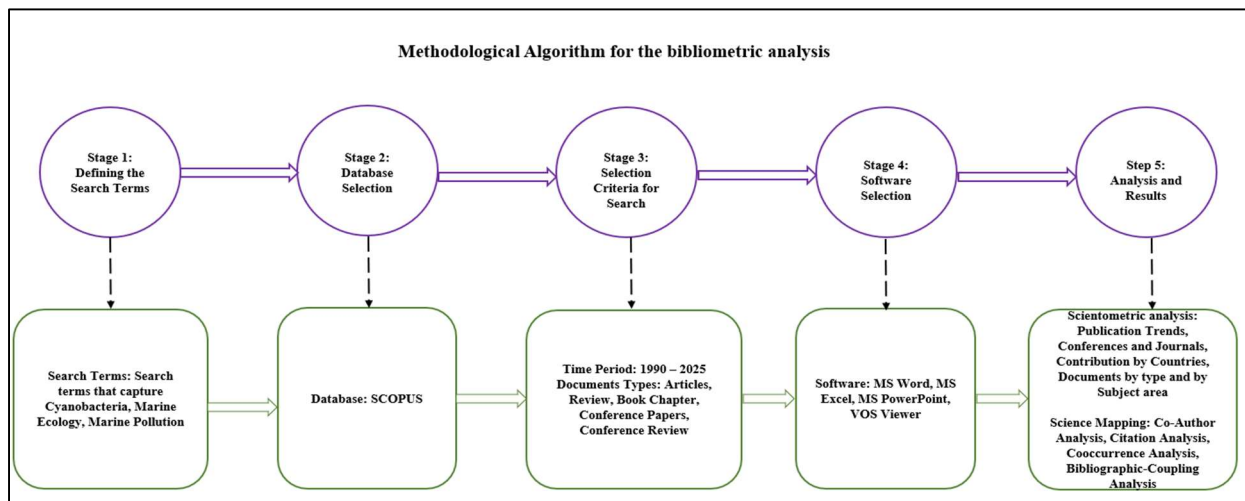


Figure 1: Methodological scheme for the bibliometric analysis

**Step 1. Definition of Search Terms:** The goal of this current article, as outlined in the introduction, is to (i) describe and evaluate the nature and progress of the literature on cyanobacteria and its relationship with marine ecology and marine pollution (ii) a complete systematic review on the evolution of the research on the association of cyanobacteria in relationship to marine ecology, as well as marine pollution their associated specific disciplines.

**Step 2. Selection of Database:** Since the Scopus database is one of the largest and most widely accepted scientific databases and a wide number of literary materials have been reviewed including colleague reviewed articles, conference proceedings, reviews, books, etc., this has become a clear option for the current course of investigation. Search for "cyanobacteria" and "marine ecosystem" or "marine pollution" in the Scopus database.

**Step 3. Selection Criteria for Search:** The following terms were searched on the grounds of the Title, Keywords and Abstract of the publications by using the search strings related to information technology and sustainable development reporting: TITLE-ABS-KEY ("*Cyanobacteria*") and TITLE-ABS-KEY ("*Marine Ecology*") or ("*Marine Pollution*"), in collecting articles' data from an electronic database of Scopus. The search process had been considered based on the above keywords provided and resulted in a total 629 documents. Considering only from the year 1992s onwards and common types of documents are considered in this study like articles from journals, review, book chapters, conferences papers, and conference review articles so further filtering of search results

were performed. The above measures were followed when using the Scopus database and after filtering the bibliographic data, all exported data (620 documents) in CSV format had processed without any further data cleansing.

**Step 4. Software Selection:** The preparation of this article included the use of several Microsoft office programs. However, the data collected and analysis of the collected data was mainly performed mainly using Microsoft Word, Microsoft PowerPoint Microsoft Excel software program. In addition, for the Advanced Bibliometric Analysis Vose Viewer, a freeware data-government program has been employed.

**Step 5. Analysis and Result:** The results of the systematic bibliographic analysis are presented through both descriptive analysis and science mapping using network visualization techniques. This bibliographic study draws on a substantial body of literature to identify key research trends related to the terms "*Cyanobacteria*", "*Marine Ecology*", and "*Marine Pollution*". Accordingly, this section focuses on the findings generated through bibliometric analysis tools. In order to do perform descriptive analysis, the search information was examined and categorised based on the annual number of publications, publication journals, contributing authors, productive nations, document type, and document by subject area. The next step was visualizing the data on "*Cyanobacteria*", "*Marine Ecology*", and "*Marine Pollution*" in terms co-authorship-related countries, co-occurrence-related author keywords, and bibliographic coupling in terms of country and publication.

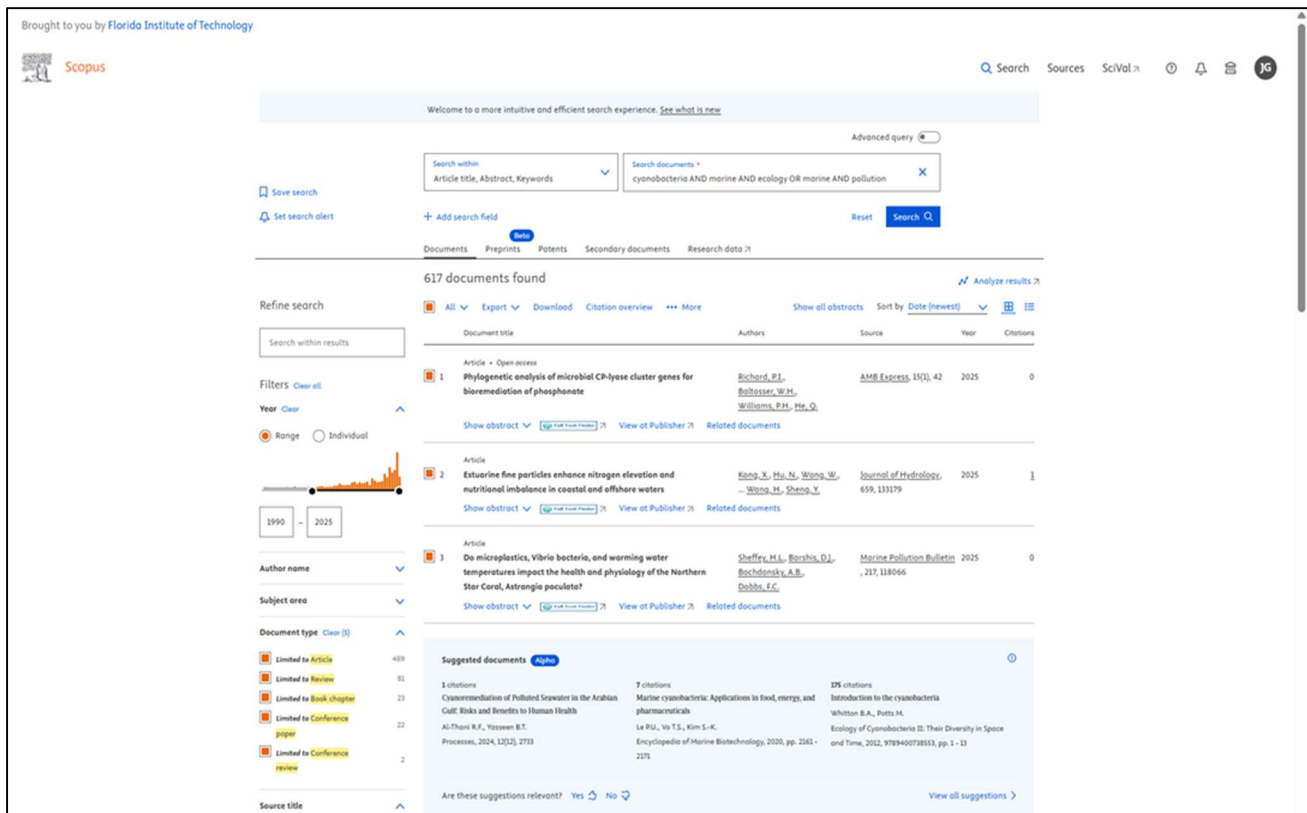


Figure 2: Search Result of 620 Documents connected to the main Key Words

**Step 5.1. Descriptive Analysis:** To review the current trends in the research development of cyanobacteria and its relationship to marine ecology or marine pollution, this subdivision will present a great overview of publication trends and citation performance on the study with an overview of the most productive countries and most significant journals and articles. The number of papers on "*Cyanobacteria and Marine Ecology or Marine pollution*" published in Scopus was our first finding, using data extracted from the Scopus database. Total number of documents retrieved are 620 after filtering.

**Step 5.1.1. Documents Per Year**

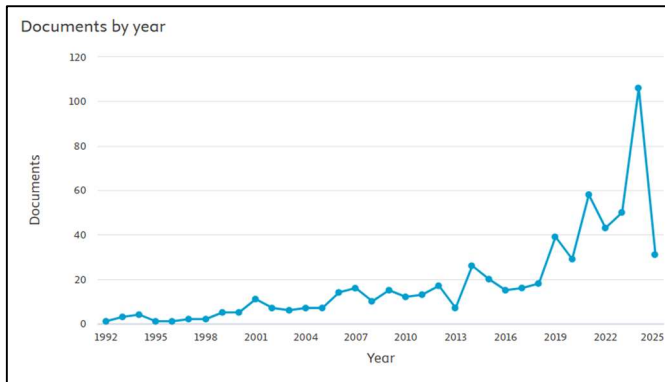


Figure 3: Documents Published Annually

The line chart of above **Figure 3**, shows the yearly trend for the published documents on "*Cyanobacteria*" and "*Marine Ecology*" or "*Marine Pollution*" between 1992 and 2025 where we can see a slow increase in output from approximately 1990 to 2017, which then sharply rose, and has continued in steady growth since. Although there was general increase in research for the years prior to 2018, there was notable increase in publications with peaked publications 2024, which may reflect an overall trend towards a greater scientific interest in the role cyanobacteria play in marine ecosystems, and to address challenges associated with pollution, which is associated with a greater concern about pollution on aquatic systems, general fields of environmental concern, and evolution of marine research of microbes. The decline in 2025 is expected to be for incomplete data for the current year, rather than a genuine decline in research.

**Step 5.1.2. Document by Country**

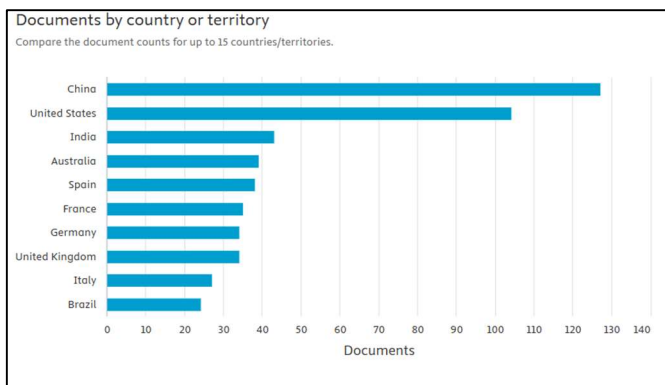


Figure 4: Documents Published Country

This horizontal bar chart titled of **Figure 4** "Documents Published Country" presents the number of documents published by the top countries or regions. China leads by a significant margin with about 127 documents, followed by about 104 documents in the United States. India is third with around 45 documents, while Australia and Spain each published about 38 and 36 documents respectively. France, Germany, and the United Kingdom respectively published between about 33 to 30 documents, demonstrating a count of similar publishing. Italy published about 27 documents and Brazil is listed with about 24 documents. This chart demonstrates that the document is a huge contributor to the documentation scenario between China and the countries listed in the United States.

**Step 5.1.3. Documents Published by Source**

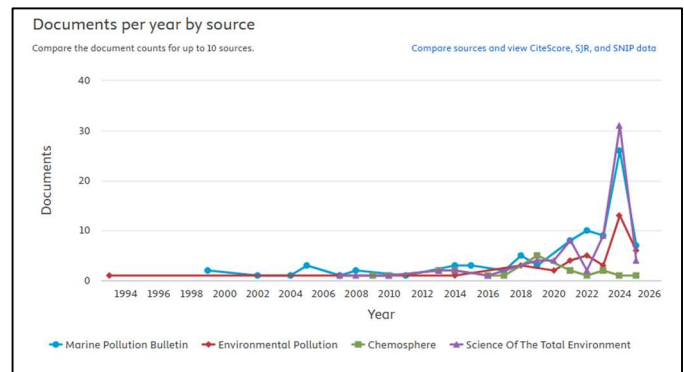


Figure 5: Documents Published by Source

This line graph of **Figure 5**, Documents Published by Source" indicates the calories of documents published per year for four sources over the perios from 1994 to 2026 (and with italics for 2024). The "Science of The Total Environment" line (purple) has a marked increase especially in 2018, and a dramatic peak in 2023, with over 30 documents published, and a slight decrease in the line for 2024. The "Marine Pollution Bulletin" (blue line) also has an upward trend with a peal in 2023 of over 25 parallels, and a decrease in 2024. The "Environmental Pollution" (red line) has relative low publication by compression over most of the timeline, has periods of increase in publication in 2018-2020, and a smaller peak in 2023 with about 12 documents and a decrease in 2024. The "Chemosphere" is the green line and is has a modest and stable publication, with slight fluctuations and small increase with the last year of renewals around 2022-2023; in general, it does not go above 10 documents per year. Overall, this graph shows a distinct recent increase in document publication, especially for the "Science Of The Total Environment" and "Marine Pollution Bulletin" sources, suggesting many more people are being engaged in research in these areas, especially over the last several years.

**Step 5.1.4. Documents by Type**

**Figure 6**, shows the distribution of documents regarding the effects of *cyanobacteria* on marine ecological health by publication type. The overwhelming majority of documents are research articles, at 79.3%, indicative of the strong emphasis on primary, peer-reviewed science about this issue. Review

articles are also significant, at 13.1%, suggesting significant work has been dedicated to synthesis and overarching guidance in the current state of knowledge. Book chapters (3.7%) and conference papers (3.6%) make more modest contributions to the document distribution, indicating interdisciplinary dialogs and/or topics of cyanobacterial relevance being included in remedies to marine ecological health. Conference review papers (0.3%) were almost not present in the literature and represent a small fraction of the academic literature due to the specialized publishing of these documents. The investigation found that journal articles are the predominant medium for the dissemination of research outputs in this area.

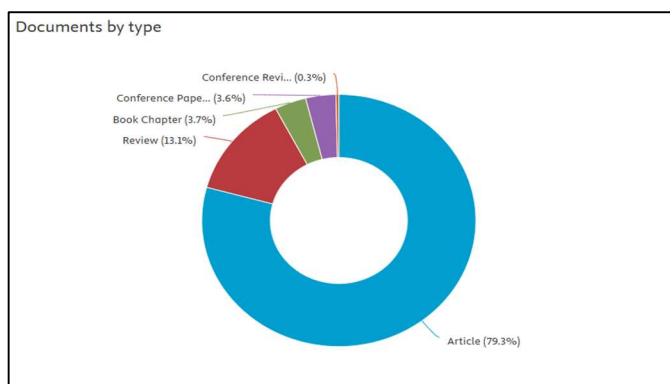


Figure 6: Documents Published by Type

#### Step 5.1.5. Documents by Subject Area

The following **Figure 7**, provides a nuanced overview of documents regarding the marine system and ecology of cyanobacteria by subject category, underscoring the multi-disciplinary nature of research within the ecology of cyanobacteria. The most significant number of publications related to the investigation of cyanobacteria fall under Environmental Science (36.2%) and captures the most immediate concern with environmental and ecological change, water quality, and environmental management. Agricultural and Biological Sciences (16.1%) likely consists of a considerable amount of research that focuses on biological processes related to *cyanobacteria* and resultant interactions with other organisms. Earth and Planetary Science represented 11.2% of the total, and could include significant geochemical and oceanographic research. In addition, the review's other categories of Pharmacology, Toxicology and Pharmaceutics (6.6%); Medicine (6.1%); Biochemistry, Genetics and Molecular Biology (5.2%); and Immunology and Microbiology (4.8%), indicated that cyanotoxins pose concerns for human health. The subject areas of Chemistry (3.9%); Engineering (3.0%); and Chemical Engineering (1.3%) emphasized important aspects of chemistry and technology used in the studies. The remaining 5.6% of publications were referred to as "Other", which represented relatively small and less obvious disciplines associated with cyanobacteria ecology. The findings of this review support the interest and need for multi-disciplinarity, especially as marine systems are increasingly complex and concern the entire microbiome.

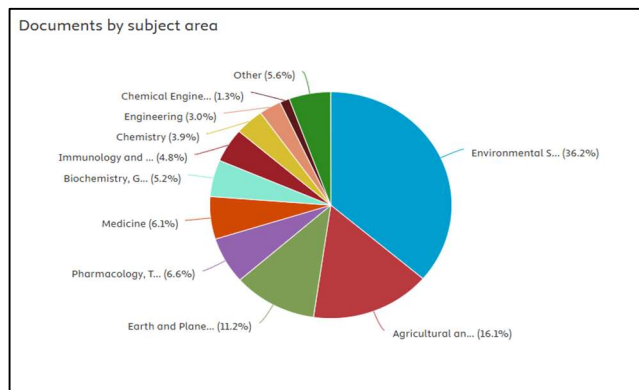


Figure 7: Documents Published by Subject Area

### Step 5.2. Network Visualization

Network visualization shows the co-authorship of countries, Citation, co-words and bibliographic coupling. In brief, network analysis can offer an intuitive graphic representation for research on collaboration, popularity of document, co-occurrences, and bibliographic coupling, where the relations between a couple of items are illustrated by the size of the nodes, colour nodes, and the thickness of linking lines (Zhang, et. al. 2019).

#### Step 5.2.1. The co-authorship network of Documents

The following Table 2 and Figure 8, display the co-authorship map in the "*Cyanobacteria* and marine ecology or marine pollution" articles. There were 84 countries according to VOS viewer. However, when a filter was applied to sources having at least 1 document per country with minimum 1 citation then 81 documents met the threshold. The China, along with USA, India and Australia have a high publication count. On the other end, countries such as Romania, Bulgaria, Iraq, Sri Lanka and so on, have very low publication count. The other counties in the scope, such as Russia, South Korea, Mexico, Qatar, and so on show moderate publication count suggesting increasing research participations. Overall, the analysis indicates variations in publication count of different countries shows that countries with higher publication counts are likely more active in research collaboration within the dataset. Network visualisation result also shows number of nodes and clusters. The distance between the nodes and the link thickness reveals the degree of cooperation between countries, while the links between the nodes represent the relationships between the countries for example big red nodes showing higher publication and strong connection of China, Australia, and India with their corresponding countries. Similarly, brown node showing higher publication count and strong connection of USA with its corresponding countries.

TABLE 2

The Top 10 Most Influential Countries in Terms of co-authorship network of articles on "Cyanobacteria and Marine Ecology or Marine Pollution"

No.	Country	Total Publication
1	China	127
2	United States of America (USA)	104
3	India	43
4	Australia	39
5	Spain	38
6	France	35
7	United Kingdom, Germany	34 each
8	Italy	27
9	Brazil	24
10	Canada	23

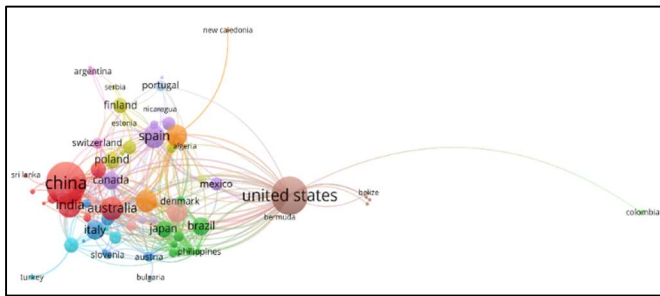


Figure 8, The co-authorship network of articles on "Cyanobacteria and Marine Ecology or Marine Pollution" in terms of countries

Step 5.2.2. The Citation trend network of Documents

Table 3 and Figure 9, "Cyanobacteria and marine ecosystem or marine pollution" display quotes maps in articles. According to VOS viewer there were 84 countries. However, when a filter was implemented that at least 1 document sources per country with minimum 2 citations, 78 documents were found from the threshold.

The following table presents the quotation tendency of documents published in terms of cyanobacteria, marine ecosystems, and marine pollution, highlighting the research effects of different countries. The United States leads with the highest number of total citations (8133) despite being less publication (104) than China (127), indicating the high impact of publication per publication. France and Spain also show strong citation performance with 2604 and 2567 citations respectively, showing the high relevance and quality of their research. Countries such as Germany, Australia and Canada show a balanced contribution in both the quantity of publication and citation, while India, despite being more published than many others, is comparatively low citation calculation (1109), which suggests either new research or low citation. The total link strength metric shows collaborative effects with the United States (52), France (50), and Australia (41), with strong international research connections, which strengthen their roles

as prominent contributors in the global research network on marine pollution and cyanobacteria.

Moreover, the following figure, generated by using VOS viewer, illustrates the international research collaboration network in the field of "Cyanobacteria, Marine Ecology, and Marine Pollution". Each node represents a country, and the size of the node reflects the volume of research publications, while the connecting lines indicate the strength and extent of collaborative efforts between countries. China, the United States, and France emerge as major hubs, indicating high research output and strong international collaborations. Countries like India, Germany, Spain, and the United Kingdom also show significant interlinkages, highlighting their active roles in global research partnerships. This visualization network analysis underscores the importance of global cooperation in addressing complex marine environmental challenges related to cyanobacterial blooms and pollution.

TABLE 3

The Top 10 Most Influential Countries in Terms of Citation trend network of articles on "Cyanobacteria and Marine Ecology or Marine Pollution" Table 3: The Top 10 Most Influential

No.	Country	Total Publication	Total Citation	Total Link Strength
1	United States of America (USA)	104	8133	52
2	France	35	2604	50
3	Spain	38	2567	16
4	China	127	2490	32
5	Germany	34	2374	36
6	Australia	39	2314	41
7	Canada	23	1209	18
8	India	43	1109	32
9	Japan	20	857	16
10	Italy	27	703	21

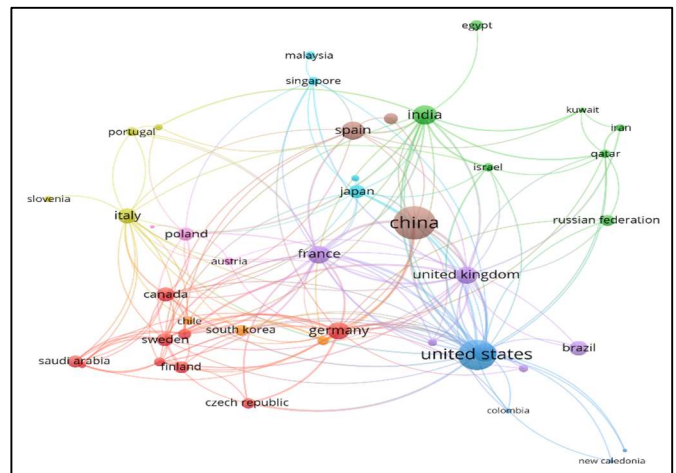


Figure 9: Countries in Terms of Citation trend network of articles on "Cyanobacteria and Marine Ecology or Marine Pollution"

### Step 5.2.3. The co-occurrence network of keywords in Documents

The analysis of keyword co-occurrence is a widely used tool in bibliometric studies, as it helps to uncover the main research topics. For this purpose, we utilized VOS viewer, which produced a keyword distribution map for articles on "Cyanobacteria" and "Marine Pollution", or "Marine Ecology" based on the authors' keywords. After filtering through 1948 keywords with a minimum appearance threshold of 10, we ended up with 24 keywords.

The following **Table 4**, showcases the top 20 keywords ranked by their frequency and total link strength in literature related to Cyanobacteria, Marine Ecology, and Marine Pollution, highlighting key research themes and their connections. "**Cyanobacteria**" stands out as the most frequently mentioned keyword (80 occurrences) with the highest link strength (121), emphasizing its pivotal role in this field of study. Other significant keywords like "Eutrophication" (30 occurrences, 56 link strength), "Pollution" (26, 51), and "Microplastics" (27, 36) point to critical environmental challenges tied to cyanobacterial activity and the degradation of marine ecosystems. Terms such as "**Microcystin**" and "Harmful Algal Bloom" address the toxicological issues related to cyanobacterial blooms, while "**Phytoplankton**" and "Nutrients" highlight important ecological interactions. The emergence of terms like "Climate Change," "Bioremediation," and "Plastisphere" indicates new themes that connect human impacts with potential mitigation strategies. Overall, the data paints a complex picture of research focused on pollution effects, ecosystem dynamics, and toxicological risks in marine environments.

The following **Figure 10**, illustrates a keyword co-occurrence network map created with VOS viewer, visually depicting the relationships among frequently used terms in the literature concerning **Cyanobacteria**, **Marine Ecology**, and **Marine Pollution**. At the center, "Cyanobacteria" emerges as the most prominent and interconnected term, showcasing its significance in the research landscape. It is closely linked with "Eutrophication," further underscoring its relevance.

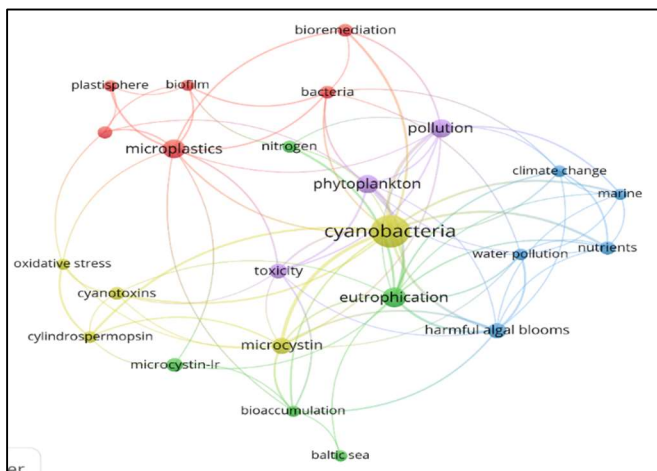


Figure 10: The co-occurrence network of keywords in articles on "Cyanobacteria and Marine Ecology or Marine Pollution"

TABLE 4

The Top 20 keywords in articles on "Cyanobacteria and Marine Ecology or Marine

No.	Keywords	Occurrence	Total Link Strength
1	Cyanobacteria	80	121
2	Eutrophication	30	56
3	Microplastics	27	36
4	Pollution	26	51
5	Phytoplankton	26	35
6	Microcystin	21	38
7	Harmful Algal Bloom	18	32
8	Toxicity	17	21
9	Microcystin-Ir	15	10
10	Nutrients	14	15
11	Bacteria	13	19
12	Bioremediation	13	15
13	Cyanotoxins	13	15
14	Nitrogen	12	18
15	Marine Pollution	12	10
16	Water Pollution	11	13
17	Climate Change	11	12
18	Marine	10	14
19	Oxidative Stress	10	12
20	Plastisphere	10	11
21	Baltic Sea	10	6

### Step 5.2.4. Bibliographic Coupling of Countries:

Bibliographic coupling between countries, as described by Gu et al. (2021), signifies a shared research interest when articles from different nations cite the same source in their reference lists. This phenomenon indicates a commonality in the foundational knowledge or specific topics being explored by researchers in those respective countries, thereby revealing the interconnectedness and proximity of their scientific work.

This coupling can be visually represented in different ways such as in terms of table as follows **Table 5**, and as network graph as depicted in **Figure 11**, by using various colours and sizes for the nodes in graph. The colours represent different clusters found in the analysis, while the size of each node indicates how much each country has contributed—bigger nodes mean a bigger contribution. The recent study I came across looked at bibliographic coupling and found that out of 84 countries analysed, 78 had at least one document and two citations each.

In terms of research specifically on cyanobacteria, marine ecology, and marine pollution, a table in the study shows some interesting findings. The United States comes out on top with 104 publications and the highest citation count of 8,133, along with a total link strength of 11,985. This clearly shows the U.S.

has a strong influence and a deep network of connections in global research.

Australia and China, even though they have fewer citations than the U.S., still have impressive link strengths of 8,660 and 8,559, respectively. This indicates that both countries are also making significant contributions through collaboration. Other important players include the United Kingdom, France, and Germany, which each have citation counts between 6,970 and 8,010, marking them as key contributors to this area of study.

Next, if we discuss about India. It has 43 publications, but only 1,109 citations, and a link strength of 4,178. The data indicates that India is gradually becoming the center of research; however, its connections are not strong yet. Overall, the figures bring out the fact that Western countries are the leaders in citation impact and interconnectedness. Nevertheless, the likes of India, Brazil, and the Netherlands are not far behind and are beginning to emerge.

Bibliographic coupling in a visual form depicts the relationships between the countries, which means that the size of the nodes represents the number of publications, and the lines or bands between them show how many references they have in common. The U.S. has the largest node and the most connections, and hence, it keeps the first place in research output as well as collaborations with other countries. On the other hand, China, Australia, Germany, and the U.K. also have good-sized nodes and connections from which can be inferred that these countries are significant contributors to worldwide research programs. Others like Brazil, Japan, and India have moderate representations, suggesting they're growing their participation. On the other hand, smaller nodes representing places like New Caledonia and Ethiopia indicate limited but still emerging contributions. Overall, this illustrates a rich network of international collaboration in environmental research.

The top 10 Countries in terms of bibliographic coupling on "Cyanobacteria and Marine Ecology or Marine Pollution"

No.	Country	Total Publication	Total Citation	Total Link Strength
1	United States of America (USA)	104	8133	11985
2	Australia	39	2314	8660
3	China	127	2490	8559
4	United Kingdom	34	2207	8010
5	France	35	2604	7263
6	Germany	34	2374	6970
7	Spain	38	2567	5404
8	Netherlands	13	1101	4350
9	India	43	1109	4178
10	Brazil	24	755	3968

### III. CONCLUSION

This bibliometric study on a extensive scale clearly states that the research field of cyanobacteria and their interactions with the marine environment and pollution has been so significantly and progressively growing, especially from 2018 on. This trend basically mirrors the global community's heightened awareness of their ecological relevance and environmental influence. With almost the highest number of publications, China is also the leading country that has the most influential research, as indicated by the number of citations and the extent of cooperation at the global level. While the likes of India and Brazil, who are likely to be the next contributors, are gaining ground, they still cannot catch up with them in terms of citation and co-operation strength. At the same time, the countries such as France, Spain, Germany, and Australia seem to achieve a balanced number of outputs and good citation impact. Research papers (79.3%) are the leading examples of mature primary research, and the distribution of such papers over several subject areas (Environmental Science, Biological Sciences, Earth Science, and Toxicology) demonstrates the multidisciplinary character of this cluster. From analyses of the networks of co-authorship, citations, keyword co-occurrence, and bibliographic coupling, several strong international research networks can be identified which focus on the role of cyanobacteria in eutrophication, their interaction with microplastics, algal blooms, and toxin generation. Ultimately, the future of global collaboration will, among other things, have to deal with the following important issues; commitment to deepened global cooperation especially of underrepresented nations, establishment of multidisciplinary collaborations among marine science, public health, and biotechnology, and last but not least, the tackling of such current and hot topics as bioremediation, the consequences of climate change and the interface between microplastics and cyanobacteria. Moreover, by being more involved in high-impact partnerships, obtaining more grants, and publishing more in open access journals, the rise in the visibility and citation of work coming from the areas with a rapid pace of publishing but fewer references is just as

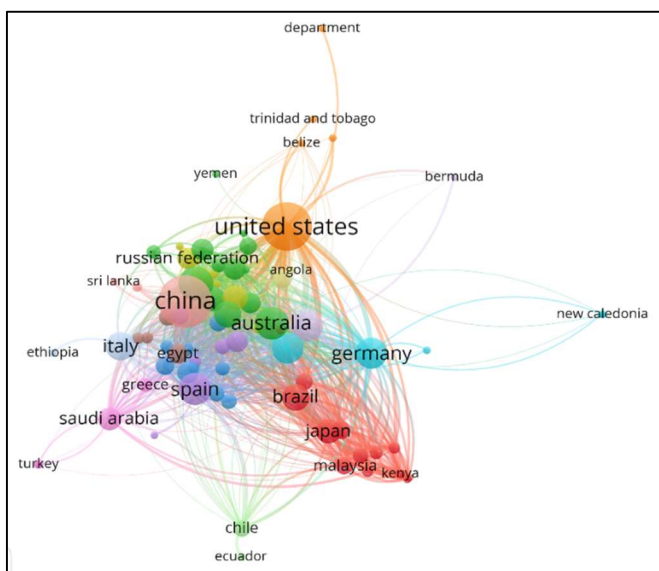


Figure 11: The bibliographic coupling network of Countries on "Cyanobacteria and Marine Ecology or Marine Pollution"

TABLE 5

important as these other initiatives. The latter two activities are essential components that, when combined with the first step, are what make it possible to achieve full knowledge and global mitigation solutions for the complicated ecological and toxicological problems caused by cyanobacteria in marine environments.

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