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A MINI REVIEW ON BIOTECHNOLOGICAL POTENTIALS OF BIOACTIVE COMPOUNDS AND BIOPRODUCTS ISOLATED FROM CYANOBACTERIA

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Abstract: Cyanobacteria are well-distributed, because of their ability to acclimate to various environments. Recently, cyanobacteria have received more research attention due to increasing pollution problems and global warming. They have many potential applications in the biotechnology sectors such as pharmaceuticals, bioplastics production, and cosmetics. Cyanobacteria produce many biologically active compounds that are utilized as anti-inflammatory, antiviral, antibacterial, and antifungal agents. The bioactive metabolites extracted from cyanobacteria include alkaloids, fatty acids, lipopeptides, and amides. In this minireview, the potential of some biotechnical applications are summarized to provide an account of the recent advancements in cyanobacteria research.

Keywords: Cyanobacteria, biotechnology, bioactive compounds, antimicrobial compounds, bioplastics, cosmetics

1. Introduction

Cyanobacteria is one of the most common microorganisms that live in different ecosystems on this planet. These microorganisms have been able to survive in environments such as exposed rocks, highly saline waters, polar regions, hot springs, arid deserts, and other extreme environments, and can form symbiotic relations with various organisms (Hu et al., 2012; Kumar et al., 2019; de la Cruz et al., 2020). Cyanobacteria are among the most important organisms that produce biomass, as they play a main function in the biogeochemical recycling of elements in the environment (Kumar et al., 2015; Van Goethem and Cowan, 2019), such as the nitrogen and carbon cycles, and many applications of biotechnology such as a biofuel, biofertilizer, bioplastics production, bioremediation, secondary metabolites production, pigments, and nitrogen fixation

(Shih et al., 2013; Garlapati et al., 2019; Yong et al., 2021). Cyanobacteria are considered as a significant source of metabolites that are mainly used as biopesticides, toxins, pharmaceutical compounds, cosmetic compounds, and growth factors (Al-Haj et al., 2016; Hassan et al., 2022), as shown on **Fig. 1**.

In recent decades, one of the major challenges that the healthcare system may face is the emergence of multi-drug resistant (MDR) bacteria, the cause of which is attributed to the excessive use of antibiotics by humans. As a result of the increase in resistance, there has become a problem for effective treatment using antibiotics, and therefore there has been an urgent need for research and exploration of new sources of antimicrobials (Laxminarayan et al., 2013; Strieth et al., 2022). Cyanobacteria are a significant unexplored source of several new bioactive compounds (Encarnação et al., 2015; Nuryadi et al., 2020).

Cyanobacteria are among the most powerful and unconventional sources of drugs against many diseases (Swain et al., 2015). Many bioactive metabolites have been isolated from cyanobacteria, which have demonstrated the potential for further more drug exploration (Mazard et al., 2016; Lange et al., 2018; Shishido et al., 2019; Schwarzenberger et al., 2020; Hassan et al., 2022; Lamare and Chaurasia, 2022; Yadav et al., 2023). Many secondary metabolites are produced by large multienzyme complexes, usually either nonribosomal peptide synthetases (NRPSs), polyketide synthases (PKSs), or PKS-NRPS hybrids, where large multienzyme complexes modify and assemble individual peptides into a single active molecule (Welker et al., 2012). Cyanobacteria produce a wide range of bioactive compounds such as polyketides, polysaccharides, alkaloids, lipids, carotenes, fatty acids, vitamins, phycocyanin, and proteins, which possess many characteristics such as antiviral, antifungal, antibacterial, algicidal, anti-inflammatory, anti-aging, and anticancer activity (Mimouni et al., 2012; Demay et al., 2019; Verma et al., 2022; Yadav et al., 2023). Cyanobacteria include many different orders, with filamentous and colonial cyanobacteria being among the most productive sources of natural products (Mazard et al., 2016). Jones et al. (2011) found that the production of filamentous cyanobacteria of the total known secondary metabolites is about 26% of the production, which belongs to the genera *Lyngbya*, *Nostoc*, *Microcystis*, *Oscillatoria*, and *Anabaena* (van der Merwe, 2015). Niveshika et al. (2016) recorded the appearance of the compound EMTAHDCA extracted from the cyanobacterium *Nostoc* sp. MGL001, which showed antibacterial activity at a concentration of 150 µg/mL.

Cyanobacteria blooms increasingly worldwide, posing a major threat to aquatic ecosystems and humans (Zhang et al., 2022). The cyanobacteria bloom causes hypoxia in aquatic environments, where the cyanobacteria accumulate, die, and decompose, resulting in the emergence of toxic compounds such as hydrogen sulfide (H_2S), and others (Huang and Zimba, 2019), which causes changes to the structure of the microorganism community and the resulting impact on animal and plant organisms (Liu et al., 2009). Many human health risks are associated with direct or indirect exposure to toxic compounds resulting from the reproduction and blooming of cyanobacteria. The health issues include mouth ulcers, acute inflammation of the stomach and intestines, skin rashes, shortness of breath (Gallitelli et al., 2005), vomiting, diarrhea (Codd et al., 2020), headaches, nausea (Thawabteh et al., 2023), eye and ear infections (Lévesque et al., 2016), and may cause cancer (Žegura et al., 2011; Zhao et al., 2013; Hernandez et al., 2021). Dermal exposure to toxic cyanobacterial compounds causes many symptoms, including skin irritation, which

ranges from mild to moderate, in addition to skin allergy in some individuals (Nielsen and Jiang, 2020). Pilotto et al. (2004) found that there was a small percentage, about 20% of healthy people, who developed skin reactions caused by cyanobacteria as a result of ordinary water recreation, and this reaction did not require any treatment because it was mild. Many skin-related problems have been reported with occupational or recreational exposure, including skin rashes, irritation, sores, peeling, swelling, and allergies resulting from contact with water containing toxic compounds of cyanobacteria (Stewart et al., 2006). The present article provides an overview of the biotechnological applications of cyanobacteria and their diverse uses in pharmaceuticals, cosmetics, and bioplastics.

2. Bioactive compounds produced by cyanobacteria

Cyanobacteria is one of the most important living organisms as a source of natural products, as it is capable of producing a number of bioactive compounds, as it is considered a modern and rich source of these compounds (Demay et al., 2019; Kini et al., 2020; Nowruzi 2022a).

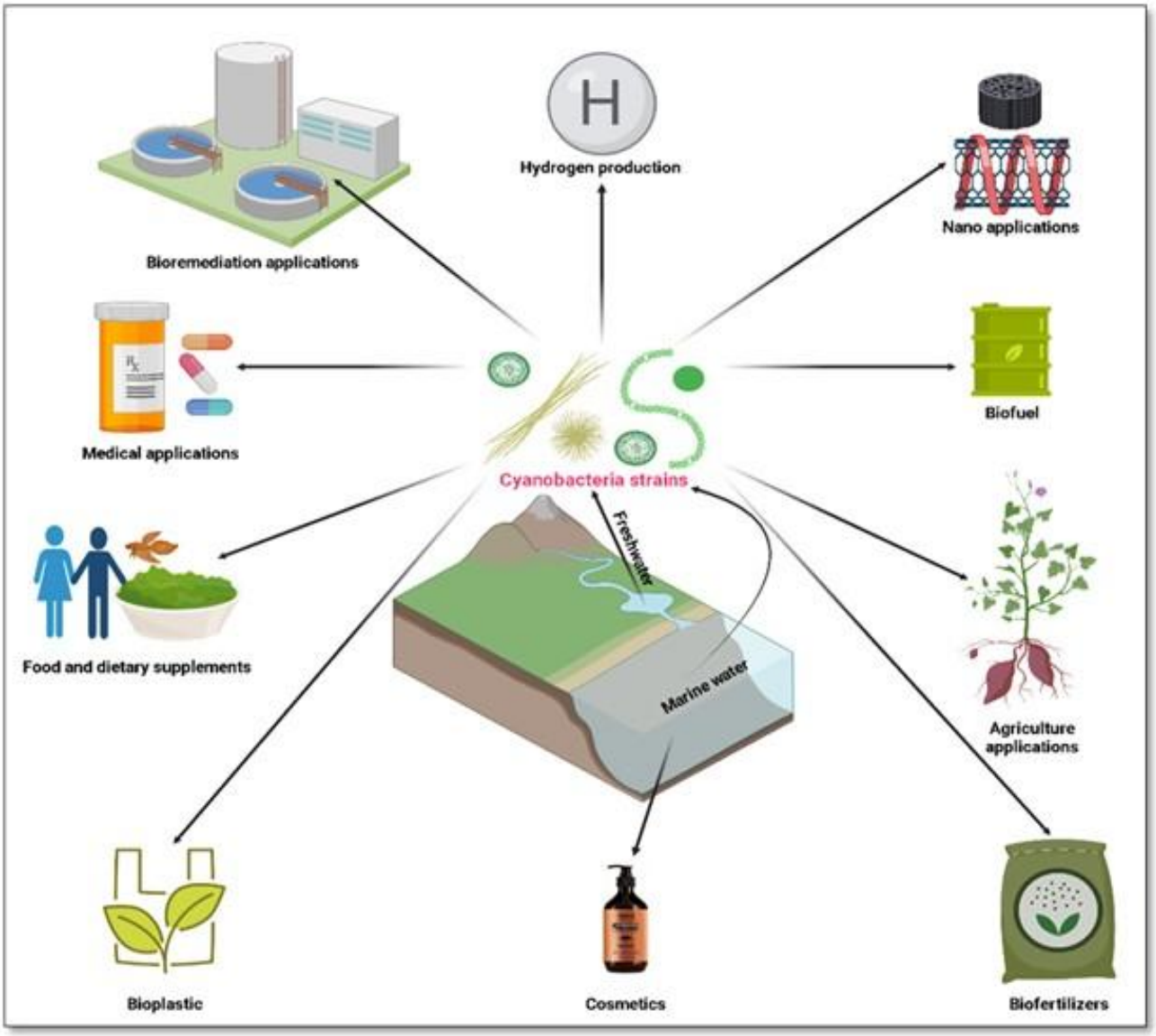

Fig. 1. Biotechnological applications of cyanobacteria

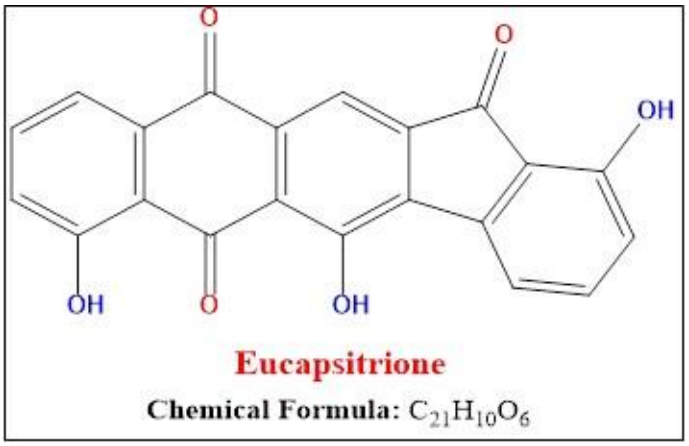

Fig. 2. Structure of Eucapsitrione compound derivative produced by the cyanobacterium *Eucapsis* sp.

Several studies and literature reviews have shown that there are about 19 strains of cyanobacteria that can produce more than 20 bioactive compounds, with most of these compounds tending to be lipopeptides (Abed et al., 2009).

Bioactive compounds are usually effectual against tissues, cells, and organisms at low concentrations, either beneficially or detrimentally to these organisms, and may cause harmful or beneficial effects on humans and other organisms.

Cyanobacteria produce some antimicrobial compounds and these compounds are used in the food industry and food conservation (Sung et al., 2013; Sun et al., 2016). Cyanobacteria can produce about 85 groups of secondary metabolites, which exhibit strong antimicrobial activity (Singh et al., 2016). Eucapsitrione (**Fig. 2**) is an anthraquinone-derived molecule which isolated from the *Eucapsis* sp. (Sturdy et al., 2010). A brief details on the bioactivity of cyanobacteria is given below.

2.1. Antibacterial activity

During recent decades, an alarming rise in antibiotic-resistant bacterial strains has been reported (Falaise et al., 2016; Hamdani et al., 2020). For this reason, alternative sources of antimicrobial compounds must be found (Stincone and Brandelli, 2020). Cyanobacterial extracts are rich sources of different classes of compounds such as peptides, siderophores, polyketones, lipopeptides, heterocyclic compounds, and alkaloids (Vijayakumar and Menakha, 2015; Řezanka et al., 2018; Saurav et al., 2019). Cyanobacteria produce secondary metabolites that have antibacterial activity against Gram-positive and Gram-negative bacteria (Swain et al., 2017; Demay et al., 2019; Cepas et al., 2021; Chauhan et al., 2022; Lykov et al., 2023). There are many secondary metabolites produced by cyanobacteria, including peptides, which contain many compounds such as tenuecyclamide A and D, lyngbyazothrin A, kawaguchipeptin A and B, scytonemin A, borophycin, scyptolin A, and muscoride A, which have documented activities against some types of pathogenic bacteria. Asthana et al. (2009) recorded antibacterial activity of hapalindole isolated from *Nostoc* CCC537 and *Fischerella* sp., against *Enterobacter aerogenes* MTCC2822, *Staphylococcus aureus* ATCC25923, *Pseudomonas aeruginosa* ATCC27853, *Salmonella typhi* MTCC3216, and multi-drug resistant strains of *Escherichia coli* GS 2003/01, 02, 03 and *Escherichia coli* ATCC25992.

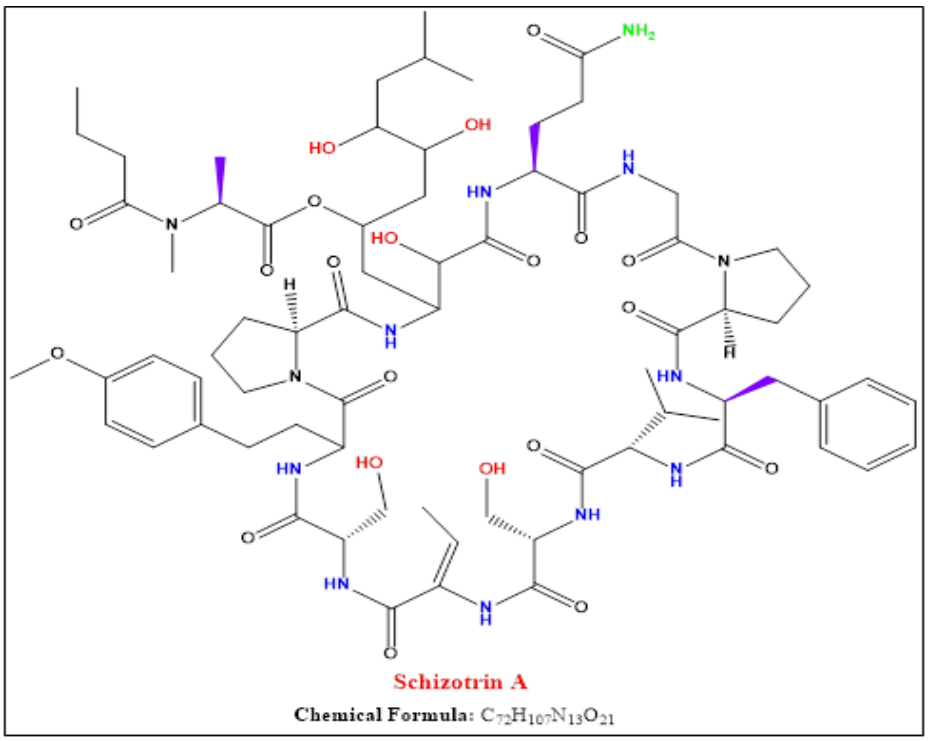

Fig. 3. Structure of antimicrobial compound schizotrin A

2.2. Antialgal activity

In testing the antialgal effect of compounds produced by cyanobacteria, it was found that approximately 10 families of metabolites have an antialgal effect on microalgae. Studies on cyanobacteria that were isolated from two strains, *Nostoc linckia* CALU 892 and *Scytonema hofmanni* UTEX 2349, showed powerful antimicrobial activity against various strains of microalgae and cyanobacteria (Mason et al., 1982; Gromov et al., 1991). There are two compounds, schizotrin A and ambigols, that exhibit antimicrobial activity against fungi, bacteria, and protozoa (**Fig. 3**). Also, these compounds are shown to inhibit the process of photosynthesis (anti-algal effect), which provides promising solutions in the fight against algae and are alternatives to chemical pesticide compounds based on PSII inhibition (Demay et al., 2019).

2.3 Antifungal activity

Cyanobacteria produce many antifungal compounds including nostodione A, fischerellin A, tolytoxin, nostocyclamide, hapalindole, tjipanazole, carazostatin, toyocamycin, and scytophycin which are commonly produced by some genera and species of the cyanobacterial orders such as Oscillatoriales, Nostocaltoriales, and Stigonematales (Abed et al., 2009), as shown **Fig. 4**. Cyanobacteria produce many peptides such as tolybyssidin A and B, fischerellin A and B, lobocyclamide B, scytonemin A, cryptophycin 1 and 52, AK-3, nostocyclamide, hormothamnin A, hassallidin A and B, laxaphycin A and B, calophycin, majusculamide C, hectochlorin, and lyngbyabellin A and B, which have been reported to have antifungal activities (Swain et al., 2017). Vestola et al. (2014) recorded hassallidin A and B (glycosylated lipopeptides) from *Hassallia* sp., with antifungal activity against *Candida* sp., which recorded the lowest inhibitory concentration value of about 4.8 mg/mL.

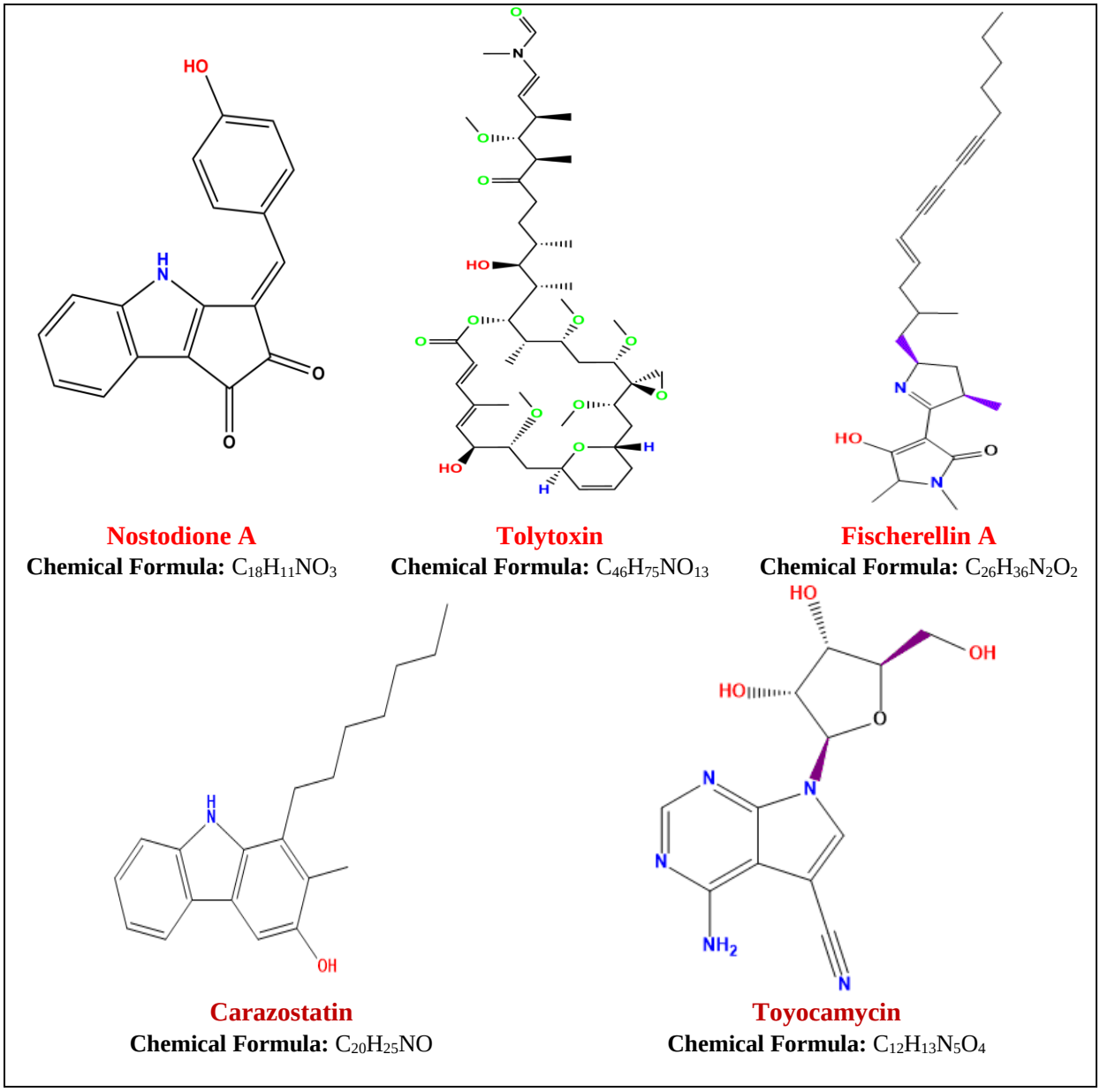

Fig. 4. Structure of some antifungal compounds produced by cyanobacteria

2.4. Antivirals activity

Through studies, it was shown that cyanobacteria can produce antivirals, and the activity of these antivirals has been determined against both human immunodeficiency virus (HIV-1 or HIV-2) and Herpes simplex virus (HSV-1 or HSV-2). Aplysiatoxins (**Fig. 5**) have also been shown to inhibit the activity of Chikungunya virus (CHIKV) but are also considered toxins produced by cyanobacteria (Chlipala et al., 2010; Gupta et al., 2014). The cyanovirin-N analogs isolated from *Cyanothece* sp., and *Nostoc ellipsosporum* showed antiviral activity against large groups of viruses (Boyd et al., 1997; Matei et al., 2016). Cyanovirin-N analogs showed activity against the measles virus, feline immunodeficiency virus, HIV-1, HIV-2, HHV-6, and SIV virus (Boyd et al., 1997; Dey et al., 2000). Therefore, it is clear that cyanobacteria produce many bioactive compounds that act against viruses, bacteria, algae, and fungi. **Table 1** shows some bioactive compounds that are isolated from cyanobacteria.

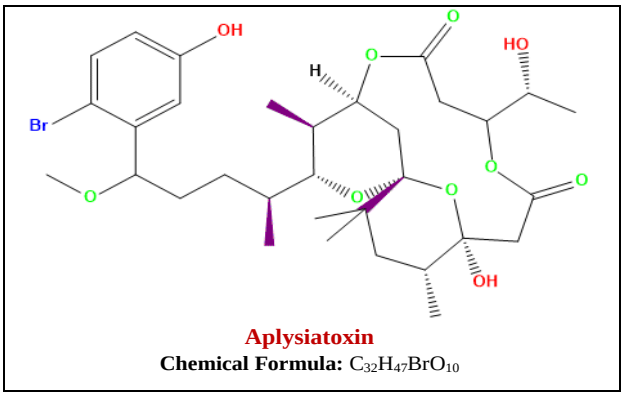

Fig. 5. Aplysiatoxins (cyanotoxin) produced by cyanobacteria

3. Bioplastics from cyanobacteria

Plastics are one of the important materials that are used in many important industries such as the automotive industry, medical equipment, household electrical appliances, computers, etc. Plastic materials are derived from petrochemical materials that are not usually biodegradable and are not renewable, which leads to many problems in the environment, humans and living creatures. In recent years, researchers' interest has increased in the importance of studying bioplastics and their use as an alternative to plastics derived from petrochemicals, as they are made from sustainable resources such as cornstarch, oils, living organisms, and fats (Chua et al., 1999; Chen and Patel, 2012; Aslam et al., 2023). Cyanobacteria produces polyesters from polyhydroxyalkanoates (PHAs) (Gomes et al., 2020; Koller, 2020), a type of thermoplastic that has properties similar to synthetic polypropylene. Among the most common PHAs, polyhydroxybutyrate (PHB) is produced by several genera of cyanobacteria, and this species also exhibits thermoplastic processability, hydrophobicity, biocompatibility, and biodegradability (Hai et al., 2001; Das and Maiti, 2021). Among the cyanobacteria that produce PHB are species such as *Scytonema geitleri* (Singh, et al. 2019), *Arthrospira platensis* (Duangsri et al., 2020b), *Spirulina* sp. (Kordi et al., 2020), *Synechocystis* sp. PCC 6803 (Koch et al., 2020), *Anabaena* sp. (Simonazzi et al., 2021), *Synechocystis* sp. (Rodríguez Lorenzo et al., 2022), and *Synechococcus leopoliensis* (Mariotto et al., 2023).

There are some promising bioplastics including PHA, polyesters, starch, polysaccharides, and cellulose (Storz and Vorlop, 2013). PHA is a fatty substance that is stocked in the cells of cyanobacteria and other living organisms where it is used as an exporter of carbon and energy. It is also produced through the microbial fermentation processes of alkanoic acids, sugars, alkenes, alkanes, and lipids and is then accumulated as granules in the cytoplasm (Reddy and Mohan, 2015). PHB was reported for the first time in 1966 in cells of the cyanobacteria *Chlorogloeopsis fritschii*. It was observed that the largest production of biopolymer was in a type of filamentous cyanobacteria of the type *Nostoc muscorum* Agardh, where the accumulation rate was about 78% dry cell weight (dcw) in heterotrophy with the restriction of nitrogen, glucose, and supplementation of acetate and valerate (Steinbüchel and Valentin, 1995). However, another cyanobacterial species, *Anabaena fertilissima* under mixotrophic cultivation with the addition of acetate, citrate, and deprivation of nitrogen and phosphorus, showed the highest cumulative percentage so far estimated at 85% dcw (Samantaray and Mallick, 2012)

Table. 1. Some bioactive compounds isolated from cyanobacterial strains

Cyanobacterial strains	Bioactive compounds	References
Antibacterial activity		
Lyngbya majuscula	Malyngolide	Dobretsov et al. (2010)
Lyngbya sp.	Lyngbyazothrin	Swain et al. (2017)
Microcystis aeruginosa	Kawaguchipeptin B	Dahms et al. (2006)
Microcoleus lacustris	Abietane	Swain et al. (2017)
Nostoc commune	Comnostins	
	Noscomin	Jaki et al. (2000)
Nostoc insulare	Norharmane	Volk and Furkert (2006)
Nostoc muscorum	Muscoride A	Nagatsu et al. (1995)
Nostoc spongiaeforme	Tenuecyclamides	Banker and Carmeli (1998)
Nostoc sp.	Nostocarboline	Swain et al. (2017)
Oscillatoria redekei	Coriolic acid	
Schizothrix sp.	Schizotrin A	Pergament and Carmeli (1994)
Scytonema sp.	Scytonemin	Swain et al. (2017)
Scytonema ocellatum, Tolypothrix conglutinate	Tolytoxin	
Antivirals activity		
Lyngbya lagerheimii	Sulpholipid	Jha and Zi-Rong (2004)
Lyngbya majuscula	Cyclic polypeptide	
Microcystis ichthyoblabe	Ichthyopeptins A and B	Pandey (2015)
Nostoc ellipsosporum	Cyanovirin-N	Burja et al. (2001)
Nostoc flagelliforme	Nostoflan	Hayashi et al. (2008)
Nostoc sphaericum	Indolocarbazoles	Cohen (2002)
Oscillatoria raoi	Acetylated sulfoglyco-lipids	Reshef et al. (1997)
Phormidium spp.	Caylobolide B	Andrianasolo et al. (2005)
Phormidium tenue	Galactosyldiacylglycerols	Jha and Zi-Rong (2004)
Scytonema	Scytovirin	Bokesch et al. (2003)
Spirulina platensis	Spirulan	Hayashi et al. (1996)
Antialgal activity		
Fischerella muscicola	Fisherellin	Dahms et al. (2006)
Gomphosphaeria aponina	Aponin	Bhadury and Wright (2004)
Nostoc linckia	Cyanobacterin LU-1	Gromov et al. (1991)
Nostoc spongiaeforme	Nostocine A	Hirata et al. (1996)

Phormidium tenue	Galactosyldiacylglycerols	Murakami et al. (1991)
Scytonema hofmanni	Cyanobactericin	Abarzua et al. (1999)
Calothrix fusca	Calophycin	Swain et al. (2017)
Hapalosiphon fontinalis	Hapalindole	Burja et al. (2001)
Antifungal activity		
Hapalosiphon fontinalis	Fontonamide	Burja et al. (2001)
Hyella caespitosa	Carazostatin	
Lyngbya majuscula	Majusculamide C	Pandey (2015)
Nostoc commune	Nostodione	Bhadury and Wright (2004)
Nostoc sp.	Cryptophycin	Singh et al. (2005)
Nostoc sp. UHCC 0450	Swinholides	Humisto et al. (2018)
Plectonema radiosum and *Tolypothrix tenuis*	Tubercidin and toyocamycin	Pandey (2015)
Schizothrix sp.	Schizotrin A	Pergament and Carmeli (1994)
Scytonema hofmanni	Cyanobacterin	Swain et al. (2017)
Scytonema ocellatum	Tolytoxin	Patterson and Carmeli (1992)
Scytonema sp.	Scytonemin	Swain et al. (2017)
Scytonema pseudohofmanni	Scytophycins	Burja et al. (2001)
Scytonema and *Tolypothrix*		Ishibashi et al. (1986)
Tolypothrix tenuis	Toyocamycin	Banker and Carmeli (1998)
	Tubercidin	Swain et al. (2017)
	Toyocamycin	
Tolypothrix tjipanasensis	Tjipanazoles	Bonjouklian et al. (1991)

Cyanobacteria are a promising source for bioplastic production on a commercial scale, but they do not cover the need for various uses of plastic. Thus, genetically modified strains that have a greater ability to accumulate PHA must be produced in order to produce bioplastics on a commercial level. **Table 2** shows some types of bioplastics that are synthesized or produced by cyanobacteria.

Table. 2. Some types of bioplastics produced or synthesized by cyanobacteria

Bioplastic compounds	**Cyanobacteria species**	**Reference**
Poly-3-hydroxybutyrate (PHB)	*Anabaena cylindrica* 10 C	Lama et al. (1996)
	Anabaena sp. VIT-BMN 1	Gopi et al. (2014)
	Arthrospira platensis	Duangsri et al. (2020a)
	Aulosira fertilissima	Samantaray and Mallick (2012)
	Calothrix elenkinii TISTR 8285	Tarawat et al. (2020)
	Calothrix scytonemicola TISTR 8095	Kaewbai-Ngam et al. (2016)
	Calothrix sp. TISTR 8110	Tarawat et al. (2020)
	Chelatococcus daeguensis TAD1	Xu et al. (2014)
	Chlorogloeopsis fritschii TISTR 8547	Tarawat et al. (2020)
	Chroococcus hansgirgi TISTR 8561	Itthirit et al. (2021)
	Hapalosiphon intricatus TISTR 8227	Tarawat et al. (2020)
	Leptolyngbya sp. NIVA-CYA 255	Kettner et al. (2022)
	Myxosarcina sp. TISTR 8678	Tarawat et al. (2020)
	Nostoc hatei TISTR 8405	
	Nostoc microscopicum TISTR 8664	
	Nostoc muscorum TISTR 8871	
	Nostoc muscorum	Panda et al. (2005)
	Nostoc piscinale TISTR 8180	Tarawat et al. (2020)
	Oscillatoria jasorvensis TISTR 8980	
	Oscillatoria sp. TISTR 8623	
	Oscillatoria willei VIT-BMN 9	Gopi et al. (2014)
	Phormidium sp. TISTR 8462	Tarawat et al. (2020)
	Phormidium sp. TISTR 8640	
	Phormidium sp. VIT-BMN 3	Gopi et al. (2014)
	Scytonema geitleri	Singh et al. (2019)
	Spirulina platensis	Campbell 3rd et al. (1982)
	Spirulina sp. LEB 18	da Silva et al. (2018)
	Synechococcus MA19	Nishioka et al. (2001)
	Synechococcus sp. PCC 7002	Zhang et al. (2015)
	Synechococcus sp. TISTR 8503	Tarawat et al. (2020)
	Synechococcus sp. VIT-BMN 2	Gopi et al. (2014)
	Synechocystis salina	Meixner et al. (2018)
	Synechocystis sp. CCALA192	Troschl et al. (2018)
	Synechocystis sp. PCC 6714	Lackner et al. (2019)
	Synechocystis sp. PCC6803	Khetkorn et al. (2016)
	Synechocystis sp. PCC 6803	Zhang et al. (2017)
	Synechocystis sp. PCC 6803	Tarawat et al. (2020)
	Synechocystis sp. VIT-BMN 4	Gopi et al. (2014)
Poly-3-hydroxybutyrate-co hydroxyvalerate [P(HB-co-HV)]	*Nostoc muscorum*	Shetye and Mendhulkar (2022)
Polylactic acid (PLA)	*Arthrospira platensis*	Park and Lee (2022)
Polyhydroxyalkanoates (PHA)	*Arthrospira maxima*	De Philippis et al. (1992)

	Arthrospira platensis	Morais et al. (2015)
	Calothrix scytonemicola TISTR 8095	Kaewbai-Ngam et al. (2016)
	Chlorogloeopsis fritschii PCC 6912	Hai et al. (2001)
	Mastigocladopsis sp.	Kaewbai-Ngam et al. (2016)
	*Nostoc muscorum*a gardh	Bhati and Mallick (2016)
	Spirulina subsalsa	Shrivastav et al. (2010)
	Synechococcus sp. strain MA19	Hai et al. (2001)
	Synechocystis sp.	Lau et al. (2014)
Poly(-3-hydroxybutyrate-co-3-hydroxyvalerate) (PHBV)	*Anabaena ambigua* TISTR 8001	Tarawat et al. (2020)
	Anabaena Spiroides TISTR 8075	
	Calothrix elenkinii TISTR 8285	
	Chlorogloeopsis fritschii TISTR 8547	
	Hapalosiphon intricatus TISTR 8227	
	Nostoc hatei TISTR 8405	
	Nostoc microscopicum TISTR 8664	
	Nostoc muscorum TISTR 8164	
	Nostoc muscorum TISTR 8871	
	Nostoc piscinale TISTR 8180	
	Nostoc sp. TISTR 9131	
	Oscillatoria sp. TISTR 8623	
	Phormidium sp. TISTR 8462	
	Phormidium sp. TISTR 8640	
	Tolypothrix distorta TISTR 8985	
Polyhydroxyvalerate (PHV)	*Anabaena cylindrica* 10 C	Lama et al. (1996)

4. Potential applications of cyanobacteria in cosmetics and skin care products

Despite the different technological applications of cyanobacteria, including the different pharmacological applications resulting from different species of cyanobacteria, there are many molecules that work on the skin as well, due to the fact that these species have the ability to renew their cells and protect themselves from external influences (environmental conditions), (Mourelle et al., 2015). Cyanobacteria produce by-products that may be used in the manufacture of personal care and cosmetic products, and they need further study on their mechanisms of action (Borowitzka 1995; Mourelle et al., 2017). Cosmetics aim to improve the morphology, structure and appearance of the skin by using active ingredients that have the ability to adapt to different skin types, and protect the skin from physical and chemical factors such as ultraviolet (UV) radiation, xenobiotics and, desiccation, which are among the major factors for flogging deterioration and aging (Mourelle et al., 2017; Morone et al., 2022b). Although the aging process is a natural physiological phenomenon, it may occur in an accelerated manner due to many mechanisms such as oxidative stress, which occurs because of free radicals, which causes of chemical havoc resulting from its high reactivity.

The production of phycobiliproteins (PBP), carotenoids, scytonemin (SCY), and phenolic compounds that are essential to the skin and makes these organisms important in the field of skin care. The aforementioned molecules play a significant role in anti-aging, because of their ability to protect against sunlight and their ability to act as antioxidants, in addition to their capability to produce enzymes that inhibit the degradation of the extracellular matrix (Morone et al., 2019; Favas et al., 2021).

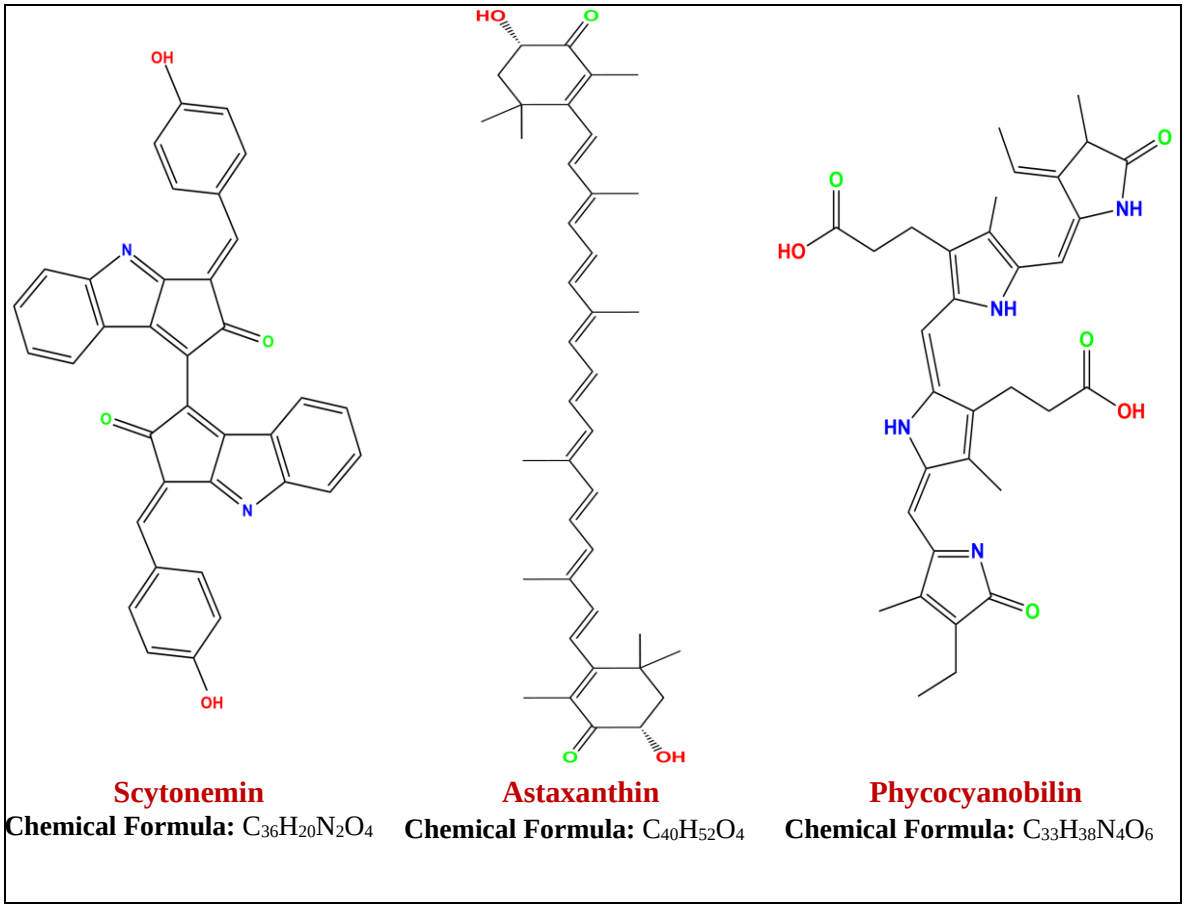

Fig. 6. Structure some carotenoids compounds produced by cyanobacteria

Cosmetics cover a large of these products such as anti-aging products (Morone et al., 2022a), UV protection (Martins et al., 2022), and skin moisturizing creams (Nowruzi, 2022b). Many current studies have focused on the active molecules in cyanobacteria and their potential in cosmetics, including the production of carotenoids, which act as antioxidants. Carotenoids are produced by some genera of cyanobacteria such as *Wollea*, *Synechocystis* and *Leptolyngbya* (Morone et al., 2019; Nowruzi et al., 2020b), and in the treatment of psoriasis by some genera such as *Leptolyngbya* and *Alkalinema aff. pantanalense*, *Nodosilinea antarctica*, *Cuspidothrix issatschenkoi* and *Cyanobium gracile* (Lopes et al., 2020). Cyanobacteria also produce active compounds belonging to the PBP family, which is a group of fluorescent proteins of different colors that produce various compounds including phycoerythrin (PE) and are produced from genera and species such as *Spirulina platensis* (Kamble et al., 2018), *Nostoc* sp. (Nowruzi et al., 2020a), *Halomicronema* (Patel et al., 2022), *Phormidium* sp. (Sonani et al., 2018) and *Microcystis aeruginosa* (Tanabe and Yamaguchi, 2018).

The PBP family also produces a pigment called phycocyanin (PC), which is produced by some genera and species cyanobacteria such as *Synechococcus* sp. (Lin et al., 2022), *Plectonema* sp. (Husain et al., 2021), *Spirulina platensis* (Gabr et al., 2020), *Arthrospira* sp. (Chentir et al., 2019), *Plectonema boryanum* (Mahfooz et al., 2017), *Geitlerinema* sp. H8DM (Patel et al., 2018), *Euhalothece* sp. (Mogany et al., 2018), *Cyanobacterium aponinum* PCC 10605 (Lin and Ng, 2021), *Leptolyngbya valderiana* (Maity and Mallick, 2023), *Pseudanabaena limnetica* (Tribhuvan et

al., 2023), and *Desertifilum tharense* UAM-C/S02 strain (Hernández–Martínez et al., 2023). A bioactive compound called allophycocyanin is also produced by cyanobacteria that include *Anabaena* sp. PCC (Ducret et al., 1998), *Phormidium* sp. A09DM (Sonani et al., 2015), and *Lyngbya* sp. A09DM (Rastogi et al., 2015). Furthermore, there is a phycoerythrocyanin (PEC) compound produced by cyanobacteria such as *Mastigocladus laminosus* (Duerring et al., 1990), *Westiellopsis prolifica* (Sai et al., 1993), *Anabaena variabilis* (Zhang et al., 1997), and *Leptolyngbya* sp. PCC 6406 (Hirose et al., 2019).

Cyanobacteria posses the ability to produce potentially active antioxidizing colorings compounds, which are utilized in cosmetic manufacture as natural pigments and cosmetic antioxidants. The pigments represent carotenoids (**Fig. 6**) such as astaxanthin from the genus *Synechocystis* sp. PCC 6803 (Shimada et al., 2020), and blue pigments phycocyanobilin from the genus *Spirulina*, which can be used in the manufacture of cosmetics such as lipsticks and eyeliners (Hamed, 2016). Many studies have documented the ability of scytonemin as an antioxidant compound, which is a carotenoid compound produced by cyanobacteria such as *Nostoc commune* (Venckus et al., 2018), *Scytonema* sp. R77DM (Rastogi et al., 2014), *Rivularia* sp. HKAR-4 (Rastogi et al., 2013), *Lyngbya* sp., (Fuentes-Tristan et al., 2019), *Leptolyngbya mycodia* (Naeimpoor and Sheibani Madrahi, 2022), and it can be used as a UV protection (cosmetic sunscreen).

Conclusions

Cyanobacteria are found in many aquatic ecosystems and adapt to live in various conditions, as they are distributed everywhere in the world, in addition to being plain to grow and maintain in the laboratory and under minimal conditions of nutritional requirements. As a result of the many characteristics of cyanobacteria, they are considered a promising candidate for the production of a large assortment of bioactive compounds. Cyanobacteria are used in many biotechnological applications due to their being a very attractive choice in the production of secondary metabolites. Many bioactive compounds have been isolated and extracted and have been identified such as antioxidants, antimicrobials, anticancer, antivirals, anti-UV, anti-aging, and anti-toxins. In recent years, cyanobacteria have been utilized in many applications, as they have been used in agricultural applications for the production of biofertilizers, in the treatment and reduction of pollutants due to their being environmentally friendly, in the exploration of many medicines and cosmetics, in the production of biofuels, and in the manufacture of nutritional supplements, vitamins and fodder. Therefore, efforts and research must be intensified to achieve high-quality products from cyanobacteria through biotechnological methods.

Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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