STUDIA UNIVERSITATIS BABEŞ-BOLYAI BIOLOGIA, 70, 1, 2025 (p. 19-47)
doi:10.24193/subbbiol.2025.1.02

Charting the academic output on cyanobacterial exopolysaccharides and their industrial applications

Maricel Bocaneala[1,2]✉, Giovani M. Goron[3] and Elena Rakosy-Tican[1]

[1]Department of Molecular Biology and Biotechnology, Faculty of Biology and Geology, "Babeş-Bolyai" University, 5-7 Clinicilor St., 400006 Cluj-Napoca, Romania; [2]National Institute for Research and Development of Isotopic and Molecular Technologies, 67-103 Donat St., 400293 Cluj-Napoca, Romania; [3]Department of Public Health, College of Political, Administrative and Communication Sciences, Babes-Bolyai University, 71 General Traian Mosoiu St., 400132 Cluj-Napoca, Romania;
✉***Corresponding author, E-mail: maricel.bocaneala@ubbcluj.ro***

Article history: Received 4 February 2025; Revised 17 March 2025; Accepted 17 March 2025; Available online 25 June 2025

Abstract. Cyanobacterial exopolysaccharides (EPS) are diverse biopolymers with significant ecological roles and growing industrial potential due to their biocompatibility, biodegradability, and functional versatility. This study presents a bibliometric and patent analysis of cyanobacterial EPS research between 2004 and 2023, exploring academic and industrial advancements. The bibliometric analysis of 1,022 articles identified pharmaceuticals and environmental applications as dominant research themes, while the food, agriculture, and energy sectors showed emerging interest. A manually curated subset of 79 articles focusing on industrial applications highlighted EPS's potential in pollutant removal, drug development, and biofertilization. Patent analysis, with data from 618 entries, revealed a surge in filings post-2014, predominantly in the USA, reflecting growing industrial interest. While healthcare and environmental sectors lead in EPS applications, translational gaps between academic research and industrial adoption persist, particularly in underdeveloped domains. This study presents the multidisciplinary appeal of cyanobacterial EPS, striving to offer insights into future research directions and their potential for sustainable innovation across diverse sectors.

Keywords: bibliometric analysis; cyanobacterial EPS; exopolysaccharide; technological transfer

Introduction

Cyanobacterial exopolysaccharides (EPS) are a diverse group of biopolymers with remarkable structural and functional properties. These extracellular polysaccharides play important roles in ecological processes such as biofilm formation, nutrient cycling, and microbial interactions (Rossi & De Philippis, 2015; Potnis *et al.*, 2021; Nishanth *et al.*, 2021; Debnath *et al.*, 2024). Beyond their environmental significance, cyanobacterial EPS have garnered increasing attention for their potential industrial applications, covering diverse fields like healthcare, environmental remediation, food production, agriculture, and bioenergy (Kumar *et al.*, 2018; Laroche, 2022).

In recent decades, the expanding interest in sustainable and biotechnological innovations has driven research into cyanobacterial EPS. These biopolymers exhibit a range of desirable properties, including high biocompatibility, biodegradability, and functional versatility, making them attractive candidates for applications such as drug delivery systems, wound healing materials, biofertilizers, and biosorbents for pollutant removal. Advancements in analytical techniques and interdisciplinary approaches have enabled the exploration of novel cyanobacterial strains and optimized EPS production processes, further stimulating scientific inquiry and industrial interest (Li *et al.*, 2001; Mota *et al.*, 2020; Potnis *et al.*, 2021; Reignier *et al.*, 2023; Rodrigues *et al.*, 2024; Yousaf *et al.*, 2024).

The technological transfer of cyanobacterial EPS from research to industrial applications involves several critical steps, including strain selection, optimization of production parameters, and downstream processing. Selecting appropriate cyanobacterial strains is essential, as EPS yield and composition can vary significantly among species. Optimization of cultivation conditions, such as nutrient availability, light intensity, and temperature, can impact EPS production. Efficient downstream processing techniques, including extraction and purification methods, are crucial to obtaining high-quality EPS suitable for industrial use (Cruz *et al.*, 2020).

Cyanobacterial EPS have demonstrated potential in various industrial settings. In the food industry, they can serve as natural thickeners, stabilizers, and emulsifiers, improving the texture and shelf-life of products (Vicente-García *et al.*, 2004; Jindal *et al.*, 2013; Najdenski *et al.*, 2013; Nath *et al.*, 2021). In pharmaceuticals, their bioactive properties, such as antioxidant, antibacterial, and antiviral activities, make them suitable for developing new therapeutic agents (Gacheva *et al.*, 2013; Bhatnagar *et al.*, 2014; Shen *et al.*, 2018; Flores *et al.*, 2019; Ramachandran *et al.*, 2020). Environmental applications include bioremediation, where EPS can bind heavy metals and pollutants, facilitating their removal from contaminated sites (Colica *et al.*, 2010; Santos *et al.*, 2014; Mota *et al.*, 2016; Mohamed *et al.*, 2023). Additionally, in agriculture, EPSproducing cyanobacteria contribute to soil stabilization and fertility, promoting sustainable farming practices (Van Camp *et al.*, 2022; Falsini *et al.*, 2023; Vinoth *et al.*, 2023).

The current study aims to map the academic and industrial landscapes of cyanobacterial EPS research through a bibliometric analysis of publication trends, prominent contributors, and thematic areas of research for potential industrial applications. Additionally, it explores the translational potential of this research through an analysis of patent filings, offering insights into the intersection of scientific discovery and technological application. While other studies have performed bibliometric analysis on cyanobacterial exopolysaccharides (Qi *et al.*, 2019; Kim *et al.*, 2024; Mugani *et al.*, 2024), to our knowledge none had approached this analysis through the concepts of technological transfer and had the scope of exploring the link between patent data and publication records for this research niche.

Materials and methods

Bibliometric data retrieval

The bibliometric data was retrieved from Clarivate's Web of Science and analyzed using Biblioshiny, a Bibliometrix R package (Aria & Cuccurullo, 2017).

The search was performed on Web of Science's Core Collection (edition: SCI-Expanded) using the following search string: (all fields) exopolysaccharide OR extracellular polysaccharide OR EPS OR exopolysaccharide-producing cyanobacteria OR exopolysaccharides OR extracellular polysaccharide EPS OR extracellular polysaccharides EPS OR exopolysaccharides OR released polysaccharides RPS AND (all fields; second row) cyanobacteria OR cyanobacterium. We then selected only the articles, in English, and published between 2004–2023. The specific year range was selected in order to explore publications within the past two decades, however, publications from 2024 are yet to be published and indexed, therefore we limited the search to 2023.

We obtained a query result of 1035 articles, based on the above-mentioned search, criteria, and filters. Data was exported in BIB format and imported into Bibliometrix. Further screening was performed using this tool - filtering out papers that were included in the WoS export, but that were flagged as indexed in 2024 issue releases. A total of 1022 articles met the inclusion criteria. In this paper, we will refer to this dataset as the "full dataset", to distinguish it from the filtered one. We proceeded to manually filter which papers out of the total 1022 report data on industrial or biotechnological application of cyanobacterial EPS (selection criteria listed in Section 2.1.1), and this dataset will be referred to as "filtered dataset" moving forward (Figure 1).

Articles selection criteria for the filtered dataset

The filtered dataset contains a subset of articles from the full dataset that reference information on possible technological applications of cyanobacterial EPS. In order to meet the selection criteria, articles must report direct or potential applications of cyanobacterial EPS that the authors have experimentally tested. Additionally, studies should relate these findings to potential industrial integration, either through proposed applications or by comparing EPS characteristics with those of existing products (e.g., gums, adhesives). Articles mentioning applications without presenting adequate methodological details were excluded from the dataset. Cyanobacterial EPS must either constitute the primary product or serve as a key ingredient within the product.

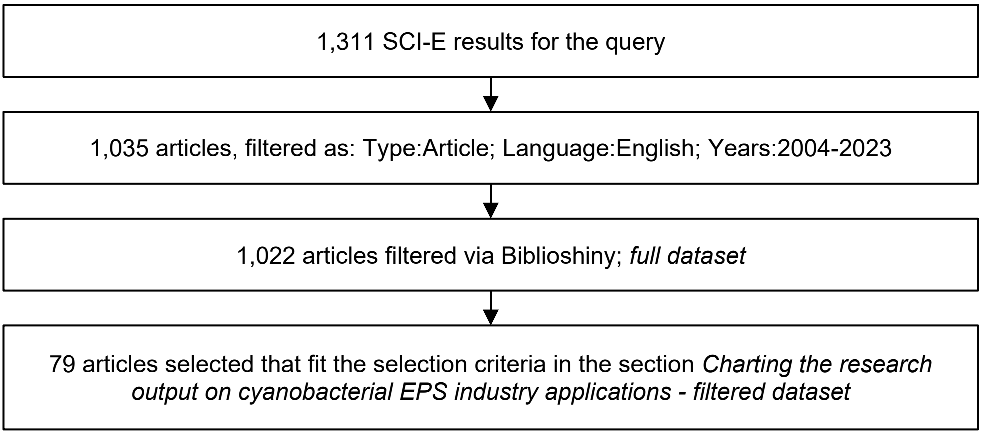


Figure 1. Chart presenting the filtering process of the articles from both the full dataset and the filtered one.

Filtered dataset

We conducted a manual screening of articles that report research on potential industrial applications of cyanobacterial EPS, following the selection criteria outlined in Section 2.1.1. From this process, 79 articles were identified and reviewed. For each selected article, we extracted and compiled relevant data into a dataset, which includes a rationale for inclusion based on the selection criteria, details on the methodologies reported or referenced, the specific properties of cyanobacterial EPS examined, potential industrial applications, industries mentioned, and the cyanobacterial organisms studied.

Espacenet patent data

In order to collect data on the patents published on cyanobacterial EPS, we performed a query on Espacenet (the European Patent Office) using the following search string: (nftxt = "cyanobacteria" OR nftxt = "cyanobacterium") AND (nftxt = "exopolysaccharide" OR nftxt = "extracellular polysaccharide" OR nftxt = "EPS"), and parameters: query language: en, filters: earliest publication date (family): 2004-01-01 — 2023-12-31. A total of 618 patents resulted. Data was exported and analyzed further using Microsoft Excel.

Results

Charting the research output on cyanobacterial EPS - full dataset

We analyzed the research output focused on cyanobacterial EPS from the full dataset. Using InCites, we determined that there are 4173 distinct authors that have contributed to the 1034 articles.

Annual scientific production

Figure 2 illustrates the annual production of articles from 2004 – 2023 on cyanobacterial EPS. Over this period, the research output has shown a steady increase, with an annual growth rate of 13.14%. This growth highlights an expanding interest and investment in the field, which can point towards potentially promising industrial and biotechnological applications of cyanobacterial EPS. The increasing volume of publications seen in almost every year suggests that researchers are actively exploring the potential of cyanobaterial EPS.

We note a dip in research output between 2014 and 2016, and then again between 2020 and 2022. In our opinion the first decrease in research output can be linked to a reduction of funds, which can be seen in the federal obligations for research and development reports for that time in the United States of America (National Center for Science and Engineering Statistics, 2021). The USA being one of the most prolific scientific outputs produced in this niche (Figure 3A), further strengthens this link. Additionally, in 2015 China launched the "Made in China 2025" initiative, a national strategic plan and industrial policy (Center for Strategic and International Studies, 2021). This marked a shift in its focus on supporting manufacturing capabilities. China also being the first country by affiliation frequency, appearing 1162 times in the full dataset (Figure 3B), can further point towards this research output dip. The reduced research output on this niche between 2020 and 2022 could be attributed in part to the COVID-19 Pandemic and/or limited access to on-site research facilities.

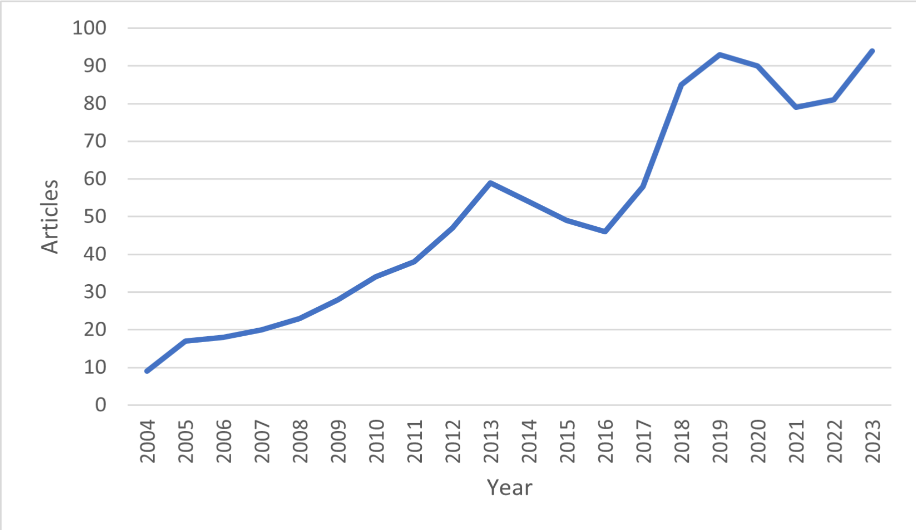
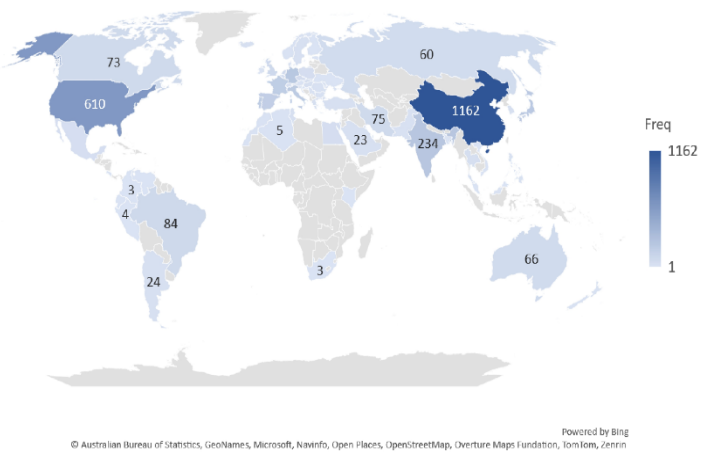


Figure 2. Annual scientific production, generated using Microsoft Excel, based on data analyzed in Bibliometrix.



Country	Frequency
China	1162
USA	610
India	234
Germany	223
Japan	210
Italy	198
Portugal	190
France	176
Spain	173
Brazil	84

Figure 3. Top 10 most prolific countries in terms of scientific production from the full dataset. Data was analyzed with Bibliometrix and Excel.
A: World map with the frequency of country of origin attributed to each publication (generated in Microsoft Excel).
B: Figure legend containing the raw data of the frequency of publications attributed to each of the top 10 countries.

Regarding the top 10 most globally cited articles (Figure 4), leading this list is an article by Borowitzka, published in the *Journal of Applied Phycology* in 2013 (Borowitzka, 2013), which has accrued 936 total citations and stands out for its high annual citation rate of 78. This prominence highlights its significant influence on the field, likely due to its focus on practical applications of EPS in biotechnology. Ward's 2009 article in *Applied and Environmental Microbiology* (Ward *et al.*, 2009) follows, with 709 citations and a steady annual citation rate of 44.31, indicating its sustained relevance within environmental microbiology. Additonally, articles by Qu (Qu *et al.*, 2012) and Parikh (Parikh *et al.*, 2006) achieved high citation counts and annual rates. We note that most of the top 10 papers in this list are published in journals that focus on applied research.

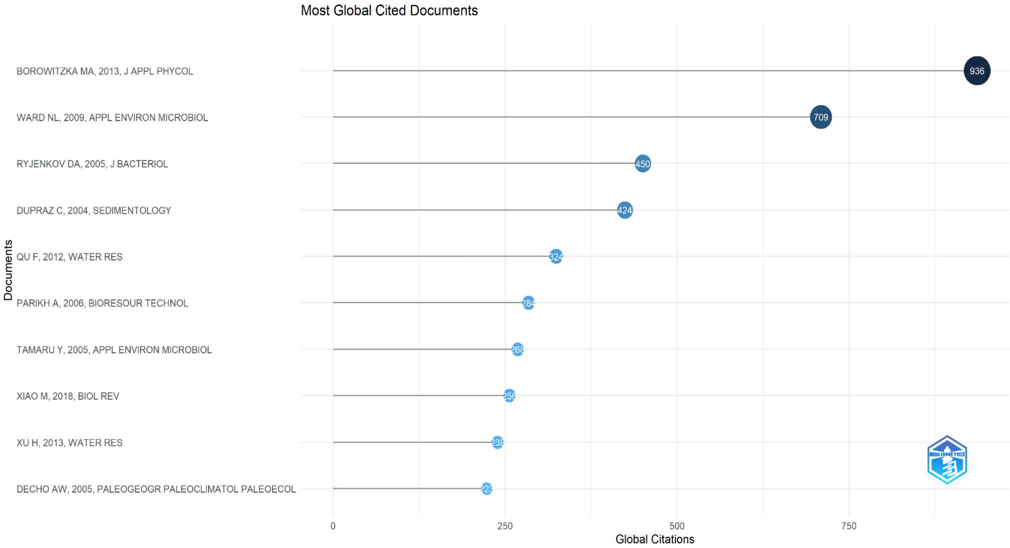


Figure 4. Top 10 most globally cited articles from the 1022 full dataset; figure generated in Bibliometrix.

Authorship and research networks

The analysis of the top 10 most prolific authors in cyanobacterial EPS research reveals a small group of researchers who have consistently contributed to advancing the field (Figure 5). Leading this group is Paula Tamagnini, with 22 articles published in the full dataset, followed closely by Roberto De Philippis with 21 articles. Both authors have significantly influenced the literature on cyanobacterial EPS, likely focusing on key topics such as EPS characterization and its industrial applications. Ming Li also stands out with 16 articles, while Shi-Ru Jia and Rita Mota each contributed 12 articles. Other notable contributors include Peter Capek, Xiang Gao, Federico Rossi, and Li Wu, each with 11 publications, and Alessandra Adessi, who has published 10 articles. The collective work of these prolific authors points to a concentrated effort among a select few researchers who are driving the development and visibility of cyanobacterial EPS studies. Their sustained productivity likely aligns with the field's shift towards applied research and suggests a readiness for industry-related exploration, particularly in biotechnology and resource management contexts.

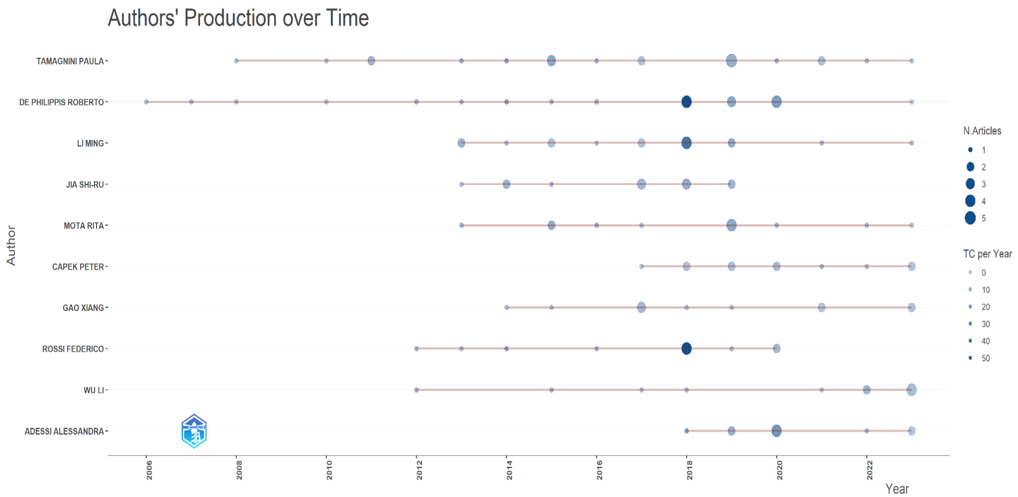


Figure 5. Top 10 most prolific authors based on the number of articles from the full dataset. Here we visualize using Bibliometrix the production over time of these authors.

In Figure 6, we visualize the collaborative efforts between countries related to publishing cyanobacterial EPS research. The United States emerges as the most collaborative nation, engaging in 132 recorded partnerships, followed by China (n=124), Germany (n=64) and Italy (n=54). This analysis illustrates a geographically diverse yet interconnected research ecosystem when it comes to exploring cyanobacterial EPS and its applications.

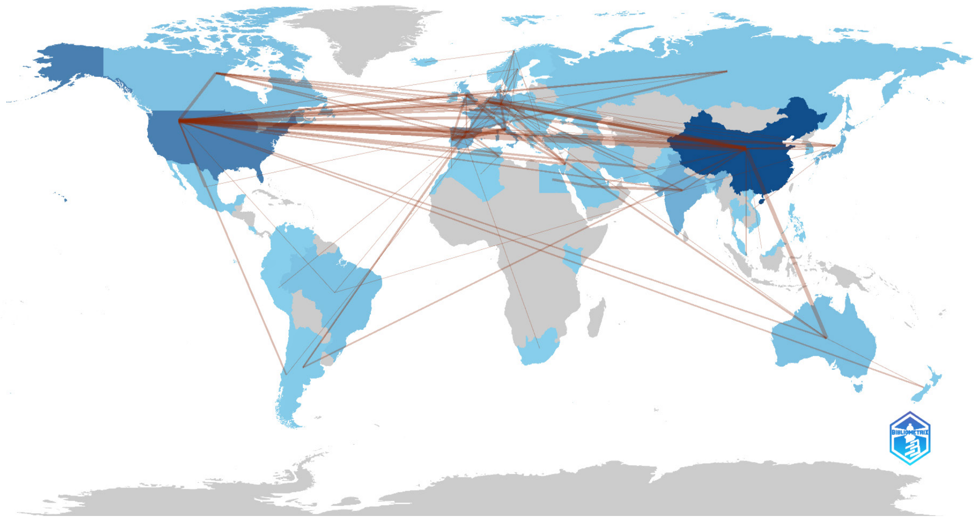


Figure 6. Countries' collaboration world map, generated using Bibliometrix.

Publishing avenues for cyanobacterial EPS research

The 1022 articles were published in 349 distinct sources (journals). Out of these, the top 10 in terms of the number of papers published from the full dataset are shown in Figure 7. This visualization indicates the core journals where cyanobacterial EPS research is most frequently published, the first being the *Journal of Applied Phycology*, with 48 published papers.

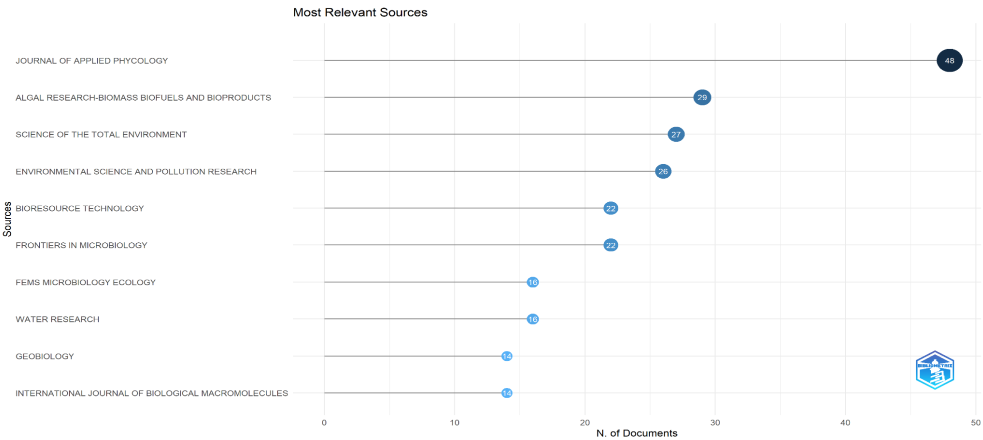


Figure 7. Top 10 most relevant journals publishing cyanobacterial EPS research, showing the distribution of the 1022 articles across the top 10 journals, highlighting the primary publication venues in this field, generated with Bibliometrix.

The growth of the number of articles published within each of the top 10 journals is highlighted in Figure 8. The analysis of publication trends across the top 10 journals for cyanobacterial EPS research reveals a distinct pattern that aligns with the hypothesis that this field is maturing toward technological transfer and industrial applications. Overall, journals with an applied focus, particularly those dedicated to biotechnology and resource management, have shown significant growth in publication counts over the years. This trend is led by the Journal of Applied Phycology and Bioresource Technology, where consistent increases in published articles indicate strong interest in potential practical applications of cyanobacterial EPS. The growth of the number of articles in these journals likely reflects a growing interest in finding solution that incorporate these polymers. In contrast, journals with a more general environmental or microbiological focus, such as Environmental Science and Pollution Research and FEMS Microbiology Ecology, maintained steady but modest publication output. These journals contribute to the fundamental understanding of EPS, particularly within environmental and ecological contexts, yet they do not exhibit the same dynamic growth as journals with applied orientations. This suggests that while cyanobacterial EPS remains a relevant topic within environmental studies, the current momentum is largely driven by its potential for practical application, which is better suited to journals emphasizing biotechnology and resource use.

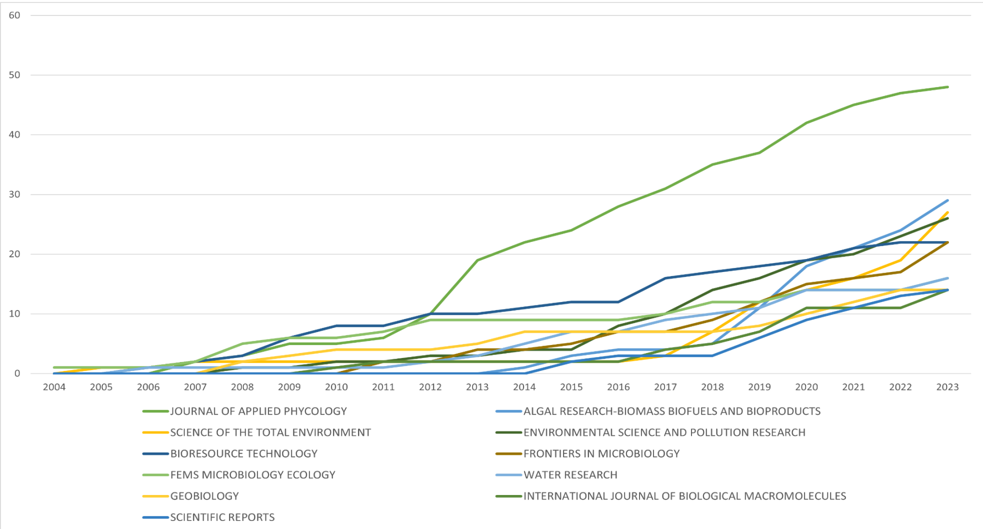


Figure 8. Annual publication growth of the number of articles on cyanobacterial EPS in the top 10 journals (2004–2023), generated using Bibliometrix data in Microsoft Excel.

Research interests

There are 2904 distinct author keywords in the full dataset. We illustrate a word cloud of the most prominent keywords used in Figure 9. This analysis reveals key research themes and concepts within cyanobacterial EPS studies. Unsurprisingly, the most frequently used term is "cyanobacteria" (179 occurrences). This is closely followed by "growth" (157), "polysaccharides" (119), and "exopolysaccharides" (108), indicating a strong emphasis on understanding both the general growth dynamics and specific biopolymer production by these organisms. Terms like "biosynthesis", "extracellular polymeric substances" and "extracellular polysaccharides" suggest ongoing interest in the biological processes and structural components that underpin EPS production, which are relevant for exploring practical applications.

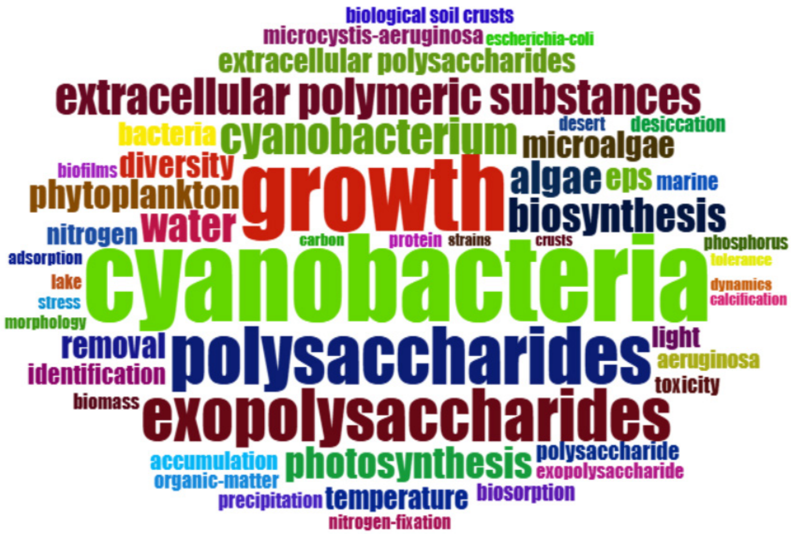


Figure 9. Word cloud generated in Bibliometrix using author keywords from the full dataset of 1022 published articles on cyanobacterial EPS.

Regarding how research trends evolved over time, in Figure 10 we visualize this concept using Bibliometrix and the author keywords. Some prominent and long-standing terms, such as "cyanobacteria", "exopolysaccharides" and "extracellular polymeric substances" while to be expected in the context of this specific dataset, reflect important concepts in this field, emphasizing them as core research areas. Notably, "microbial", "microalgae" and "biosynthesis" have also shown continuous interest, pointing towards ongoing research into both EPS origins and production mechanisms. In recent years, there has been a rise in terms associated with applied and environmental applications, such as “adsorption”, “removal” and “biosorption”, which can indicate growing attention towards using cyanobacterial EPS for bioremediation, pollutant binding, and environmental cleanup. Additionally, terms like “ultrafiltration”, “nitrate” and “diatoms”, even though they might not be directly linked to cyanobacterial EPS on a first look, might reflect an applied focus, potentially linked to water treatment technologies and the use of EPS in managing specific environmental contaminants. Similarly, terms like “biocrusts”, “phytoplankton” and “stromatolite” suggest a niche interest in studying EPS within ecological and geological contexts, connected to soil stabilization and their impact on geological history records.

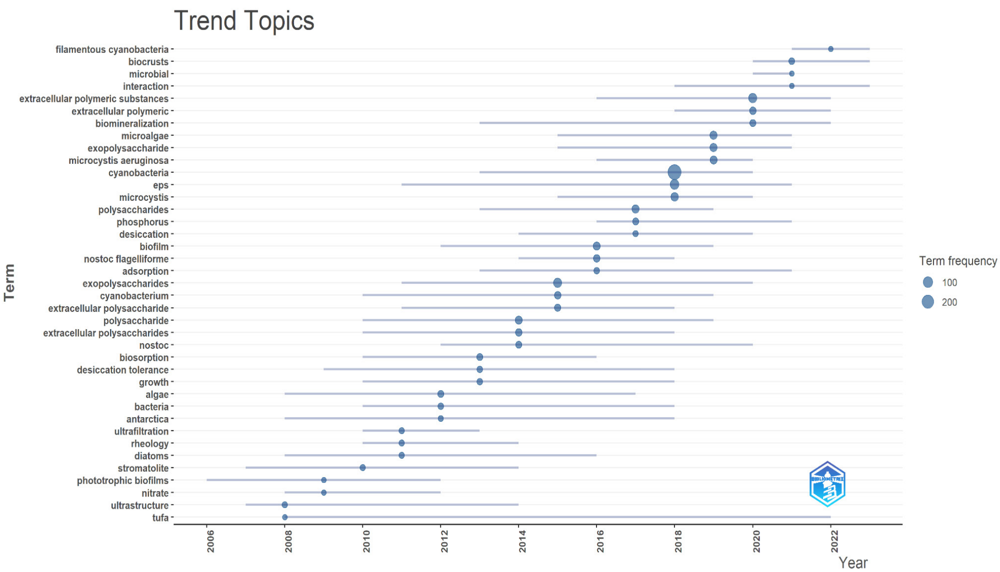


Figure 10. Author keywords are visualized as trends through time (2004-2023) and the frequency of use within the full dataset, generated with Bibliometrix. Horizontal axis: time; vertical axis: author keywords. The horizontal blue lines represent the time span in which each keyword was used within articles, while the circular dots and their dimensions are directly correlated with the frequency of use in the dataset.

The thematic map (Figure 11) highlights a few prominent trends within cyanobacterial EPS research. The Motor Themes quadrant contains terms like “extracellular polymeric substances” (EPS), “microbial mats” and “biomineralization.”

These topics are relevant and well-developed, suggesting they are important to the field and involve complex, multidisciplinary applications. Their placement reflects an advanced understanding of EPS roles in environmental contexts, such as the formation of microbial mats and biomineral structures, which are key to ecological and industrial applications. In the Basic Themes quadrant, terms such as "cyanobacteria", "exopolysaccharides", "polysaccharide" and "microalgae" represent foundational areas that form the scientific basis of the field. These themes seem less intensively developed recently, indicating they serve as the foundation of cyanobacterial EPS research but may be more mature with fewer current innovations.

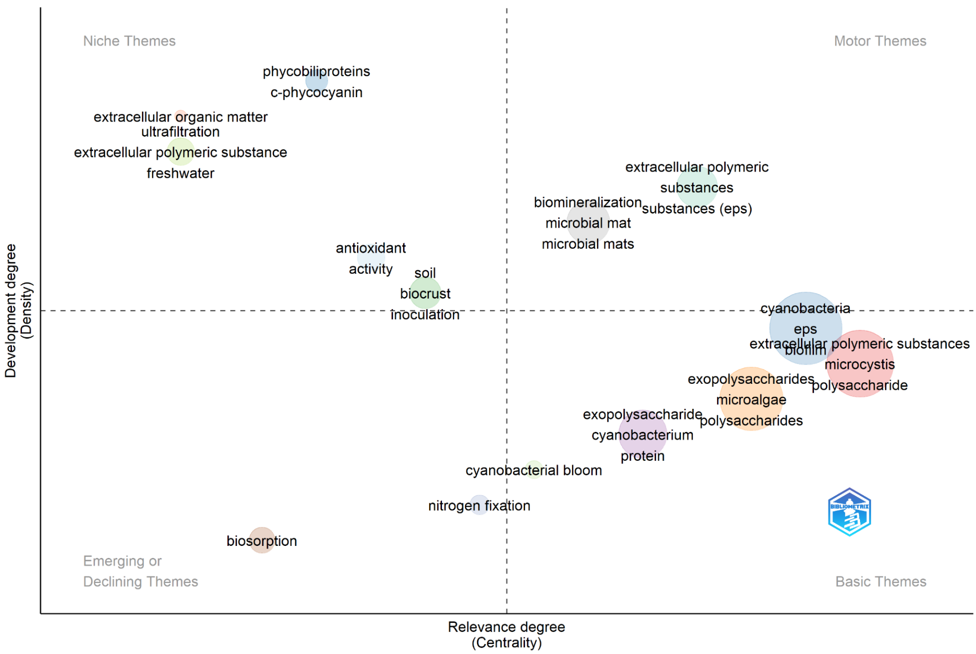


Figure 11. Thematic map of cyanobacterial EPS research showing four quadrants: Niche Themes, Motor Themes, Basic Themes, and Emerging or Declining Themes. Each term represents a distinct research focus, with its position on the map determined by relevance (centrality) and development (density). Topics in the Motor Themes quadrant are highly relevant and developed, indicating advanced and widely applicable research areas. Niche Themes are specialized but less central, focusing on specific applications or topics. Basic Themes represent foundational areas with broad importance but limited recent development. Emerging or Declining Themes are less relevant and show lower density, indicating potential areas of decreasing interest or nascent topics in need of further exploration; generated with Bibliometrix.

Niche Themes like “antioxidant activities” and “soil biocrust inoculation” occupy a specialized role within the field, showing strong development. These topics relate to particular applications, with reference to bioactive compounds derived from cyanobacteria or specific extraction techniques, pointing towards ongoing interest in specific technological and biochemical applications that may not be widely explored across the field. The presence of other types of molecules within this quadrant, namely “phycobiliproteins” also indicates the catalog of potentially useful molecules that cyanobacteria have to offer and the ability to be a multiple compound-producing organism without significant human intervention. Emerging or declining themes are represented by “biosorption” positioned with low density and centrality. This suggests that while biosorption may hold potential in applications like pollutant removal, it remains underdeveloped within the current EPS research framework, or it may be an area of declining interest as other approaches become more favorable.

The thematic evolution (Figure 12) is divided into three branches. During the 2004–2014 period, themes such as “cyanobacteria”, “extracellular polymeric substances” and “biological soil crust” are seen, laying the foundation for understanding EPS structures and their ecological roles. Themes such as “biosorption” and “phylogeny” also reflect an early interest in the environmental applications and genetic backgrounds of cyanobacteria. Then, in the 2015–2020 period, more diverse and application-oriented themes emerged, including “biofilm”, “antioxidant” and “biosynthesis”. This shift reflects a growing interest in the functional properties of EPS and its biochemical applications, aligning with industry-related uses in biotechnology. Topics like “16S rRNA gene” and “biomineralization” indicate increased focus on microbial community dynamics and EPS’s role in mineralization processes, suggesting that researchers were expanding their scope from basic characterization to more complex environmental interactions. The most recent period, 2021–2023, shows a further transition towards specialized applications and environmental relevance, with the emergence of terms like “microbial community”, “water quality”, “adsorption” and “biodeterioration”. These themes indicate a strong emphasis on EPS in ecological and environmental contexts, with applications in water treatment, pollutant removal, and microbial community interactions.

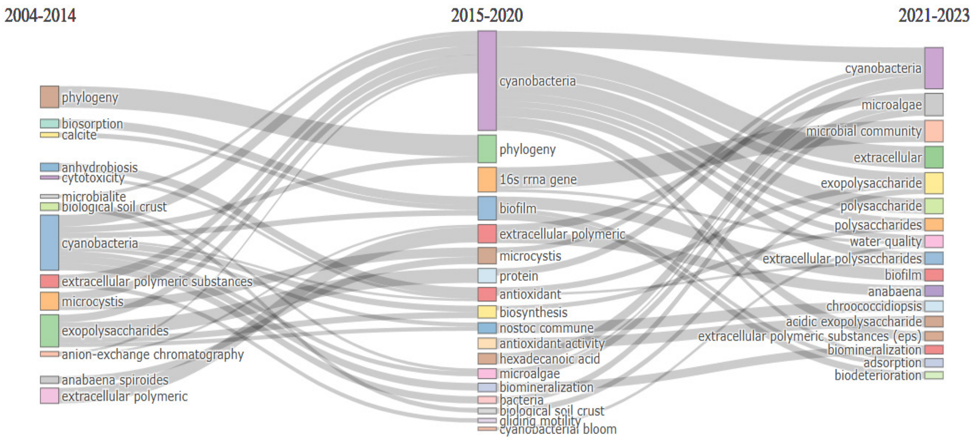


Figure 12. Thematic evolution of author keywords in cyanobacterial EPS research from 2004 to 2023. It illustrates the transition and development of major themes in 2004–2014, 2015–2020, and 2021–2023. Each colored block represents a research theme, with the size of each block indicating the relative focus on that theme. Lines between blocks connect related themes across periods, showing the continuity or emergence of research areas over time.

Charting the research output on cyanobacterial EPS industry applications - filtered dataset

There are 1022 articles in the full dataset and only 79 in the filtered one. The papers that focus specifically on industry applications of cyanobacterial EPS make up only 7.73% of the total articles in English that report research on cyanobacterial EPS indexed in Web of Science between 2004 and 2023. In this section, we analyze the industry-specific research applications of cyanobacterial EPS by examining the curated subset of 79 studies from the larger dataset. These papers were manually selected based on their explicit focus on potential industrial uses of cyanobacterial EPS. In this section we analyze these papers, providing a closer look at the specific industries that are emerging as key areas of interest for EPS applications, as well as the unique properties and functions driving their relevance.

In Figure 13 we visualize the analysis of the 79 studies from the perspective of industries mentioned as potential beneficiaries of each research. There seems to be a strong emphasis on healthcare and pharmaceutical applications for cyanobacterial EPS, with 35 papers reporting potential uses in this sector. Of these, 29 studies specifically mention pharmacological applications, indicating a significant interest in EPS's bioactive properties for drug development, therapeutic interventions, immune modulation, and other related applications. A smaller subset (6 articles) highlights uses in general healthcare, most being related to the EPS's biocompatibility and potential in wound healing. Environmental applications constitute the second-largest category, with 20 studies focusing on sustainability-oriented uses. Metal removal is the primary environmental sub-category (12 articles), followed by wastewater treatment (8 articles), both being related to the potential of EPS's utilities in pollution control. In the food and agriculture field, 12 studies highlight applications, with food industries accounting for the majority (9 articles), most mentioning their potential uses in food preservation and additives. The agriculture subset includes 3 studies, with specific references to biofertilizers (2 articles) and biopesticides (1 article). Applications in the energy sector remain exploratory, with individual studies mentioning hydrogen production and energy production (bioethanol) as potential uses. Other applications make up a total of 16 mentions, with diverse fields represented. This distribution illustrates that, while healthcare and environmental applications dominate, there is emerging interest in other industrial uses of cyanobacterial EPS.

Figure 13. Potential applications for cyanobacterial EPS across various industries and sub-industries. Diagram created using SankeyMATIC.

We examined the publication trends across the main unified industries to identify potential distinct patterns that emerge over time, based on the publication year of the filtered dataset, as shown in Figure 14 (where x-axis represents the publication years, and the y-axis shows the publication count - each paper being counted once for each industry it mentions). Environmental applications, as well as healthcare and pharma-focused ones consistently exhibit high research activity, suggesting that these fields have maintained constant scientific interest, likely due to their relevance. In contrast, food and agriculture-related industries and other industries reveal sporadic peaks, which may correlate with periods of relevance, possibly driven by specific advancements or funding opportunities targeting these sectors. Energy-related industries show relatively low representation, indicating limited research in this direction or slower adoption of cyanobacterial EPS uses in this domain.

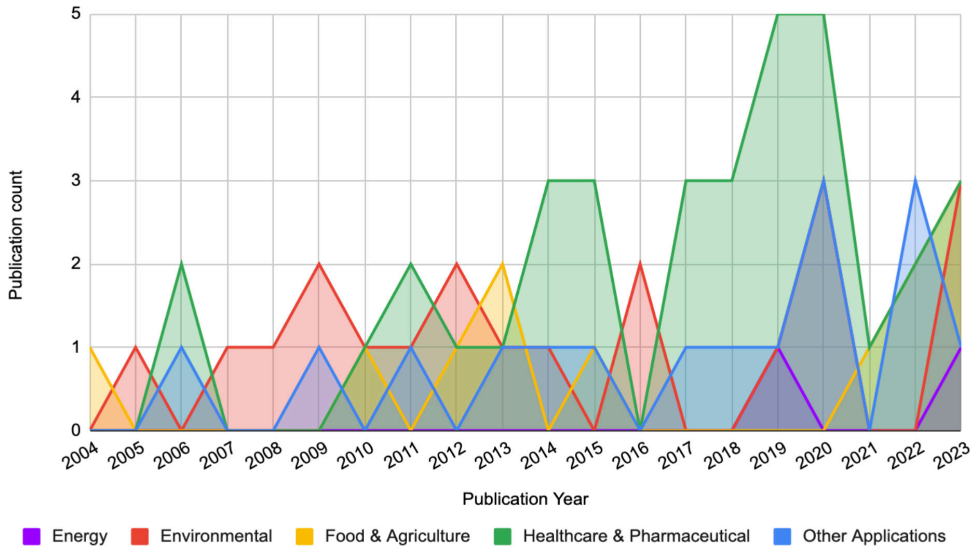


Figure 14. Distribution of publication counts across various main industries over time.

We also examined the distribution of cyanobacteria genera per main industry based on the data. We compiled this analysis in Figure 15. This heatmap reveals distinct patterns in the focus of cyanobacterial EPS research across industries. Healthcare and pharmaceutical, as well as environmental applications, dominate the distribution, with several genera such as *Cyanothece*, *Nostoc*, and *Synechocystis* frequently cited, reflecting these genera's known benefits in therapeutic and ecological contexts (Colica *et al.*, 2010; Santos *et al.*, 2014; Leite *et al.*, 2017; Strieth *et al.*, 2020). Genera like *Phormidium* and *Spirulina*, which have established roles in nutritional and agricultural products (Vicente-García *et al.*, 2004; Li *et al.*, 2011; Ruangsomboon *et al.*, 2013; Vinoth *et al.*, 2023), were associated with applications in food and agriculture in our analysis. Notably, the top 10 genera mention in the filtered dataset (by the number of mentions) are *Nostoc* (23 occurrences), *Cyanothece* (11 occurrences), *Anabaena* (11 occurrences), *Synechocystis* (8 occurrences), *Oscillatoria* (5 occurrences), *Phormidium* (4 occurrences), *Gloeocapsa* (4 occurrences), *Lyngbya* (3 occurrences), *Aphanothece* (3 occurrences), *Cyanobacterium* (3 occurrences).

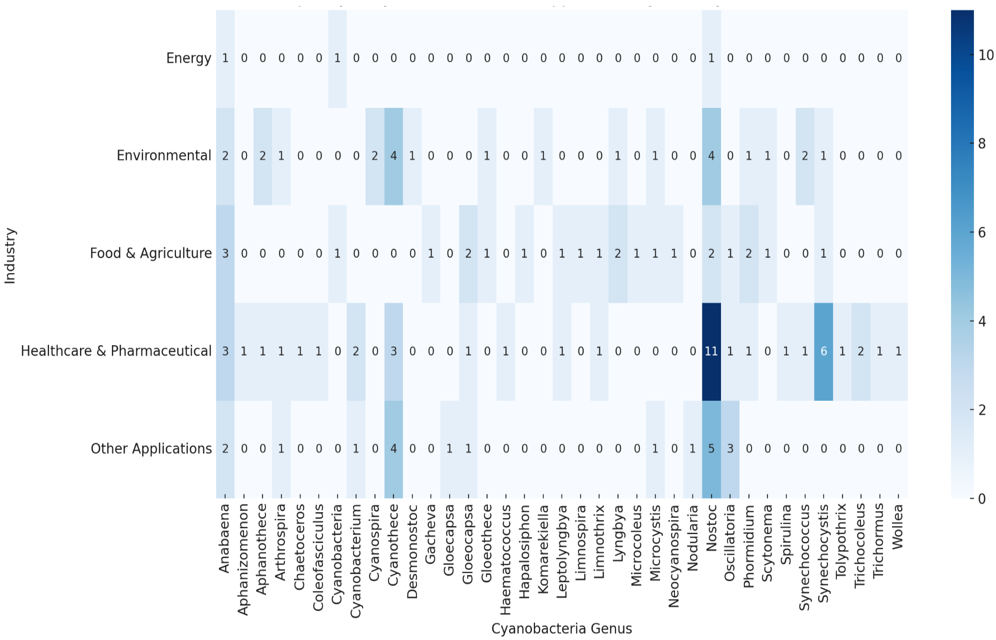


Figure 15. Heatmap that illustrates the distribution of unique genera (39) across the five main industries (Energy, Environmental, Healthcare & Pharmaceutical, Food & Agriculture, and Other Applications). Each cell indicates the count of unique publications where a specific genus is mentioned within a particular industry. Darker shades represent higher publication counts, showing which genera are most frequently associated with each industry.

Espacenet patent analysis

In this section, we analyze the patent landscape for cyanobacterial EPS using data extracted from the Espacenet database of the European Patent Office. This section highlights the industrial relevance and translational potential of cyanobacterial EPS. Our analysis aims to explore the connections between academic research output and industry adoption (through the intellectual property space) in the context of technological transfer.

Upon performing the search query as mentioned in the Materials and Methods (section 2.3), a total of 618 patents resulted.

Analyzing the geographical distribution of the patent document applications, we observe 59 distinct countries or jurisdictions for which a total of 2162 documents were filed. Here we mention that the discrepancy between the total number of patent documents (2162) and unique patent entries (618) reflects the grouping of related patents under a single patent family. Each patent family may include multiple filings across different jurisdictions for the same invention. For most countries (42 jurisdictions) there were between 1 and 12 documents filed. In Figure 16 we illustrate the distribution of the top 15 countries or entities for which intellectual property protection was sought based on the number of patent documents filed between 2004 and 2023 on cyanobacterial EPS. While we note some diversity in terms of the countries, it is clear that notable jurisdictions of interest where legal protection is of interest emerge. USA leads with the highest number of document filings (329), reflecting its interest in patenting potential industrial and research applications of the cyanobacterial EPS. This is closely followed by documents filed under the World Intellectual Property Organization (312), indicating international interest in securing broad patent protection, while China ranks third (286). Other jurisdictions, including the European Patent Office (205) and Canada (154), also demonstrate moderate interest.

When comparing the publication frequency of each country based on co-authors (Figure 3), China emerges as the leader. This aligns with China's growing interest in biotechnology and environmental sciences (Cao & Zhang, 2023; Xiao & Kerr, 2022). However, the majority of patents are filed in the USA and through the World Intellectual Property Organization (WO), with China coming in third (Figure 16). This discrepancy suggests a divergence between academic output and intellectual property strategies. Filing through WO under the Patent Cooperation Treaty (PCT) indicates a strategic approach to securing global intellectual property rights, while the USA's robust biotech industry incentivizes direct filings within its jurisdiction.

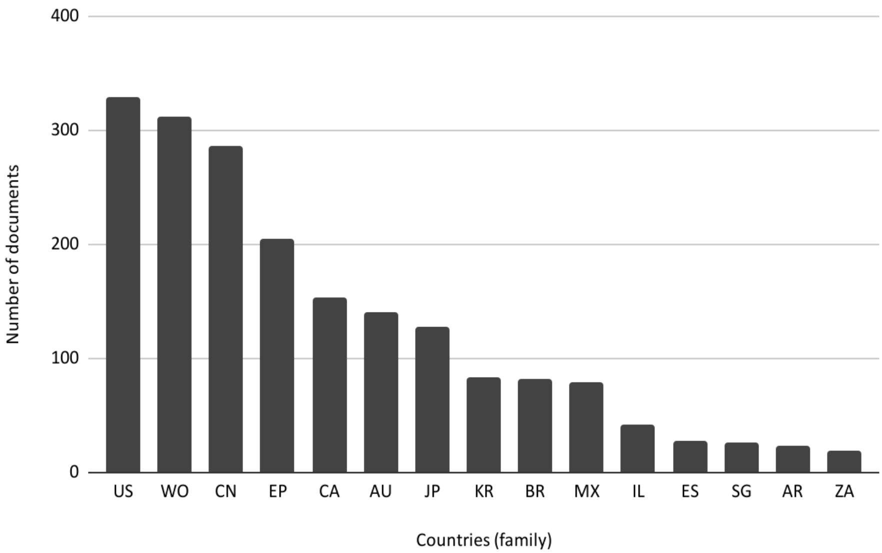


Figure 16. Geographical distribution of patent filings related to cyanobacterial EPS based on Espacenet data. The bar chart depicts the number of patent documents for the top 15 countries or jurisdictions (by the total number of documents filed between 2004 and 2023). OX-axis: countries (family) indicates the country or patent jurisdiction where the patent family was filed (e.g., US for the United States, CN for China, EP for European Patent Office, etc.). OY-axis: the number of documents represents the number of patent documents filed in that country or jurisdiction.

Next, we analyzed the temporal distribution of patent document filings for cyanobacterial EPS (Figure 17). Patent filings were sporadic between 2004 and 2010, with fewer than 15 patent documents published annually. This period likely represents the early stages of research and industrial interest in cyanobacterial EPS. Which matches the observations regarding the number of articles published in that period (Figure 2). A notable increase in patent activity began around 2011, with a sharp rise observed from 2014 onwards. This trend suggests a growing recognition of the commercial and biotechnological potential of cyanobacterial EPS. Additionally, the sustained high level of filings in recent years suggests an ongoing interest and active development in this field, which is confirmed by the growing number of articles published in the same time span (Figure 2).

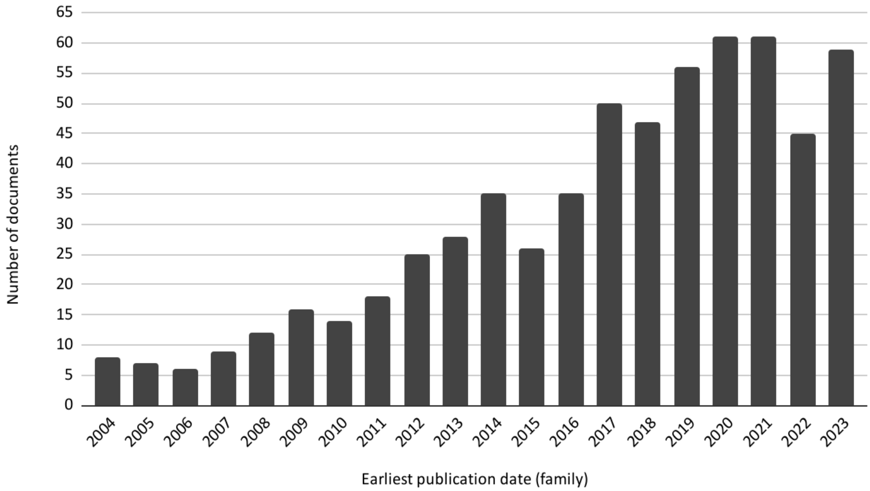


Figure 17. Temporal trends in patent filings for cyanobacterial EPS. Horizontal axis: the earliest publication date (family) refers to the year when the earliest patent in a family was published, representing the initial disclosure of the invention. Vertical axis: the number of documents represents the number of patent documents filed in that year.

In the dataset, between the 618 entities exported and the 2162 documents, there are 1000 distinct applicants. Most of the 1000 distinct applicants (971 applicants) have filed between 1 and 3 documents to be patented, and a select few have filed for more than that. Table 1 encompasses the top 10 applicants based on the total number of documents they have applied for, as well as the countries in which these entities are based, alongside a short description of their business focus based on publicly available information. The analysis of patent applicants highlights key players driving innovation in cyanobacterial EPS. Pivot Bio Inc leads with 26 patent documents, followed by Cool Planet Energy Systems Inc with 21 documents. The third player would be Native Microbials Inc with 20 documents - 10 plus the 10 from Ascus Biosciences Inc (company rebranded). Other notable applicants include Heliae Dev LLC (15 documents), Carbon Tech Holdings LLC (13 documents), and Algenol Biotech LLC (12 documents). The concentration of the number of patents among a few organizations suggests the presence of industry leaders heavily engaged in the research and commercialization of cyanobacterial EPS applications. Interestingly, the University of California seems to be the only educational-focused entity from the top applicants.

Table 1. The top 10 applicants filing patents related to cyanobacterial EPS, based on the total number of documents in the extracted Espacenet database.

Applicants	Documents	Focus	Country
Pivot Bio Inc	26	Specializes in developing microbial solutions to enhance nitrogen delivery to crops, aiming to reduce reliance on synthetic fertilizers.	USA
Cool Planet Energy Systems Inc	21	Developes engineered biocarbon technology designed to improve soil health while sequestering carbon. Their technology produced biochar-based agricultural products from biomass.	USA
Heliae Dev LLC	15	Focuses on developing microalgae-based technologies for agriculture, nutrition, and personal care products.	USA
Carbon Tech Holdings LLC	13	Involved in developing technologies for carbon capture and utilization, aiming to create sustainable materials and chemicals from carbon dioxide.	USA
Algenol Biotech LLC	12	Industrial biotechnology company that commercializes patented algae technology for the production of ethanol and other fuels. They utilize proprietary technologies to produce various products, including personal care items, food supplements, and industrial products, from a patented strain of cyanobacteria and a proprietary photobioreactor system.	USA
Univ California	2	US-based university.	USA
Sumitomo Chemical Co	11	Develops a wide range of products, including chemicals, petrochemicals, and agrochemicals. They invest in biotechnology research for applications in agriculture and materials science.	Japan
Ascus Biosciences Inc	10	Develops microbiome-based solutions for animal health and nutrition. It was later rebranded as *Native Microbials Inc.*	USA
Ecolab USA Inc	10	Develops solutions for water treatment, purification, cleaning, and hygiene across various industries, including food, healthcare, and hospitality.	USA
Native Microbials Inc	10	Rebrand of *Ascus Biosciences Inc*	USA

We observe that among the top 10 applicants, 9 are US-based companies, which explains why the majority of patent applications seek legal protection in the USA (Figure 16). This observation also somewhat explains the earlier discrepancy noted in this section that while China leads in the number of co-authors affiliated with publications, it ranks third in patent filings. This suggests that the robust academic collaboration in China does not yet fully translate into comparable levels of patent activity, unlike in the USA, where strong industry participation drives patent filings.

Discussion

Our study offers an analysis of the academic and industrial landscape surrounding cyanobacterial EPS between 2004 and 2023. By using bibliometric and patent analyses, we have identified key trends, contributors, and an increased potential for industrial applications of cyanobacterial EPS research. Below, we discuss the implications of these findings, their relevance to the scientific and industrial communities, and the limitations of this study.

Our findings reveal a steadily growing body of research on cyanobacterial EPS, with an annual growth rate of 13.14% over the study period (2004–2023). This growth shows an increased interest in this field. However, the thematic focus remains concentrated around healthcare, pharmaceuticals, and environmental applications, hence we understand that these industries dominate the research agenda.

The analysis of authorship and collaborative networks highlights the concentrated effort among a select group of researchers and institutions, particularly in China, the USA, India, and Europe. This collaboration aligns with the multidisciplinary nature of EPS applications but also indicates geographic and institutional disparities in research intensity and focus.

The filtered dataset illustrates a notable interest in the healthcare and environmental sectors, accounting for over half of the research focus. The bioactive and bioremediation properties of EPS have driven these trends, making them promising candidates for drug development, wound healing, and pollutant removal. Despite this focus, research on applications in the food, agriculture, and energy sectors remains sporadic and underdeveloped, possibly due to limited funding.

The positive annual growth rate of publications, dominance of leading global economies as top research producers, and the applied focus of top journals and highly cited articles highlight the field's translational orientation.

These findings point to the fact that cyanobacterial EPS research is oriented towards potential applications.

The increase in patent filings post-2014 mirrors the expansion of potential industrial interest, with the USA and China being prominent players. However, a disconnect between academic output and patent filings is evident, particularly in countries like China, which leads in publication frequency but lags in patent activity. This may suggest challenges in translating academic research into commercial products.

We note potential IP-related search limitations – the Espacenet search was done based on two terms: *cyanobacteria* and *exopolysaccharide*. It is possible that some patent filings would be more specific and name a particular cyanobacteria genus, species, strain, a particular extracellular polysaccharide, or process, and not necessarily use these relatively general terms. However, we have conducted the search using the "full text" filter, meaning all patents having the keywords within the documentation were included. While this does not guarantee all relevant patents were included, it brings the result closer to reality.

Regarding the publishing data collection – our study relies on WoS for bibliometric data, and we have included only English-language articles. We have used a relatively general search string, which should have included the majority of relevant research. We did not include in the search query specific cyanobacteria species names, but we used the "*all fields*" option. Since it is unlikely that papers focusing on specific cyanobacterial strains would not have used the term *cyanobacteria* or similar in any of the indexing fields, we believe all relevant results have been included.

Conclusions

Our study provides a bibliometric and patent analysis of cyanobacterial EPS, highlighting their academic and industrial significance. The growth in publications (13.14% annual growth), the active involvement of leading global economies, and the applied focus of top journals and cited articles underscore the increasing translational potential of these versatile biopolymers. Healthcare and environmental applications dominate the research landscape, reflecting the bioactive and bioremediation properties of EPS, while interest in other industries, such as food, agriculture, and energy, remains emergent. Patent data further supports the industrial readiness of EPS, with a growing number of filings and significant contributions from key players in biotechnology. Patent data further substantiates the industrial readiness of EPS, with a sharp increase in filings post-2014 and a concentration of activity in the USA and globally through the Patent Cooperation Treaty. Leading contributors, including industry and some academic institutions, are driving innovation, with patents addressing diverse applications ranging from microbial solutions in agriculture to bio-based materials and energy production. These findings highlight the multidisciplinary appeal and industrial potential of cyanobacterial EPS. With sustained academic and industrial investment, EPS are positioned to contribute significantly to sustainable technologies and solutions across a range of sectors. This study provides a potential roadmap for future research and innovation, emphasizing the critical role of EPS in advancing biotechnology and sustainability.

Acknowledgements: Certain data included herein are derived from Clarivate™ (Web of Science™) and InCites. © Clarivate 2025. All rights reserved.

Author Contributions: Conceptualization, M.B. and G.M.G.; methodology, M.B. and G.M.G.; software, G.M.G..; validation, E.R.-T., M.B. and G.M.G.; formal analysis, E.R.-T.; data curation, M.B.; writing—original draft preparation, M.B., G.M.G. and E.R.-T.; writing—review and editing, M.B., G.M.G. and E.R.-T.; visualization, G.M.G.; supervision, E.R.-T. All authors have read and agreed to the published version of the manuscript.

Funding: This work was supported through the "Nucleu" Program within the National Research Development and Innovation Plan 2022–2027, Romania, carried out with the support of MEC, project no. 27N/03.01.2023, component project code PN 23 24 01 02.

Data Availability Statement: Data is available upon request from authors.

References

Aria, M., & Cuccurullo, C. (2017). bibliometrix: An R-tool for comprehensive science mapping analysis. *J. Informetr. 11*(4), 959–975. https://doi.org/10.1016/j.joi.2017.08.007

Bhatnagar, M., Parwani, L., Sharma, V., Ganguly, J., & Bhatnagar, A. (2014). Exopolymers from *Tolypothrix tenuis* and three *Anabaena sp*. (Cyanobacteriaceae) as novel blood clotting agents for wound management. *Carbohyd. Polym. 99*, 692–699. https://doi.org/10.1016/j.carbpol.2013.09.005

Borowitzka, M. A. (2013). High-value products from microalgae—their development and commercialisation. *J. Appl. Phycol. 25*(3), 743–756. https://doi.org/10.1007/s10811-013-9983-9

Cao, X., & Zhang, Y. (2023). Environmental regulation, foreign investment, and green innovation: A case study from China. *Environ. Sci. Pollut. R. 30*(3), 7218–7235. https://doi.org/10.1007/s11356-022-22722-5.

Center for Strategic and International Studies (2021). China power project: Is China catching up to the United States in research and development (R&D) [Accessed 27 December 2024] https://chinapower.csis.org/china-research-and-development-rnd/

Colica, G., Mecarozzi, P. C., & De Philippis, R. (2010). Treatment of Cr(VI)-containing wastewaters with exopolysaccharide-producing cyanobacteria in pilot flow through and batch systems. *Appl. Microbiol. Biot. 87*(5), 1953–1961. https://doi.org/10.1007/s00253-010-2665-5

Cruz, D., Vasconcelos, V., Pierre, G., Michaud, P., & Delattre, C. (2020). Exopolysaccharides from cyanobacteria: strategies for bioprocess development. *Appl. Sci. 10*(11), Article 11. https://doi.org/10.3390/app10113763

Debnath, S., Muthuraj, M., Bandyopadhyay, T. K., Bobby, Md. N., Vanitha, K., Tiwari, O. N., & Bhunia, B. (2024). Engineering strategies and applications of cyanobacterial exopolysaccharides: A review on past achievements and recent perspectives. *Carbohyd. Polym.*, 328, 121686. https://doi.org/10.1016/j.carbpol.2023.121686

European Patent Office. (n.d.). Espacenet patent search. Retrieved November 2, 2024, from https://worldwide.espacenet.com/

Falsini, S., Rosi, M. C., Ravegnini, E., Schiff, S., Gonnelli, C., Papini, A., Adessi, A., Urciuoli, S., & Ristori, S. (2023). Nanoformulations with exopolysaccharides from cyanobacteria: Enhancing the efficacy of bioactive molecules in the Mediterranean fruit fly control. *Environ. Sci. Pollut. R. 30*(35), 83760–83770. https://doi.org/10.1007/s11356-023-28180-x

Flores, C., Lima, R. T., Adessi, A., Sousa, A., Pereira, S. B., Granja, P. L., De Philippis, R., Soares, P., & Tamagnini, P. (2019). Characterization and antitumor activity of the extracellular carbohydrate polymer from the cyanobacterium *Synechocystis* ΔsigF mutant. *Int. J. Biol. Macromol. 136*, 1219–1227. https://doi.org/10.1016/j.ijbiomac.2019.06.152

Gacheva, G., Gigova, L., Ivanova, N., Iliev, I., Toshkova, R., Gardeva, E., Kussovski, V., & Najdenski, H. (2013). Suboptimal growth temperatures enhance the biological activity of cultured cyanobacterium *Gloeocapsa sp*. *J. Appl. Phycol. 25*(1), 183–194. https://doi.org/10.1007/s10811-012-9852-y

Hyo Gyeom Kim, Kyung Hwa Cho, & Recknagel, F. (2024). Bibliometric network analysis of scientific research on early warning signals for cyanobacterial blooms in lakes and rivers. *Ecol. Inform.* 102503–102503. https://doi.org/10.1016/j.ecoinf.2024.102503

Jindal, N., Pal Singh, D., & Singh Khattar, J. (2013). Optimization, characterization, and flow properties of exopolysaccharides produced by the cyanobacterium *Lyngbya stagnina*. *J. Basic. Microb. 53*(11), 902–912. https://doi.org/10.1002/jobm.201200201

Kumar, D., Kaštánek, P., & Adhikary, S. P. (2018). Exopolysaccharides from cyanobacteria and microalgae and their commercial application. *Curr. Sci. 115*(2), 234–241

Laroche, C. (2022). Exopolysaccharides from microalgae and cyanobacteria: diversity of strains, production strategies, and applications. *Mar. Drugs 20*(5). https://doi.org/10.3390/md20050336

Leite, J. P., Mota, R., Durão, J., Neves, S. C., Barrias, C. C., Tamagnini, P., & Gales, L. (2017). Cyanobacterium-derived extracellular carbohydrate polymer for the controlled delivery of functional proteins. *Macromol. Biosci. 17*(2), 1600206. https://doi.org/10.1002/mabi.201600206

Li, H., Li, Z., Xiong, S., Zhang, H., Li, N., Zhou, S., Liu, Y., & Huang, Z. (2011). Pilot-scale isolation of bioactive extracellular polymeric substances from cell-free media of mass microalgal cultures using tangential-flow ultrafiltration. *Process Biochem. 46*(5), 1104–1109. https://doi.org/10.1016/j.procbio.2011.01.028

Li, P., Harding, S. E., & Liu, Z. (2001). Cyanobacterial exopolysaccharides: their nature and potential biotechnological applications. *Biotechnol. Genet. Eng. 18*(1), 375–404. https://doi.org/10.1080/02648725.2001.10648020

Mohamed, Z. A., Elnour, R. O., Alamri, S., & Hashem, M. (2023). Increased production of extracellular polysaccharides in *Arthrospira platensis* as a protective response against saxitoxin: Implications to outdoor mass production. *Algal Res. 74*, 103184. https://doi.org/10.1016/j.algal.2023.103184

Mota, R., Flores, C., & Tamagnini, P. (2020). Cyanobacterial extracellular polymeric substances (EPS). In J. M. Oliveira, H. Radhouani, & R. L. Reis (ed.), *Polysaccharides of Microbial Origin: Biomedical Applications* (pp. 1–28). Springer International Publishing. https://doi.org/10.1007/978-3-030-35734-4_11-1

Mota, R., Rossi, F., Andrenelli, L., Pereira, S. B., De Philippis, R., & Tamagnini, P. (2016). Released polysaccharides (RPS) from *Cyanothece sp*. CCY 0110 as biosorbent for heavy metals bioremediation: Interactions between metals and RPS binding sites. *Appl. Microbiol. Biot. 100*(17), 7765–7775. https://doi.org/10.1007/s00253-016-7602-9

Mugani, R., Fatima El Khalloufi, El Mahdi Redouane, Haida, M., Roseline Prisca Aba, Yasser Essadki, El, S., Abdessamad Hejjaj, Naaila Ouazzani, Campos, A., Hans-Peter Grossart, Mandi, L., Vasconcelos, V., & Brahim Oudra. (2024). Unlocking the potential of bacterioplankton-mediated microcystin degradation and removal: A bibliometric analysis of sustainable water treatment strategies. *Water Res. 255*, 121497–121497. https://doi.org/10.1016/j.watres.2024.121497

Najdenski, H. M., Gigova, L. G., Iliev, I. I., Pilarski, P. S., Lukavský, J., Tsvetkova, I. V., Ninova, M. S., & Kussovski, V. K. (2013). Antibacterial and antifungal activities of selected microalgae and cyanobacteria. *Int. J. Food Sci. Tech. 48*(7), 1533–1540. https://doi.org/10.1111/ijfs.12122

Nath, P. C., Tiwari, O. N., Devi, I., Bandyopadhyay, T. K., & Bhunia, B. (2021). Biochemical and morphological fingerprints of isolated *Anabaena sp*.: A precious feedstock for food additives. *Biomass Conversion and Biorefinery*, 11(6), 2723–2733. https://doi.org/10.1007/s13399-020-00651-y

National Center for Science and Engineering Statistics. Survey of federal funds for research and development, volume 70, FYs 2020–21. National Science Foundation (2021). [Accessed 27 December 2024]. https://ncses.nsf.gov/surveys/federal-funds-research-development/2021#data.

Nishanth, S., Bharti, A., Gupta, H., Gupta, K., Gulia, U., & Prasanna, R. (2021). Chapter 14 - Cyanobacterial extracellular polymeric substances (EPS): Biosynthesis and their potential applications. In: S. Das & H. R. Dash (Eds.), *Microbial and Natural Macromolecules*,pp. 349–369. Academic Press. https://doi.org/10.1016/B978-0-12-820084-1.00015-6

Parikh, A., Madamwar, D., & Patel, H. (2006). Aerobic decolorization of textile dyes by a mixed bacterial consortium DMC. *Bioresource Technol. 97*(16), 2193–2198. https://doi.org/10.1016/j.biortech.2005.09.008

Potnis, A. A., Raghavan, P. S., & Rajaram, H. (2021). Overview on cyanobacterial exopolysaccharides and biofilms: Role in bioremediation. *Rev. Environ. Sci. Bio. 20*(3), 781–794. https://doi.org/10.1007/s11157-021-09586-w

Qi, Y., Chen, X., Hu, Z., Song, C., & Cui, Y.-L. (2019). Bibliometric analysis of algal-bacterial symbiosis in wastewater treatment. *Int. J. Env. Res. Pub. He. 16*(6), 1077–1077. https://doi.org/10.3390/ijerph16061077

Qu, F., Zhu, A., Ma, Y., Zhang, L., & Ding, Y. (2012). Anaerobic digestion of rice straw in a constructed wetland for biogas and biofertilizer production. *Water Res. 46*(8), 2670–2676. https://doi.org/10.1016/j.watres.2012.02.045

Ramachandran, L., Marappa, N., Sethumadhavan, K., & Nooruddin, T. (2020). Glycoprotein prompted plausible bactericidal and antibiofilm outturn of extracellular polymers from *Nostoc microscopicum*. *Appl. Biochem. Biotech. 191*(1), 284–298. https://doi.org/10.1007/s12010-019-03179-8

Reignier, O., Bormans, M., Marchand, L., Sinquin, C., Amzil, Z., Zykwinska, A., & Briand, E. (2023). Production and composition of extracellular polymeric substances by a unicellular strain and natural colonies of Microcystis: Impact of salinity and nutrient stress. *Env. Microbiol. Rep. 15*(6), 783–796. https://doi.org/10.1111/1758-2229.13200

Rodrigues, F., Mendonça, I., Faria, M., Gomes, R., Pinchetti, J. L. G., Ferreira, A., & Cordeiro, N. (2024). Response surface methodology applied to cyanobacterial eps production: steps and statistical validations. *Processes 12*(8), Article 8. https://doi.org/10.3390/pr12081733

Rossi, F., & De Philippis, R. (2015). Role of cyanobacterial exopolysaccharides in phototrophic biofilms and in complex microbial mats. *Life 5*(2), Article 2. https://doi.org/10.3390/life5021218

Ruangsomboon, S., Wongrat, L., Choochote, S., Ganmanee, M., & Saparnklang, A. (2013). Effects of low pH and Pb2+ stress on living cyanobacterium, *Phormidium angustissimum* West & G.S.West: A test of its feasibility as a living biosorbent. *J. Appl. Phycol. 25*(3), 905–911. https://doi.org/10.1007/s10811-013-0004-9

SankeyMATIC. (n.d.). Sankey diagram builder. [Accessed 2 November 2024] http://sankeymatic.com

Santos, C., Silva, C. J., Büttel, Z., Guimarães, R., Pereira, S. B., Tamagnini, P., & Zille, A. (2014). Preparation and characterization of polysaccharides/PVA blend nanofibrous membranes by electrospinning method. *Carbohyd. Polym. 99*, 584–592. https://doi.org/10.1016/j.carbpol.2013.09.008

Shen, S., Jia, S., Wu, Y., Yan, R., Lin, Y.-H., Zhao, D., & Han, P. (2018). Effect of culture conditions on the physicochemical properties and antioxidant activities of polysaccharides from *Nostoc flagelliforme*. *Carbohyd. Polym. 198*, 426–433. https://doi.org/10.1016/j.carbpol.2018.06.111

Van Camp, C., Fraikin, C., Claverie, E., Onderwater, R., & Wattiez, R. (2022). Capsular polysaccharides and exopolysaccharides from *Gloeothece verrucosa* under various nitrogen regimes and their potential plant defence stimulation activity. *Algal Res. 64*, 102680. https://doi.org/10.1016/j.algal.2022.102680

Vicente-García, V., Ríos-Leal, E., Calderón-Domínguez, G., Cañizares-Villanueva, R. O., & Olvera-Ramírez, R. (2004). Detection, isolation, and characterization of exopolysaccharide produced by a strain of *Phormidium* 94a isolated from an arid zone of Mexico. *Biotechnol. Bioeng. 85*(3), 306–310. https://doi.org/10.1002/bit.10912

Vinoth, M., Sivasankari, S., Ahamed, A. K. K., Alsamhary, K. I., Al-enazi, N. M., Abdel-Raouf, N., Alharbi, R. M., Govindarajan, R. K., Ravi, G., Alarjani, K. M., & Sholkamy, E. N. (2023). Bio-characterization and liquid chromatography–mass spectrometry analysis of exopolysaccharides in biofilm-producing cyanobacteria isolated from soil crust: exploring the potential of microalgal biomolecules. *Biology 12*(8). https://doi.org/10.3390/biology12081065

Ward, N. L., Challacombe, J. F., Janssen, P. H., Henrissat, B., Coutinho, P. M., Wu, M., ... & Kuske, C. R. (2009). Three genomes from the phylum *Acidobacteria* provide insight into the lifestyles of these microorganisms in soils. *Appl. Environ. Microb. 75*(7), 2046–2056. https://doi.org/10.1128/aem.02294-08

Xiao, Z., & Kerr, W. A. (2022). Biotechnology in China – regulation, investment, and delayed commercialization. *GM Crops Food 13*(1), 86–96. https://doi.org/10.1080/21645698.2022.2068336

Yousaf, F., Bukhari, S. A. R., Shakir, H. A., Khan, M., Franco, M., & Irfan, M. (2024). Cyanobacterial exopolysaccharides: extraction, processing, and applications. In M. A. Mehmood, P. Verma, M. P. Shah, & M. J. Betenbaugh (Eds.*), Pharmaceutical and Nutraceutical Potential of Cyanobacteria*, pp. 277–309. Springer International Publishing. https://doi.org/10.1007/978-3-031-45523-0_11