İSTANBUL UNIVERSITY PRESS

European Journal of Biology
Eur J Biol 2024; 83 (1): 94–105
DOI: 10.26650/EurJBiol.2024.1357041

REVIEW ARTICLE

From Pond Scum to Miracle Molecules: Cyanobacterial Compounds New Frontiers

Arbab Husain[1], Md Nematullah[2], Hamda Khan[3], Ravi Shekher[1], Alvina Farooqui[4], Archana Sahu[5], Afreen Khanam[1]

[1]Mangalayatan University, Institute of Biomedical Education and Research, Department of Biotechnology and Life Sciences, Aligarh, India
[2]Integral University, Faculty of Pharmacy, Department of Pharmacy Practice, Lucknow, India
[3]Aligarh Muslim University Jawahar Lal Nehru Medical College, Department of Biochemistry, Aligarh, Uttar Pradesh, India
[4]Integral University, Faculty of Engineering, Department of Bioengineering, Lucknow, India
[5]Usha Martin University, Faculty of Health Sciences, Department of Pharmacy, Ranchi, India

ABSTRACT

Cyanobacteria are a diverse group of photosynthetic microorganisms known for their production of bioactive compounds with various biological activities. This review explores cyanobacterial bioactive compounds' current and future prospects and their roles in different fields. These compounds have great potential for pharmaceuticals, agriculture, and environmental remediation applications. Cyanobacterial bioactive compounds, such as cyanotoxins, peptides, polyketides, alkaloids, and terpenoids, exhibit remarkable properties, including antimicrobial, antifungal, antiviral, antioxidant, anti-inflammatory, and anticancer activities. Advances in genomics, metabolomics, synthetic biology, screening techniques, and bioinformatics have facilitated the identification, characterization, and manipulation of cyanobacterial compounds. The future prospects involve exploring untapped cyanobacterial diversity, integrating advanced technologies like machine learning and high-throughput screening, and sustainable production through biotechnological approaches. These efforts hold promise for discovering new bioactive compounds with unique properties and applications, contributing to the development of innovative pharmaceuticals, agricultural solutions, and environmental remedies.

Keywords: Cyanobacteria, Bioactive compounds, Pharmaceutical applications, Environmental remediation, Cyanobacterial diversity, Biotechnological approaches

INTRODUCTION

Cyanobacteria, also known as blue-green algae, are a diverse group of photosynthetic microorganisms that have gained significant attention for their ability to produce bioactive compounds with a wide range of biological activities.[1,2] These compounds hold great potential for various applications, including pharmaceuticals, agriculture, and environmental remediation. This review explores the current and future prospects of bioactive compounds derived from cyanobacteria, highlighting their promising roles in different fields. Cyanobacterial bioactive compounds exhibit remarkable properties, making them attractive candidates for drug discovery and development. They have demonstrated activities such as antimicrobial, antifungal, antiviral, antioxidant, anti-inflammatory, and anticancer properties.[3] These activities arise from cyanobacterial compounds' diverse chemical structures and functions. For example, cyanotoxins, a group of cyanobacterial bioactive compounds, have shown potential therapeutic applications in cancer treatment. Microcystins, a common cyanotoxin, have exhibited promising anticancer activity and are being investigated as potential leads for novel therapies.[4–6]

Furthermore, cyanobacteria produce a wide array of secondary metabolites, including peptides, polyketides, alkaloids, and terpenoids, which possess diverse bioactivities.[7] Cyanobacterial peptides have shown antimicrobial and anticancer activities, while cyanobacterial polyketides have demonstrated antifungal and antiviral properties. Cyanobacterial alkaloids and terpenoids have also shown potential as pharmaceutical leads and have garnered attention in drug discovery efforts.[8–10]

The current prospects of cyanobacterial bioactive compounds are promising due to advancements in various scientific disciplines. Genomics and metabolomics have facilitated the identification and characterizing of novel cyanobacterial compounds, providing valuable insights into their biosynthetic pathways and

Corresponding Author: Afreen Khanam **E-mail:** afreen.iul@gmail.com
Submitted: 08.09.2023 • **Accepted:** 13.12.2023

regulatory mechanisms.[11] Synthetic biology approaches enable the manipulation of biosynthetic pathways, producing bioactive compounds with improved properties and yields. Additionally, innovative screening techniques and bioinformatics tools have enabled the efficient identification and isolation of novel compounds from cyanobacteria.[12,13]

Looking ahead, the future prospects of cyanobacterial bioactive compounds are exciting. Continued exploration of untapped cyanobacterial diversity holds promise for discovering new bioactive compounds with unique properties and applications.[14] Moreover, the sustainable production and scaling-up of cyanobacterial bioactive compounds through the integration of advanced technologies, such as machine learning and high-throughput screening, can accelerate the discovery and characterization of cyanobacterial compounds. Biotechnological approaches offer tremendous potential for meeting the increasing demand for natural products.[15]

In conclusion, cyanobacteria are valuable sources of bioactive compounds with diverse properties and applications.[16] The current advancements in genomics, metabolomics, synthetic biology, and screening techniques have paved the way for discovering and developing novel bioactive compounds from cyanobacteria.[17] The prospects involve the continued exploration of cyanobacterial diversity, the application of advanced technologies, and the sustainable production of bioactive compounds. These efforts will undoubtedly contribute to developing innovative pharmaceuticals, agricultural solutions, and environmental remedies.

CYANOBACTERIA

Cyanobacteria, a group of prokaryotic microorganisms also known as blue-green algae, are characterized by their ability to carry out oxygenic photosynthesis.[18] They play crucial ecological roles in various environments, including freshwater, marine ecosystems, and terrestrial habitats. Cyanobacteria have distinctive cellular structures, such as thylakoids, where photosynthetic pigments like chlorophyll-a, phycocyanin, and phycoerythrin are localized.[19]

The morphological diversity of cyanobacteria encompasses unicellular, filamentous, and colonial forms, which exhibit a range of adaptations to different ecological niches.[20] Some cyanobacteria can fix atmospheric nitrogen through specialized structures called heterocysts, allowing them to contribute to nitrogen availability in ecosystems.[21]

Cyanobacteria have gained significant attention for their production of bioactive compounds, which have diverse chemical structures and biological activities. These compounds exhibit antimicrobial, antiviral, antitumor, and antioxidant properties. For instance, cyanopeptides derived from cyanobacteria have shown promising antimicrobial and cytotoxic activities.[22–25]

Ongoing research on cyanobacteria focuses on understanding the genetic and metabolic mechanisms underlying their unique characteristics and bioactive compound production.[26] This knowledge holds potential for various applications in biotechnology, environmental remediation, and pharmaceutical development.[27] Cyanobacteria are photosynthetic prokaryotes that occupy diverse ecological niches and contribute significantly to global primary production. Their intricate cellular structures and metabolic capabilities enable them to thrive in various environments. Furthermore, their ability to produce bioactive compounds with valuable biological activities makes them a subject of interest for both ecological and biotechnological research (Figure 1).[28]

Secondary Metabolites of Cyanobacteria

Secondary metabolites produced by cyanobacteria are a diverse group of compounds that possess a wide range of properties and biological activities. These metabolites include peptides, polyketides, alkaloids, terpenoids, and other specialized molecules.[28]

Cyanobacterial Peptides

Cyanobacterial peptides are a diverse group of secondary metabolites produced by cyanobacteria. They exhibit various properties and activities, including antimicrobial, antiviral, and anticancer effects.[8,29] For example, microcystins, a class of cyanobacterial peptides, have been found to possess potent hepatotoxic and anticancer properties.[30,31]

Another example is cyanopeptolin, a peptide isolated from cyanobacteria, which has shown significant antimicrobial activity against various pathogens.[30]

Cyanobacterial Polyketides

Cyanobacterial polyketides are complex organic compounds produced through polyketide synthase pathways in cyanobacteria.[8] These metabolites exhibit diverse biological activities, including antimicrobial, antiviral, and cytotoxic effects. An example is jamaicamide, a polyketide produced by *Lyngbya majuscula*, which has displayed potent cytotoxicity against cancer cells.[32] Another noteworthy cyanobacterial polyketide is cryptophycin, which exhibits full antiproliferative activity against various cancer cell lines.[33]

Cyanobacterial Alkaloids

Cyanobacterial alkaloids are nitrogen-containing secondary metabolites produced by cyanobacteria.[34] They possess diverse biological properties, including cytotoxic, neurotoxic, and antifungal activities. Anatoxin-a, an alkaloid produced by several cyanobacterial species, is a potent neurotoxin.[35,36] Another well-known cyanobacterial alkaloid is saxitoxin, which exhibits full neurotoxic and paralytic effects.[37]

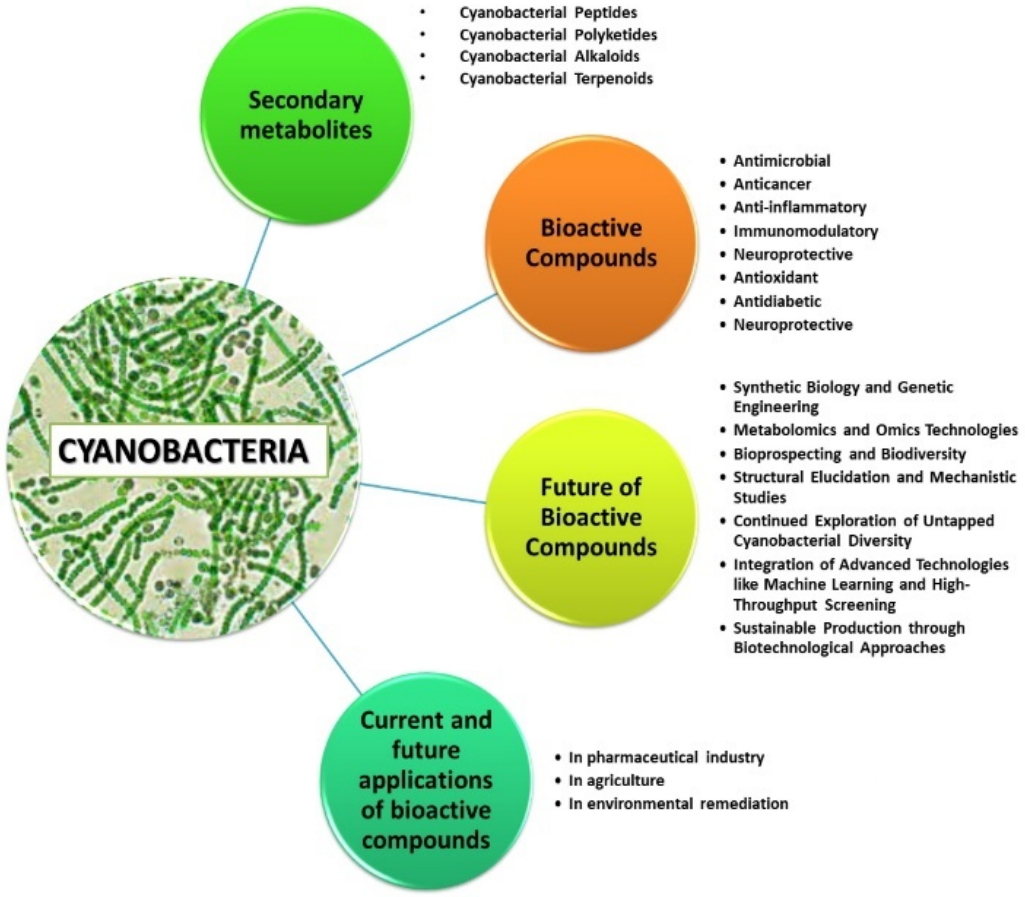

Figure 1. Bioactive compounds, future potential and diverse applications of Cyanobacteria.

Cyanobacterial Terpenoids

Cyanobacterial terpenoids are a diverse group of secondary metabolites with a terpenoid backbone produced by cyanobacteria. These compounds exhibit various biological activities, including antimicrobial, antiviral, and antifungal effects. For instance, nostocyclin, a terpenoid produced by *Nostoc* species, has demonstrated potent antimicrobial activity against various pathogens.[38] Another example is cryptosporioptide, a terpenoid derived from the cyanobacterium *Cryptosporiopsis* sp., which exhibits antifungal activity.[39]

Cyanobacteria and Its Bioactive Compounds

Microcystins

Microcystins are cyclic heptapeptides produced by various cyanobacteria, including species from the genera *Microcystis, Anabaena*, and *Planktothrix*. They are well-known for their hepatotoxicity and tumor-promoting properties. Microcystins inhibit protein phosphatases, disrupting cellular signaling pathways and causing liver damage.[40]

Cyanopeptides

Cyanopeptides are a diverse group of peptides produced by cyanobacteria, exhibiting a wide range of biological activities. These compounds possess antimicrobial, antiviral, cytotoxic, and immunosuppressive properties. They are of interest for their potential therapeutic applications.[31]

Anabaenopeptins

Anabaenopeptins are cyclic peptides predominantly produced by species of the cyanobacterial genus *Anabaena*. These compounds display a broad spectrum of bioactivities, including antimicrobial, antifungal, antiviral, and antitumor properties. They are considered promising candidates for drug development.[41]

Aeruginosins

Aeruginosins are a class of bioactive peptides produced by certain cyanobacteria, such as *Microcystis aeruginosa* and *Planktothrix spp*. These compounds exhibit diverse activities, including neurotoxicity, antiproliferative effects, and antibacterial properties.[31]

Lyngbyatoxins

Lyngbyatoxins are complex secondary metabolites produced by cyanobacteria, particularly from the genus *Lyngbya*. These compounds possess cytotoxic, neurotoxic, antifungal, and antimicrobial activities. They are of interest for their potential biomedical applications.[42]

Nodularins

Nodularins are cyclic peptides produced by certain cyanobacteria, including *Nodularia spumigena*. These compounds are known for their hepatotoxicity and tumor-promoting effects. Nodularins inhibit protein phosphatases, disrupting cellular signaling and leading to liver damage.[43]

Phycocyanin

Phycocyanin is a blue pigment and a significant component of the light-harvesting phycobiliprotein complex in cyanobacteria and algae. It is an accessory pigment for photosynthesis and exhibits antioxidant, anti-inflammatory, and immunomodulatory properties. Phycocyanin is of interest for various biotechnological and medicinal applications.[2,44]

Scytonemin

Scytonemin is a UV-absorbing pigment synthesized by certain cyanobacteria as a protective mechanism against high-intensity UV radiation. It exhibits strong photoprotective and antioxidant activities, making it of interest for applications in sunscreen formulations and photoprotection.[45]

Patellamides

Patellamides are cyclic peptides isolated from cyanobacteria, particularly from the genus *Prochloron*. These compounds exhibit potent cytotoxic and antimicrobial activities. They have attracted attention as potential drug candidates and are valuable tools for chemical biology studies.[46]

Geosmin

Geosmin is a volatile organic compound produced by various cyanobacteria and other microorganisms. It is responsible for the characteristic earthy odor associated with some bodies of water. Geosmin is also interested in biotechnology due to its potential use in the flavor and fragrance industries.[47]

Cylindrospermopsin

Cylindrospermopsin is a potent toxin produced by certain cyanobacteria, including species of the genus *Cylindrospermopsis*. It exhibits hepatotoxicity and has been implicated in animal and human poisonings. Cylindrospermopsin inhibits protein synthesis and affects cellular functions.[48,49]

General Properties of Bioactive Compounds in Cyanobacteria

Cyanobacteria, also known as blue-green algae, are photosynthetic microorganisms that produce a wide array of bioactive compounds with diverse properties and applications. These bioactive compounds have attracted significant attention due to their potential therapeutic, pharmaceutical, and industrial value. This article provides a comprehensive overview of the general properties of bioactive compounds found in cyanobacteria, supported by relevant citations.

Chemical Diversity

Bioactive compounds derived from cyanobacteria exhibit remarkable chemical diversity. They encompass a wide range of chemical classes, including peptides, alkaloids, polyketides, lipids, terpenoids, and pigments. This diverse array of chemical structures contributes to the broad spectrum of biological activities displayed by cyanobacterial bioactive compounds.[50–53]

Biological Activities

Cyanobacterial bioactive compounds possess various biological activities, making them valuable for numerous applications. They exhibit antimicrobial, antiviral, antifungal, anticancer, antiparasitic, anti-inflammatory, antioxidant, neuroprotective, and immunomodulatory properties.[54–57] These activities stem from the interaction of cyanobacterial compounds with specific targets, such as enzymes, receptors, and signaling pathways, in various biological systems.

Ecological Roles

Bioactive compounds in cyanobacteria play important ecological roles, contributing to their survival and competitive advantage in natural environments. Some compounds function as allelochemicals, enabling cyanobacteria to inhibit the growth of competing microorganisms and establish dominance.[58] Additionally, cyanobacterial compounds can act as signaling molecules, mediating cell-cell communication and physiological responses within cyanobacterial populations.[59]

Biosynthetic Pathways

The biosynthesis of cyanobacterial bioactive compounds involves complex enzymatic pathways. Biosynthetic gene clusters responsible for producing these compounds have been identified in cyanobacterial genomes through genomic analysis and comparative genomics. Understanding the biosynthetic pathways and regulatory mechanisms governing the production of bioactive compounds is crucial for their manipulation and optimization in biotechnological applications.[12]

Structural Elucidation

Structural elucidation of cyanobacterial bioactive compounds is critical in their characterization and understanding of their activity. Advanced analytical techniques such as mass spectrometry, nuclear magnetic resonance spectroscopy, and X-ray crystallography are employed to determine their chemical structures.[60] The elucidation of the structural features facilitates the development of structure-activity relationships and aids in designing analogs with improved properties.

Biotechnological Applications

Bioactive compounds from cyanobacteria have significant potential for various biotechnological applications. They can be explored for developing new drugs, pharmaceutical leads, nutraceuticals, cosmeceuticals, and agrochemicals.[61,62] Furthermore, cyanobacterial compounds have shown promise as sources of natural dyes, biofuels, and biosurfactants.[63,64] These applications highlight the importance of cyanobacterial bioactive compounds in various industries.

Bioactive compounds derived from cyanobacteria exhibit chemical diversity and possess a wide range of biological activities. Their ecological roles, biosynthetic pathways, structural elucidation, and potential biotechnological applications make them subjects of significant research interest. Further exploration of cyanobacterial bioactive compounds holds tremendous potential for the discovery of novel therapeutics, industrial applications, and sustainable solutions (Table 1).[29,31,41,42,65–71]

CURRENT RESEARCH ON BIOACTIVE COMPOUNDS OF CYANOBACTERIA

Cyanobacteria, commonly known as blue-green algae, are photosynthetic microorganisms that have gained significant attention for their production of bioactive compounds with diverse therapeutic properties. Current research in this field has focused on exploring these cyanobacterial compounds' bioactivity and potential applications. This article provides an overview of the recent research on bioactive compounds derived from cyanobacteria, highlighting their various biological activities, supported by relevant citations.

Antimicrobial Activity

Cyanobacterial bioactive compounds have shown significant antimicrobial activity against a range of pathogenic microorganisms.[72] For instance, it was demonstrated the antimicrobial potential of *Oscillatoria sancta* extracts against multidrug-resistant bacteria, including *Staphylococcus aureus* and *Escherichia coli*. Another study reported the antibacterial activity of a cyanobacterium, *Nostoc muscorum*, against clinically important human pathogens. These findings indicate the potential of cyanobacterial compounds as natural antimicrobial agents.[73,74]

Anticancer Effects

The bioactive compounds derived from cyanobacteria have exhibited promising anticancer effects. Research conducted by Jaki et al. demonstrated the cytotoxic activity of Nostoc commune extracts against human breast cancer cells.[75] Similarly, a study by Akbarizare et al. identified a cyanobacterial metabolite, largamides, which exhibited potent anticancer activity against colorectal cancer cells.[76] These studies highlight the potential of cyanobacterial compounds as a source of novel anticancer agents.

Anti-inflammatory and Immunomodulatory Properties

Cyanobacterial compounds have also shown significant anti-inflammatory and immunomodulatory properties. A study investigated the anti-inflammatory potential of *Phormidium persicinum* extracts and found them to inhibit the production of pro-inflammatory cytokines.[77] Furthermore, research demonstrated the immunomodulatory effects of a cyanobacterium, *Spirulina platensis*, which enhanced the activity of immune cells. These findings suggest the therapeutic potential of cyanobacterial compounds in inflammation-related disorders and immune modulation.[78]

Neuroprotective Effects

Current research has focused on exploring the neuroprotective effects of cyanobacterial bioactive compounds. A study investigated the neuroprotective activity of *Nostoc muscorum* extracts and demonstrated their ability to protect neuronal cells from oxidative stress-induced damage.[79] Similarly, cyanobacterial peptides, such as anabaenopeptins, have shown neuroprotective effects against amyloid-beta-induced neurotoxicity.[80] These studies suggest the potential of cyanobacterial compounds in developing neuroprotective therapies.

Antioxidant and Antidiabetic Properties

Cyanobacterial compounds have been investigated for their antioxidant and antidiabetic properties. Previous research by revealed the antioxidant activity of cyanobacterial extracts from *Microcystis aeruginosa*, which demonstrated free radical scavenging effects.[1,31] Additionally, a study by Kaushik et al. reported the antidiabetic potential of cyanobacterial bioactive compounds, as they showed inhibitory effects on critical enzymes involved in glucose metabolism.[81] These findings support the exploration of cyanobacterial compounds as potential antioxidants and antidiabetic agents.[81,82]

Current research on bioactive compounds derived from

Table 1. Bioactive compounds derived from cyanobacteria and their properties.

Bioactive Compound	Properties	References
Microcystins	Hepatotoxic, tumor-promoting, protein phosphatase inhibition	65
Cyanopeptides	Antimicrobial, antiviral, cytotoxic, immunosuppressive	31
Anabaenopeptins	Antimicrobial, antifungal, antiviral, antitumor	41
Aeruginosins	Neurotoxic, antiproliferative, antibacterial	29
Lyngbyatoxins	Cytotoxic, neurotoxic, antifungal, antimicrobial	42
Nodularins	Hepatotoxic, tumor-promoting, protein phosphatase inhibition	66
Phycocyanin	Antioxidant, anti-inflammatory, immunomodulatory	67
Scytonemin	UV-protective, antioxidant, antimicrobial	68
Patellamides	Antimicrobial, antifungal, cytotoxic, antiparasitic	69
Geosmin	Earthy odor, involved in cyanobacterial bloom formation	70
Cylindrospermopsin	Hepatotoxic, genotoxic, carcinogenic	71

cyanobacteria has highlighted their diverse therapeutic potential, including antimicrobial, anticancer, anti-inflammatory, neuroprotective, antioxidant, and antidiabetic activities. These findings underscore the importance of further exploration and investigation of cyanobacterial compounds for developing novel drugs and therapeutic interventions.

Neuroprotective Properties

Neurodegenerative diseases, such as Alzheimer's, Parkinson's, and Huntington's disease, present an increasing global health challenge due to the aging population. Despite intensive research, effective treatments for these devastating conditions remain elusive. In recent years, there has been growing interest in exploring natural compounds, and cyanobacteria have emerged as a promising source of bioactive molecules with potential neuroprotective properties.[83,84]

Several bioactive compounds derived from cyanobacteria have been investigated for their neuroprotective properties. For example, β-N-methylamino-l-alanine (BMAA), originally isolated from cyanobacteria, has been linked to neurotoxicity and implicated in neurodegenerative diseases such as amyotrophic lateral sclerosis and Alzheimer's disease.[85,86] However, research on BMAA's precise role in neurodegeneration is ongoing, and its potential therapeutic applications are yet to be fully elucidated. In addition to BMAA, other cyanobacterial compounds, such as anatoxin-a, have shown a potential to modulate neural pathways and reduce neuroinflammation, factors involved in the progression of neurodegenerative diseases.[87]

FUTURE OF BIOACTIVE COMPOUNDS OF CYANOBACTERIA

Bioactive compounds derived from cyanobacteria have shown immense potential in various therapeutic applications, ranging from antimicrobial and anticancer activities to neuroprotective and immunomodulatory effects. As research in this field continues to advance, the future of bioactive compounds of cyanobacteria holds great promise for drug discovery and development.

Synthetic Biology and Genetic Engineering

Advancements in synthetic biology and genetic engineering techniques offer exciting prospects for the future of cyanobacterial bioactive compounds. By manipulating the genetic makeup of cyanobacteria, researchers can enhance the production of specific bioactive compounds or engineer new compounds with improved properties. For example, genetic modifications in cyanobacteria have successfully increased the production of bioactive peptides and pigments.[88] Such approaches hold the potential for the sustainable and efficient production of bioactive compounds with enhanced therapeutic properties.

Metabolomics and Omics Technologies

Metabolomics and omics technologies enable comprehensive profiling and analysis of cyanobacterial metabolites, facilitating the discovery of novel bioactive compounds. Researchers

can identify and characterize previously unknown cyanobacterial metabolites by employing mass spectrometry, nuclear magnetic resonance, and other analytical techniques.[89] Additionally, omics approaches, such as genomics, transcriptomics, and proteomics, provide insights into cyanobacteria's biosynthetic pathways and regulatory mechanisms of bioactive compound production.[90] These technologies pave the way for discovering new bioactive compounds and optimizing production processes.[11]

Bioprospecting and Biodiversity

Cyanobacteria represent a vast and diverse group of organisms, offering untapped potential for discovering bioactive compounds. Exploring various cyanobacterial strains from different habitats can lead to identifying unique and potent bioactive compounds. Bioprospecting expeditions targeting unexplored environments, such as marine ecosystems and extreme environments, may yield valuable cyanobacterial species with novel bioactive compounds.[91,92] Furthermore, integrating culture-dependent and culture-independent approaches, along with high-throughput screening methods, can expedite the discovery of bioactive compounds from cyanobacteria.[93–95]

Structural Elucidation and Mechanistic Studies

To fully understand the potential of cyanobacterial bioactive compounds, extensive structural elucidation, and mechanistic studies are crucial. Advanced spectroscopic techniques, such as nuclear magnetic resonance spectroscopy and X-ray crystallography, enable the determination of the three-dimensional structures of bioactive compounds, providing insights into their interactions with targets and mechanisms of action. Elucidating the structure-activity relationships of cyanobacterial compounds will guide the design and optimization of novel therapeutic agents.[60,96]

Continued Exploration of Untapped Cyanobacterial Diversity

As a diverse group of microorganisms, cyanobacteria offer immense potential for discovering bioactive compounds. The future prospects of bioactive compounds derived from cyanobacteria rely on the continued exploration of untapped cyanobacterial diversity. By conducting extensive sampling and characterization efforts, researchers can uncover novel cyanobacterial species and strains that may harbor unique bioactive compounds.[97,98] These untapped resources hold the potential for discovering compounds with previously unknown biological activities and therapeutic applications.[99]

Integration of Advanced Technologies Like Machine Learning and High-Throughput Screening

The integration of advanced technologies such as machine learning, artificial intelligence, and high-throughput screening can revolutionize the discovery and development of cyanobacterial bioactive compounds. Machine learning algorithms can analyze vast datasets, identify patterns, and predict potential bioactivities.[100,101] This approach accelerates the screening process, enabling researchers to prioritize compounds with the highest likelihood of exhibiting desired biological properties. High-throughput screening allows for the rapid testing of large compound libraries, facilitating the identification of bioactive molecules efficiently.[91,102] By combining these advanced technologies, researchers can streamline the discovery and optimization of cyanobacterial bioactive compounds.

Sustainable Production through Biotechnological Approaches

Sustainable production methods are crucial for cyanobacterial bioactive compounds' future viability and scalability. Biotechnological approaches offer promising solutions in this regard. Techniques such as synthetic biology, metabolic engineering, and cultivation optimization can enhance the production of desired compounds.[103] By modifying cyanobacterial metabolic pathways, researchers can increase the yield and purity of target compounds. Cultivation optimization strategies, including nutrient optimization, light modulation, and bioreactor design, contribute to higher productivity and efficiency while minimizing environmental impacts.[104] These biotechnological approaches enable sustainable and cost-effective production of cyanobacterial bioactive compounds, facilitating their translation into practical applications.

CURRENT AND FUTURE APPLICATIONS OF BIOACTIVE COMPOUNDS OF CYANOBACTERIA IN PHARMACEUTICALS, AGRICULTURE, AND ENVIRONMENTAL REMEDIATION

Cyanobacterial bioactive compounds have diverse applications in pharmaceuticals, agriculture, and environmental remediation. These compounds exhibit a wide range of biological activities and have the potential to address various challenges in these fields.

A. In the pharmaceutical industry, bioactive compounds derived from cyanobacteria have shown significant potential for drug discovery and development. They have demonstrated activities such as antimicrobial, antifungal, antiviral, antioxidant, anti-inflammatory, and anticancer properties.[105] Cyanotoxins, a group of cyanobacterial bioactive compounds, have garnered attention for their potential therapeutic applications in cancer treatment.[106] For example, microcystins, a common cyanotoxin, have exhibited promising anticancer activity and are being investigated as potential leads for novel therapies.[107]

B. In agriculture, the bioactive compounds of cyanobacteria offer opportunities for sustainable crop protection and enhancement. They have demonstrated activity against plant

pathogens and pests, making them potential alternatives to synthetic pesticides.[108] Cyanobacterial compounds, including cyanotoxins, have also been explored for their allelopathic effects, which can contribute to weed control and crop protection. Furthermore, cyanobacterial biofertilizers show promise in improving nutrient availability and enhancing crop growth.[109]

C. Cyanobacterial bioactive compounds also play a role in environmental remediation. They have been studied for their potential in water and soil treatment. Cyanobacterial peptides, for instance, exhibit inhibitory effects on harmful bacteria in water sources, contributing to the control of waterborne diseases.[110] Moreover, the metal-binding and detoxification capabilities of cyanobacterial compounds have implications for the removal of heavy metals and pollutants from the environment.[111]

Looking ahead, the future applications of cyanobacterial bioactive compounds are promising. Continued exploration of cyanobacterial diversity and technological advancements will likely expand their range of applications. Integrating advanced techniques such as genomics, metabolomics, and synthetic biology can further enhance the discovery and development of novel compounds with improved properties.[112] Additionally, the sustainable production and scaling-up of cyanobacterial bioactive compounds through biotechnological approaches offer tremendous potential for meeting the increasing demand for natural products.[113]

CONCLUSION

In conclusion, cyanobacteria are valuable sources of bioactive compounds with diverse properties and applications. The current advancements in genomics, metabolomics, synthetic biology, and screening techniques have paved the way for discovering and developing novel bioactive compounds from cyanobacteria. The future prospects involve the continued exploration of cyanobacterial diversity, the application of advanced technologies, and the sustainable production of bioactive compounds. These efforts will undoubtedly contribute to developing innovative pharmaceuticals, agricultural solutions, and environmental remedies. Harnessing the potential of cyanobacteria and their bioactive compounds will offer new avenues for drug discovery and provide sustainable and eco-friendly solutions to various challenges in medicine, agriculture, and the environment. Therefore, further research and investment in this field are crucial to unlock the full potential of cyanobacterial bioactive compounds for the benefit of society.

Peer Review: Externally peer-reviewed.

Author Contributions: Conception/Design of Study- A.K.; Data Acquisition- M.D.N.; Data Analysis/Interpretation- A.H.; Drafting Manuscript- A.K.; Critical Revision of Manuscript- A.H., H.K.; Final Approval and Accountability- A.K., A.H., M.D.N., R.S. A.F., A.S.

Conflict of Interest: Author declared no conflict of interest.

Financial Disclosure: Authors declared no financial support.

ORCID IDs of the authors

Arbab Husain 0000-0002-9487-9284
Md Nematullah 0000-0002-5935-6699
Hamda Khan 0000-0003-2448-9878
Ravi Shekher 0000-0001-5984-0678
Alvina Farooqui 0000-0002-7260-0414
Archana Sahu 0000-0002-6526-2402
Afreen Khanam 0000-0002-5380-1667

REFERENCES

1. Husain A, Alouffi S, Khanam A, et al. Non-inhibitory effects of the potent antioxidant C-phycocyanin from Plectonema sp. on the *in vitro* glycation reaction. *Rev Rom Med Lab*. 2022;30(2):199-213.
2. Husain A, Alouffi S, Khanam A, Akasha R, Farooqui A, Ahmad S. Therapeutic efficacy of natural product 'c-phycocyanin' in alleviating streptozotocin-induced diabetes via the inhibition of glycation reaction in rats. *Int J Mol Sci*. 2022;23(22):14235. doi:10.3390/ijms232214235
3. Husain A, Farooqui A, Khanam A, et al. Physicochemical characterization of C-phycocyanin from *Plectonema* sp. and elucidation of its bioactive potential through in silico approach. *Cell Mol Biol*. 2022;67(4):68-82.
4. Rajneesh, Singh SP, Pathak J, Sinha RP. Cyanobacterial factories for the production of green energy and value-added products: An integrated approach for economic viability. *Renew Sustain Energy Rev*. 2017;69:578-595.
5. Khanam A, Ahmad S, Husain A. A Perspective on the impact of advanced glycation end products in the progression of diabetic nephropathy. *Curr Protein Pept Sci*. 2022;24(1):2-6.
6. Khanam A, Kavita K, Sharma RK, et al. *In-silico* exploration of cyanobacterial bioactive compounds for managing diabetes: Targeting alpha-amylase and beta-glucosidase. *Intell Pharm*. 2023;1(4):232-243.
7. Choudhary A, Naughton LM, Montánchez I, Dobson ADW, Rai DK. Current status and future prospects of marine natural products (MNPs) as antimicrobials. *Mar Drugs*. 2017;15(9):272. doi:10.3390/md15090272
8. Nandagopal P, Steven AN, Chan LW, Rahmat Z, Jamaluddin H, Mohd Noh NI. Bioactive metabolites produced by cyanobacteria for growth adaptation and their pharmacological properties. *Biology (Basel)*. 2021;10(10):1061. doi:10.3390/biology10101061
9. Alouffi S, Khanam A, Husain A, Akasha R, Rabbani G, Ahmad S. D-ribose-mediated glycation of fibrinogen: Role in the induction of adaptive immune response. *Chem Biol Interact*. 2022;367:110147. doi:10.1016/j.cbi.2022.110147

10. Khanam A, Alouffi S, Alyahyawi AR, et al. Generation of autoantibodies against glycated fibrinogen: Role in diabetic nephropathy and retinopathy. *Anal Biochem*. 2023;685:115393. doi:10.1016/j.ab.2023.115393
11. Lauritano C, Ferrante MI, Rogato A. Marine natural products from microalgae: An -omics overview. *Mar Drugs*. 2019;17(5):269. doi:10.3390/md17050269
12. Alam K, Hao J, Zhang Y, Li A. Synthetic biology-inspired strategies and tools for engineering of microbial natural product biosynthetic pathways. *Biotechnol Adv*. 2021;49:107759. doi:10.1016/J.BIOTECHADV.2021.107759
13. Khanam A, Alouffi S, Rehman S, Ansari IA, Shahab U, Ahmad S. An *in vitro* approach to unveil the structural alterations in d-ribose induced glycated fibrinogen. *J Biomol Struct Dyn*. 2021;39(14):5209-5223.
14. Majolo F, de Oliveira Becker Delwing LK, Marmitt DJ, Bustamante-Filho IC, Goettert MI. Medicinal plants and bioactive natural compounds for cancer treatment: Important advances for drug discovery. *Phytochem Lett*. 2019;31:196-207.
15. Li JWH, Vederas JC. Drug discovery and natural products: End of an era or an endless frontier? *Science*. 2009;325(5937):161-165.
16. Raja R, Hemaiswarya S, Ganesan V, Carvalho IS. Recent developments in therapeutic applications of Cyanobacteria. *Crit Rev Microbiol*. 2016;42(3):394-405.
17. Gulder TA, Moore BS. Chasing the treasures of the sea — bacterial marine natural products. *Curr Opin Microbiol*. 2009;12(3):252-260.
18. Saad A, Atia A. Review on freshwater blue-green algae (Cyanobacteria): Occurrence, classification and toxicology. *Biosci Biotechnol Res ASIA*. 2014;11(3):1319-1325.
19. Madhyastha HK, Vatsala TM. Pigment production in *Spirulina fussiformis* in different photophysical conditions. *Biomol Eng*. 2007;24(3):301-305.
20. Sánchez-Baracaldo P, Bianchini G, Di Cesare A, Callieri C, Chrismas NAM. Insights into the evolution of Picocyanobacteria and Phycoerythrin genes (mpeBA and cpeBA). *Front Microbiol*. 2019;10(JAN):45. doi:10.3389/fmicb.2019.00045
21. Di Rienzi SC, Sharon I, Wrighton KC, et al. The human gut and groundwater harbor non-photosynthetic bacteria belonging to a new candidate phylum sibling to Cyanobacteria. *Elife*. 2013;2:e01102. doi:10.7554/elife.01102
22. Altaf MM, Ahmad Khan MS, Ahmad I. Diversity of bioactive compounds and their therapeutic potential. *New Look to Phytomedicine Adv Herb Prod as Nov Drug Leads*. 2018:15-34.
23. Khalifa SAM, Elias N, Farag MA, et al. Marine natural products: A source of novel anticancer drugs. *Mar Drugs*. 2019;17(9):491. doi:10.3390/md17090491
24. Pandey VD. Cyanobacterial natural products as antimicrobial agents. *IntJ Curr Microbiol App Sci*. 2015;4(1):310-317.
25. Plaza M, Herrero M, Alejandro Cifuentes A, Ibáñez E. Innovative natural functional ingredients from microalgae. *J Agric Food Chem*. 2009;57(16):7159-7170.
26. Kleigrewe K, Gerwick L, Sherman DH, Gerwick WH. Unique marine derived cyanobacterial biosynthetic genes for chemical diversity. *Nat Prod Rep*. 2016;33(2):348-364.
27. Zahra Z, Choo DH, Lee H, Parveen A. Cyanobacteria: Review of current potentials and applications. *Environ*. 2020;7(2):13. doi:10.3390/ENVIRONMENTS7020013
28. Coates RC, Trentacoste E, Gerwick WH. Bioactive and novel chemicals from microalgae. *Handb Microalgal Cult Appl Phycol Biotechnol Second Ed*., 2013:504-531. doi:10.1002/9781118567166.CH26
29. Tikhonova I, Kuzmin A, Deeva D, et al. Cyanobacteria *Nostoc punctiforme* from abyssal benthos of Lake Baikal: Unique ecology and metabolic potential. *Indian J Microbiol*. 2017;57(4):422-426.
30. Fidor A, Konkel R, Mazur-Marzec H. Bioactive peptides produced by Cyanobacteria of the genus *Nostoc*: A Review. *Mar Drugs*. 2019;17(10):561. doi:10.3390/md17100561
31. Isaacs JD, Strangman WK, Barbera AE, Mallin MA, McIver MR, Wright JLC. Microcystins and two new micropeptin cyanopeptides produced by unprecedented *Microcystis aeruginosa* blooms in North Carolina's Cape Fear River. *Harmful Algae*. 2014;31:82-86.
32. Edwards DJ, Marquez BL, Nogle LM, et al. Structure and biosynthesis of the Jamaicamides, new mixed polyketide-peptide neurotoxins from the marine cyanobacterium *Lyngbya majuscula*. *Chem Biol*. 2004;11(6):817-833.
33. hih C, Teicher B. Cryptophycins: A Novel class of potent antimitotic antitumor depsipeptides. *Curr Pharm Des*. 2005;7(13):1259-1276.
34. Tan LT. Bioactive natural products from marine cyanobacteria for drug discovery. *Phytochemistry*. 2007;68(7):954-979.
35. Colas S, Marie B, Lance E, Quiblier C, Tricoire-Leignel H, Mattei C. Anatoxin-a: Overview on a harmful cyanobacterial neurotoxin from the environmental scale to the molecular target. *Environ Res*. 2021;193:110590. doi:10.1016/J.ENVRES.2020.110590
36. Osswald J, Rellán S, Gago A, Vasconcelos V. Toxicology and detection methods of the alkaloid neurotoxin produced by cyanobacteria, anatoxin-a. *Environ Int*. 2007;33(8):1070-1089.
37. Aráoz R, Vilariño N, Botana LM, Molgó J. Ligand-binding assays for cyanobacterial neurotoxins targeting cholinergic receptors. *Anal Bioanal Chem*. 2010;397(5):1695-1704.
38. Swain SS, Paidesetty SK, Padhy RN. Antibacterial, antifungal and antimycobacterial compounds from cyanobacteria. *Biomed Pharmacother*. 2017;90:760-776.
39. Abdel-Razek AS, El-Naggar ME, Allam A, Morsy OM, Othman SI. Microbial natural products in drug discovery. *Process*. 2020;8(4):470. doi:10.3390/PR8040470
40. Scoglio S. Microcystins in water and in microalgae: Do microcystins as microalgae contaminants warrant the current public alarm? *Toxicol Reports*. 2018;5:785-792.
41. Harms H, Kurita KL, Pan L, et al. Discovery of anabaenopeptin 679 from freshwater algal bloom material: Insights into the structure–activity relationship of anabaenopeptin protease inhibitors. *Bioorganic Med Chem Lett*. 2016;26(20):4960-4965.
42. Catherine Q, Susanna W, Isidora ES, Mark H, Aurélie V, Jean-François H. A review of current knowledge on toxic benthic freshwater cyanobacteria- Ecology, toxin production and risk management. *Water Res*. 2013;47(15):5464-5479.
43. Nowruzi B, Blanco S, Nejadsattari T. Chemical and molecular evidences for the poisoning of a duck by anatoxin-a, nodularin and cryptophycin at the coast of lake Shoormast (Mazandaran province, Iran). *Algologia*. 2018;28(4):409-427.
44. De Morais MG, Da Fontoura Prates D, Moreira JB, Duarte JH, Costa JAV. Phycocyanin from microalgae: Properties, extraction and purification, with some recent applications. *Ind Biotechnol*. 2018;14(1):30-37.
45. Stevenson CS, Capper EA, Roshak AK, et al. Scytonemin-A ma-

rine natural product inhibitor of kinases key in hyperproliferative inflammatory diseases. *Inflamm Res*. 2002;51(2):112-114.

46. Rumengan IFM, Modaso RH, Lintang R, Rumampuk ND, Posangi J. Cytotoxicity of methanol extracts of *Prochloron didemni* originated from ascidians *Lissoclinum patella* and *Didemnum molle* collected from Manado Bay, North Sulawesi. *IOP Conf Ser Earth Environ Sci*. 2020;517(1):012018. doi:10.1088/1755-1315/517/1/012018
47. Amaral SC do, Santos AV, Schneider MP da C, Silva JKR da, Xavier LP. Determination of volatile organic compounds and antibacterial activity of the amazonian cyanobacterium *Synechococcus* sp. strain GFB01. *Molecules*. 2020;25(20):4744. doi:10.3390/molecules25204744
48. Dinh QT, Munoz G, Simon DF, Vo Duy S, Husk B, Sauvé S. Stability issues of microcystins, anabaenopeptins, anatoxins, and cylindrospermopsin during short-term and long-term storage of surface water and drinking water samples. *Harmful Algae*. 2021;101:101955. doi:10.1016/j.hal.2020.101955
49. Mazmouz R, Chapuis-Hugon F, Mann S, Pichon V, Méjean A, Ploux O. Biosynthesis of cylindrospermopsin and 7-epicylindrospermopsin in *Oscillatoria* sp. strain PCC 6506: Identification of the cyr gene cluster and toxin analysis. *Appl Environ Microbiol*. 2010;76(15):4943-4949.
50. Ejike CECC, Collins SA, Balasuriya N, Swanson AK, Mason B, Udenigwe CC. Prospects of microalgae proteins in producing peptide-based functional foods for promoting cardiovascular health. *Trends Food Sci Technol*. 2017;59:30-36.
51. Hillwig ML, Liu X. A new family of iron-dependent halogenases acts on freestanding substrates. *Nat Chem Biol*. 2014;10(11):921-923.
52. Plech A, Salditt T, Münster C, Peisl J. Molecular biology of peptide and polyketide biosynthesis in cyanobacteria. *Appl Microbiol Biotechnol*. 2001;57(4):467-473.
53. Tillett D, Dittmann E, Erhard M, Von Döhren H, Börner T, Neilan BA. Structural organization of microcystin biosynthesis in *Microcystis aeruginosa* PCC7806: An integrated peptide-polyketide synthetase system. *Chem Biol*. 2000;7(10):753-764.
54. Dewi IC, Falaise C, Hellio C, Bourgougnon N, Mouget JL. Anticancer, antiviral, antibacterial, and antifungal properties in microalgae. *Microalgae Heal Dis Prev*. 2018:235-261.
55. Finamore A, Palmery M, Bensehaila S, Peluso I. Antioxidant, immunomodulating, and Microbial-modulating activities of the sustainable and ecofriendly *Spirulina*. *Oxid Med Cell Longev*. 2017;2017:1-14.
56. Ibrahim EA, Aly HF, Abou Baker DH, Mahmoud K, El-Baz FK. Marine algal sterol hydrocarbon with anti-inflammatory, anticancer and anti-oxidant properties. *Int J Pharma Bio Sci*. 2016;7(3):392-398.
57. Portmann C, Blom JF, Kaiser M, Brun R, Jüttner F, Gademann K. Isolation of aerucyclamides C and D and structure revision of microcyclamide 7806A: Heterocyclic ribosomal peptides from *Microcystis aeruginosa* PCC 7806 and their antiparasite evaluation. *J Nat Prod*. 2008;71(11):1891-1896.
58. Holland A, Kinnear S. Interpreting the possible ecological role(s) of cyanotoxins: Compounds for competitive advantage and/or physiological aide? *Mar Drugs*. 2013;11(7):2239-2258.
59. Kar J, Ramrao DP, Zomuansangi R, et al. Revisiting the role of cyanobacteria-derived metabolites as antimicrobial agent: A 21st century perspective. *Front Microbiol*. 2022;13:034471. doi:10.3389/fmicb.2022.1034471
60. Niveshika, Verma E, Mishra AK, Singh AK, Singh VK. Structural elucidation and molecular docking of a novel antibiotic compound from cyanobacterium *Nostoc* sp. MGL001. *Front Microbiol*. 2016;7(NOV):231637. doi:10.3389/FMICB.2016.01899/BIBTEX
61. Kumar J, Singh D, Tyagi MB, Kumar A. Cyanobacteria: Applications in biotechnology. *Cyanobacteria from Basic Sci to Appl*. 2018:327-346. doi:10.1016/B978-0-12-814667-5.00016-7
62. Vijayakumar S, Menakha M. Pharmaceutical applications of cyanobacteria-A review. *J Acute Med*. 2015;5(1):15-23.
63. Kumar L, Bharadvaja N. A review on microalgae biofuel and biorefinery: Challenges and way forward. *Energy Sources, Part A Recover Util Environ Eff*. 2020:1-24.
64. Singh NK, Dhar DW. Microalgae as second generation biofuel. A review. *Agron Sustain Dev*. 2011;31(4):605-629.
65. Ibelings BW, Chorus I. Accumulation of cyanobacterial toxins in freshwater "seafood" and its consequences for public health: A review. *Environ Pollut*. 2007;150(1):177-192.
66. Cerasino L, Salmaso N. Diversity and distribution of cyanobacterial toxins in the Italian subalpine lacustrine district. *Oceanol Hydrobiol Stud*. 2012;41(3):54-63.
67. Patel HM, Rastogi RP, Trivedi U, Madamwar D. Structural characterization and antioxidant potential of phycocyanin from the cyanobacterium *Geitlerinema* sp. H8DM. *Algal Res*. 2018;32:372-383.
68. Assunção J, Amaro HM, Malcata FX, Guedes AC. Cyanobacterial pigments: Photosynthetic function and biotechnological purposes. *Pharmacol Potential Cyanobacteria*. 2022:201-256. doi:10.1016/B978-0-12-821491-6.00008-9
69. Donia MS, Hathaway BJ, Sudek S, et al. Natural combinatorial peptide libraries in cyanobacterial symbionts of marine ascidians. *Nat Chem Biol*. 2006;2(12):729-735.
70. Wang Z, Shao J, Xu Y, Yan B, Li R. Genetic basis for geosmin production by the water bloom-forming cyanobacterium, *Anabaena ucrainica. Water.* 2014;7(1):175-187. doi:10.3390/W7010175
71. Wu Z, Yang S, Shi J. Overview of the distribution and adaptation of a bloom-forming cyanobacterium *Raphidiopsis raciborskii*: integrating genomics, toxicity, and ecophysiology. *J Oceanol Limnol*. 2022;40(5):1774-1791.
72. Singh T, Basu P, Singh TA, Boudh S, Shukla P. Cyanobacteria as source of novel antimicrobials: A boon to mankind. *Microorg Sustain Environ Heal*. 2020:219-230.
73. Shamim A, Mahfooz S, Hussain A, Farooqui A. Ability of Al-acclimatized Immobilized *Nostoc muscorum* to combat abiotic stress and its potential as a biofertilizer. *J Pure Appl Microbiol*. 2020;14(2):1377-1386.
74. Mahfooz S, Jahan S, Shamim A, Husain A, Farooqui A. Oxidative stress and response of antioxidant system in *Nostoc muscorum* exposed to different forms of zinc. *Turkish J Biochem*. 2018;43(4):352-361.
75. Jaki B, Orjala J, Heilmann J, Linden A, Vogler B, Sticher O. Novel extracellular diterpenoids with biological activity from the cyanobacterium *Nostoc commune. J Nat Prod*. 2000;63(3):339-343.
76. Akbarizare M, Ofoghi H, Hadizadeh M, Moazami N. *In vitro* assessment of the cytotoxic effects of secondary metabolites from *Spirulina platensis* on hepatocellular carcinoma. *Egypt Liver J*. 2020;10(1):11. doi:10.1186/s43066-020-0018-3
77. Blas-Valdivia V, Rojas-Franco P, Serrano-Contreras JI, et al. C-phycoerythrin from *Phormidium persicinum* prevents acute kidney injury by attenuating oxidative and endoplasmic reticulum stress. *Mar Drugs*. 2021;19(11):589. doi:10.3390/MD19110589

78. Pagarete A, Ramos AS, Puntervoll P, Allen MJ, Verdelho V. Antiviral potential of algal metabolites—A comprehensive review. *Mar Drugs*. 2021;19(2):94. doi:10.3390/md19020094

79. Pavón-Fuentes N, Marín-Prida J, Llópiz-Arzuaga A, et al. Phycocyanobilin reduces brain injury after endothelin-1- induced focal cerebral ischaemia. *Clin Exp Pharmacol Physiol*. 2020;47(3):383-392.

80. Romay C, Gonzalez R, Ledon N, Remirez D, Rimbau V. C-Phycocyanin: A biliprotein with antioxidant, anti-inflammatory and neuroprotective effects. *Curr Protein Pept Sci*. 2005;4(3):207-216.

81. Kaushik A, Sangtani R, Parmar HS, Bala K. Algal metabolites: Paving the way towards new generation antidiabetic therapeutics. *Algal Res*. 2023;69:102904. doi:10.1016/j.algal.2022.102904

82. Khanam A, Ahmad S, Husain A, Rehman S, Farooqui A, Yusuf MA. Glycation and antioxidants: Hand in the glove of antiglycation and natural antioxidants. *Curr Protein Pept Sci*. 2020;21(9):899-915.

83. Tabrizi S. Neurodegenerative diseases neurobiology pathogenesis and therapeutics. *J Neurol Neurosurg Psychiatry*. 2006;77(2):284. doi:10.1136/JNNP.2005.072710

84. Castaneda A, Ferraz R, Vieira M, Cardoso I, Vasconcelos V, Martins R. Bridging cyanobacteria to neurodegenerative diseases: A new potential source of bioactive compounds against alzheimer's disease. *Mar Drugs*. 2021;19(6):343. doi:10.3390/md19060343

85. Banack SA, Johnson HE, Cheng R, Cox PA. Production of the neurotoxin BMAA by a marine cyanobacterium. *Mar Drugs*. 2007;5(4):180-196.

86. Banack SA, Caller TA, Stommel EW. The Cyanobacteria derived toxin beta-n-methylamino-l-alanine and amyotrophic lateral sclerosis. *Toxins (Basel)*. 2010;2(12):2837. doi:10.3390/TOXINS2122837

87. Sini P, Dang TBC, Fais M, et al. Cyanobacteria, cyanotoxins, and neurodegenerative diseases: Dangerous liaisons. *Int J Mol Sci*. 2021;22(16):8726. doi:10.3390/ijms22168726

88. Spolaore P, Joannis-Cassan C, Duran E, Isambert A. Commercial applications of microalgae. *J Biosci Bioeng*. 2006;101(2):87-96.

89. Schwarz D, Orf I, Kopka J, Hagemann M. Recent applications of metabolomics toward cyanobacteria. *Metabolites*. 2013;3(1):72-100.

90. Pathania R, Srivastava A, Srivastava S, Shukla P. Metabolic systems biology and multi-omics of cyanobacteria: Perspectives and future directions. *Bioresour Technol*. 2022;343:126007. doi:10.1016/J.BIORTECH.2021.126007

91. Abida H, Ruchaud S, Rios L, et al. Bioprospecting marine plankton. *Mar Drugs*. 2013;11(11):4594. doi:10.3390/MD11114594

92. Paul SI, Majumdar BC, Ehsan R, Hasan M, Baidya A, Bakky MAH. Bioprospecting potential of marine microbial natural bioactive compounds. *J Appl Biotechnol Reports*. 2021;8(2):96-108.

93. Rotter A, Barbier M, Bertoni F, et al. The Essentials of marine biotechnology. *Front Mar Sci*. 2021;8:158. doi:10.3389/fmars.2021.629629

94. Zymański P, Markowicz M, Mikiciuk-Olasik E. Adaptation of high-throughput screening in drug discovery—Toxicological screening tests. *Int J Mol Sci*. 2012;13(1):427. doi:10.3390/IJMS13010427

95. Ferreira L, Morais J, Preto M, et al. Uncovering the bioactive potential of a cyanobacterial natural products library aided by untargeted metabolomics. *Mar Drugs*. 021;19(11):633. doi:10.3390/md19110633

96. Kim W, Chen TY, Cha L, et al. Elucidation of divergent desaturation pathways in the formation of vinyl isonitrile and isocyanoacrylate. *Nat Commun*. 2022;13(1):5343. doi:10.1038/s41467-022-32870-4

97. Van Wagoner RM, Drummond AK, Wright JLC. Biogenetic diversity of cyanobacterial metabolites. *Adv Appl Microbiol*. 2007;61:89-217.

98. Komárek J. A polyphasic approach for the taxonomy of Cyanobacteria: Principles and applications. *Eur J Phycol*. 2016;51(3):346-353.

99. Srinivasan R, Kannappan A, Shi C, Lin X. Marine bacterial secondary metabolites: A treasure house for structurally unique and effective antimicrobial compounds. *Mar Drugs* 2021;19(10):530. doi:10.3390/MD19100530

100. Hong K, Gao AH, Xie QY, et al. Actinomycetes for marine drug discovery isolated from mangrove soils and plants in China. *Mar Drugs*. 2009;7(1):24-44.

101. Wang K, Khoo KS, Leong HY, et al. How does the internet of things (IoT) help in microalgae biorefinery? *Biotechnol Adv*. 2022;54:107819. doi: 10.1016/j.biotechadv.2021.107819

102. Wase N V., Wright PC. Systems biology of cyanobacterial secondary metabolite production and its role in drug discovery. *Expert Opin Drug Discov*. 2008;3(8):903-929.

103. Sandybayeva SK, Kossalbayev BD, Zayadan BK, et al. Prospects of cyanobacterial pigment production: Biotechnological potential and optimization strategies. *Biochem Eng J*. 2022;187:108640. doi:10.1016/J.BEJ.2022.108640

104. Manirafasha E, Ndikubwimana T, Zeng X, Lu Y, Jing K. Phycobiliprotein: Potential microalgae derived pharmaceutical and biological reagent. *Biochem Eng J*. 2016;109:282-296.

105. Chu WL, Phang SM. Bioactive compounds from microalgae and their potential applications as pharmaceuticals and nutraceuticals. *Gd Challenges Biol Biotechnol*. 2019:429-469. doi:10.1007/978-3-030-25233-5_12

106. Pradhan B, Ki JS. Phytoplankton toxins and their potential therapeutic applications: A Journey toward the quest for potent pharmaceuticals. *Mar Drugs*. 2022;20(4):271. doi:10.3390/MD20040271/S1

107. Zanchett G, Oliveira-Filho EC. Cyanobacteria and Cyanotoxins: From impacts on aquatic ecosystems and human health to anticarcinogenic effects. *Toxins*. 2013;5(10):1896-1917. doi:10.3390/TOXINS5101896

108. Costa JAV, Freitas BCB, Cruz CG, Silveira J, Morais MG. Potential of microalgae as biopesticides to contribute to sustainable agriculture and environmental development. 2019;54(5):366-375.

109. Haque F, Banayan S, Yee J, Chiang YW. Extraction and applications of cyanotoxins and other cyanobacterial secondary metabolites. *Chemosphere*. 2017;183:164-175.

110. Levasseur W, Perré P, Pozzobon V. A review of high value-added molecules production by microalgae in light of the classification. *Biotechnol Adv*. 2020;41:107545. doi:10.1016/J.BIOTECHADV.2020.107545

111. Yaashikaa PR, Kumar PS, Jeevanantham S, Saravanan R. A review on bioremediation approach for heavy metal detoxification and accumulation in plants. *Environ Pollut*. 2022;301:119035. doi:10.1016/J.ENVPOL.2022.119035

112. Mishra A, Medhi K, Malaviya P, Thakur IS. Omics approaches for microalgal applications: Prospects and challenges. *Bioresour Technol*. 2019;291:121890.

doi:10.1016/J.BIORTECH.2019.121890

113. Olguín EJ, Sánchez-Galván G, Arias-Olguín II, et al. Microalgae-based biorefineries: challenges and future trends to produce carbohydrate enriched biomass, high-added value products and bioactive compounds. *Biol*. 2022;11(8):1146. doi:10.3390/BIOLOGY11081146

How to cite this article

Husain A, Nematullah MD, Khan H, Shekher R, Farooqui A, Sahu A, Khanam A. From Pond Scum to Miracle Molecules: Cyanobacterial Compounds New Frontiers. Eur J Biol 2024; 83(1): 94–105. DOI:10.26650/EurJBiol.2024.1357041