**CYANOBACTERIA, A TOOL FOR PLANETARY ENGINEERING**

Merin Ann Ninan1, Merin Grace Jiji1, Thomas Valukattil Ponnachen1, Sabu Thomas2 and Binoy Thundiathu Thomas1,3

Merin Ann Ninan1, Research scholar, Department of Botany, Catholicate College Pathanamthitta, [merinann93@gmail.com,](mailto:merinann93@gmail.com,%209562400870) Orcid Id- 0000-0001-6714-017X.

Merin Grace Jiji1, Research scholar, Department of Botany, Catholicate College Pathanamthitta, Kerala-689645, India, merinjiji95@gmail.com Orcid Id- 0000-0002-1990-8292

Thomas Valukattil Ponnachen1, Assistant Professor & Research Guide, Department of Botany, Catholicate College, Pathanamthitta, Kerala, India,689645, [amomum@gmail.com](mailto:amomum@gmail.com) Orcid Id-0000-0003-3673-4535

Sabu Thomas2, Professor of polymer science and Engineering, School of chemical science and Director international and inter-university centre for Nano-science and Nano-technology, Mahatma Gandhi University, Priyadarsini Hills, Kottayam, Kerala, India, [sabuthomas@mgu.ac.in](mailto:sabuthomas@mgu.ac.in), Orcid Id-0000-0003-4726-5746

Binoy Thundiathu Thomas**1\*** Head and Research Guide, Department of Botany, Catholicate College, Pathanamthitta, Kerala, India,689645, [bttkripa@gmail.com](mailto:bttkripa@gmail.com) Orcid Id-0000-0002-3517-2246

1.Phycotechnology Lab, Department of Botany, Catholicate College, Pathanamthitta

2. Polymer science and Engineering, School of chemical science and international and inter-university centre for nano-science and nano-technology, Mahatma Gandhi University, Priyadarsini Hills, Kottayam, Kerala, India

3.Corresponding Author: Binoy Thundiathu Thomas1\* Head and Research Guide, Department of Botany, Catholicate College, Pathanamthitta, Kerala, India,689645. Email id-bttkripa@gmail.com, Mobile Number- 9447087024, Orcid Id-0000-0002-3517-2246, Fax number-+91468 232 5223.

**Abstract**

Cyanobacteria, the prokaryote played a pivotal role in the formation of present-day earth. During the null and void times of earth with extreme climatic conditions there could be traced the presence of cyanobacteria and their mode of survival includes a number of reasons which is being discussed in detail through this paper. This review details into cyanobacterial evolution of photosynthesis and its stress adaptations and avoidance mechanisms. Furthermore, details into the key cause for evolution of life forms in the initial earth.

**Key words**: Evolutionary ecology, Cyanobacteria, Adaptations, Mars, Survival strategies, Stress avoidance mechanisms, Photoprotective substances, life beyond earth

**1.Introduction**

Rothman (2017) notes that Earth survived catastrophic events before the evolution of life. Changes in atmospheric gases, climate, and the emergence of photosynthesis were correlated with the presence of oxygen (Kump, 2008). The "Great Oxygenation Event" was a prerequisite for these rapid events (Lyons et al., 2014), and cyanobacteria have been advocated as an ancient terrestrial form of life since primordial times (Drews, 2011; DiGregorio, 2007). The earliest fossil record of cyanobacteria dates back 3.5 million years, during the Precambrian period, and they likely played a significant role in producing oxygen in the atmosphere due to their photosynthetic capabilities (Schopf, 2000).

The viewpoint that cyanobacteria are an ancient form of terrestrial life is further substantiated by well-established algal fossil records, such as *Eosynechoccus amadeus* Hofmann 1976, the unicellular Cyanobacteria *Gloeothece coerulea* Geitler nom.rejic.1928, and silicified fossils of *the Palaeopleurocapsa* genus (Willmer and Rasser, 2022; Knoll, 2008). Additionally, cyanobacteria's wide range of tolerance in toxic environments (Parikh et al., 2006), exposure to ultraviolet radiation (Sinha et al., 1996), ability to thrive in Mars-like conditions (Baque et al., 2013), hot springs (Bhakta et al., 2016), saline and hypersaline environments (Sorensen et al., 2005a) further corroborate their primordial presence. Furthermore, their presence in ice-based ecosystems (Makhalanyane et al., 2015; Quesada and Vincent, 2012) and warmer deserts (Nienow, 2009) make them of particular interest.

Extensive reports have documented the presence of blue-green algae in the McMurdo ice shelves of Antarctica. *Phormidium frigidium* F.E.Fritsch 1912, *Phormidium murrayi* (West and G.S.West) Anagnostidis & Komarek.1988, and *Oscillatoria priestleyi* West and G.S.West 1911 are among the strains identified (Quesada and Vincent, 2012; Vincent, 2000; Vincent and Quesada, 1994). These strains have an optimum temperature that is higher than their existing environment, suggesting they may be cryosensitive but not cryotolerant. Additionally, approximately 250 strains of *Chroococcidiopsis* sp. have been identified in desert environments, including the Atacama Desert and Rose desert of McMurdo Dry Valley, Antarctica, which have been identified as Mars analogues due to their environmental conditions of cold and aridity (Warren-Rhodes et al., 2006). Mars analogues are simulated regions on Earth where one or more physiological factors are similar to those on Mars (Leveille, 2014).

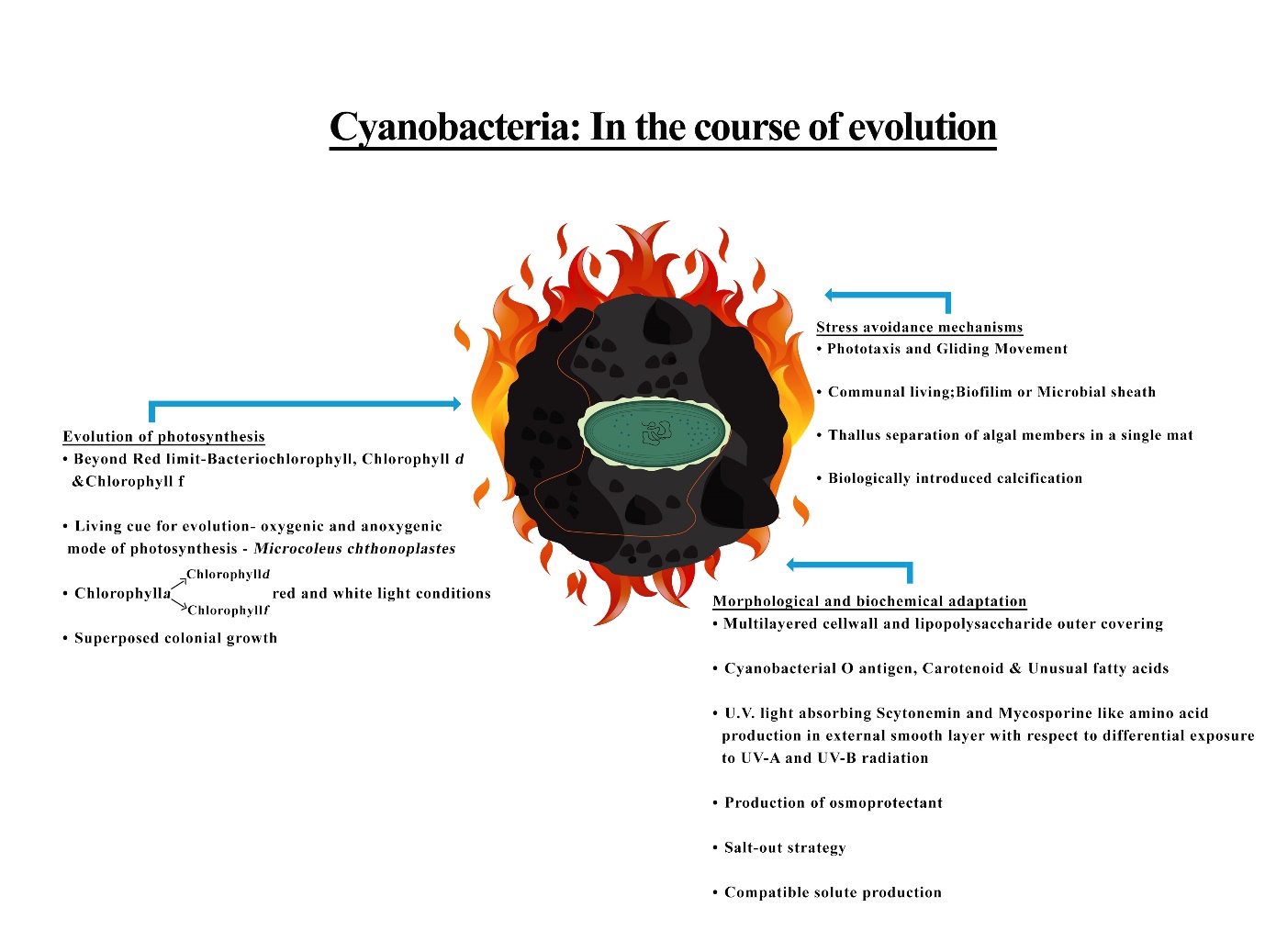
The secret behind the adaptations of cyanobacteria to hostile environments and the rapidity of these adaptations remain unknown. Nevertheless, due to their billion years of evolution, cyanobacteria are considered to be the primary ancestors that independently originated life (Kulasooriya, 2011), which may have allowed them to develop adaptability to a broad range of harsh environments. Terrestrial algae are likely the most advanced group of algae, as their niches often experience frequent fluctuations in climatic factors like humidity, light, and temperature, in contrast to the more stable conditions of aquatic ecosystems. As such, they possess various biochemical and physiological adaptations, including changes in their structure and pigment pattern (Fritsch, 1922), reductions in growth (Warren-Rhodes et al., 2006), and changes in the cellular composition of macromolecules (Rindi, 2011). This review aims to shed light on the mechanisms of evolution and adaptation of terrestrial algae and provide examples of their ability to survive or even thrive in extreme niches.

**2. The key cause for formation of life on earth**

Questions related to the origin of earth is unresolved. It’s still suspicious among gravitational theory, gaseous hypothesis, nebular hypothesis, supernova, inter stellar, planetesimal hypothesis(Halliday A & Canup R, 2023). The key factor which mediates adaptation of first evolved life form in the molten initial days of earth is unaware. This review put forth a hypothesis for unearthing the key cause for evolution of life on earth. The very first hydrogen coated thermophilic cyanobacteria had survived under the extreme gravitational force, temperature and pressure of initial earth.

Molten lava could be a portion of earth’s interior core where rise and decline in temperature experience at different regions. In this heterogenous pressure, temperature condition thermophilic cyanobacteria would have found a habitable environment.

Molecular, biochemical and structural data of nitrogenase and hydrogenase enzymes contributed to the hydrogen metabolism by cyanobacteria. As the cyanobacteria possess key enzymes of hydrogen production ie is, nitrogenase; catalysing the reduction of nitrogen to ammonia with simultaneous production of hydrogen, uptake hydrogenase which take up hydrogen produced by nitrogenase and bidirectional hydrogenase for the uptake and release of hydrogen, this particular gas is the life promoting factor of thermophilic cyanobacteria in the initial earth(Tamagnini et al., 2002). There is a possibility of hydrogen to be the primary light element in the earth’s core (Hallsworth et al., 2023). The hydrogen gas is a poor conductor of heat and electricity(Schiller R, 2022), so the spongy covering of hydrogen gas is a protective covering for life in the initial earth. Other than conductivity, hydrogen gas is a radioprotectant and also non-toxic(Hu et al., 2020).The spongy covering became a favourable condition for the growth and survival of cyanobacteria. Other than hydrogen coating, additional adaptations that enables survival of cyanobacteria is reviewed shortly below (FigureⅠ).



**2.1 Evolution of photosynthesis**

To commence photosynthesis in the anoxygenic condition of ancient earth, cyanobacteria utilized molybdenum, sulfur or iron as the electron donor (Stal, 2012). The presence of mass-independent fractionation of sulfur and molybdenum isotopes in sedimentary rocks is indicative of anoxygenic photosynthesis mediated by these elements (Arnold et al., 2004; Watanabe et al., 2009). An ancestral bacterium that oxidizes hydrogen peroxide by bacteriochlorophyll containing reaction centers may have been a precursor to oxygenic photosynthesis, as proposed by scientists (Blankenship and Hartman, 1998). In *Microcoleus chthonoplastes* Thruet ex Gomont 1892, both oxygenic and anoxygenic modes of photosynthesis have been reported, which could be a living evidence for the evolution of photosynthesis (Jorgensen et al., 1986; Stal, 2012).

As oxygen started to accumulate in the Earth's atmosphere, greenhouse gases like methane gradually reduced (Zahnle et al., 2006; Pavlov and Kasting, 2002). Anoxygenic photosynthesis can be considered a prerequisite for reducing toxic gases, changing the potential of elements in the Earth, and depositing organic carbon. Photosynthetic organic molecules fixed in the thallus may become a part of humus when it decays, and the accumulation of layers of humus and sediments might have contributed to the weathering of rocks.

Cyanobacteria display diversity in their adaptation to light, which is attributed to the functional variation of their photosynthetic pigments. Chlorophyll is the pigment that becomes photochemically excited at the red limit of photosynthesis, between 680-700 nm (Lal, 2018). During the early stages of the Earth's history, the sun gradually increased its brightness (Gudel, 2007). At that time, cyanobacteria may have been exposed to low-frequency radio waves, infrared radiation, and visible light outside of the optical range, specifically 700-760 nm. It is unclear how chlorophyll a, b, and c functioned in such low-intensity light. Perhaps, under these conditions, cyanobacteria evolved pigments that absorb long-wavelength and low-energy light, such as chlorophyll d and f (Allakhverdiev et al., 2016).

*Acaryochloris marina* Miyashita and Chihara 2003, a unicellular cyanobacterium, has been found to have extended photosynthetic efficiency by containing 97% of chlorophyll d and only a small amount of chlorophyll a in one or two key positions (Loughlin et al., 2013; Miyashita et al., 2014). This species has been reported from various habitats such as coastal basins, Antarctic saline habitats, epilithic microbial mats on rocks, and as an epiphyte on red algae *Ahnfeltiopsis flabelliformis* (Kashiyama et al., 2008; Murakami et al., 2004). Chlorophyll d, with an absorption maximum at 711 nm, allows for photosynthesis beyond the red limit of photosynthesis (Chen et al., 2010), and thus can be considered an adaptation of this algae in terrestrial ecosystems. Similarly, cyanobacteria such as *Leptolyngbya* strain JSC1, Cyanobacteria strain KC1, and *Halomicronema hongdechloris* Chen, Li, Birch, and Willows 2012 carry out oxygenic photosynthesis in the near-infrared region due to their ability to use the red-shifted chlorophyll f pigment, which has an absorption range from 700-760 nm (Gan et al., 2015; Miyashita et al., 2014; Nurnberg et al., 2018; Trampe et al., 2020).

In cyanobacteria, the differential production of pigments is also influenced by environmental changes. For example, in Halomicronema hongdechloris Chen, Li, Birch, and Willows 2012 and cyanobacteria strain KC1, the ratio of chlorophyll f to chlorophyll a increased when cultures grown under white light were transferred to red light, while the ratio decreased when transferred from far red light to white fluorescent light (Chen et al., 2012; Miyashita et al., 2014). This pigment remodelling process can be considered an adaptation. Chlorophyll d and f are produced from chlorophyll a by oxidation, but their interconversion to chlorophyll a has not yet been discovered (Koizumi et al., 2005; Zahnle et al., 2006). It is possible that photoreceptors such as phytochromes or bacterial bicomponent signal transduction systems sense critical changes in sunlight and initiate the production of chlorophyll d and f.

*Chlorogloeopsis fritschii* A.K. Mitra and D.C. Pandey 1967 is known for its predominant level of adaptation through microsporine-like amino acids, in addition to chlorophyll d and f. Halder (2017) reported that this cyanobacterium grows in irregular superposed packets of colony, which acts as a self-shielding adaptation where cells on the periphery protect the underlying cells, creating an environment without visible light. This adaptation might be necessary for the proper functioning of chlorophyll d and f, as reported by Airs et al. (2014). Soil algae are more likely to be exposed to UV light, and *C. fritschii* synthesizes UV light-absorbing pigment in the form of microsporine-like amino acids, as observed in *Chlorogloeopsis* sp. PCC 6912 (Portwich and Garcia-Pichel, 1999).

Singh et al. (2010) utilized bioinformatics tools such as ORF finder and BLAST to analyze the genes responsible for the biosynthesis of microsporine-like amino acids (MAAs). The complete sequences of four species - *Anabaena* sp. PCC 7120, *A. variabilis* PCC 7937, *Synechocystis* sp. PCC 6803, and *Synechococcus* sp. PCC 6301 - were used for comparative analysis. The genes of interest were identified, and their nucleotide sequences were translated into corresponding amino acids using the ORF. A similarity search for related proteins was then conducted using BLAST, and phylogenetic trees were constructed.

Their analysis revealed that the unique combination of DHQS gene (YP\_324358) and O-methyltransferase gene (YP\_324357) responsible for the biosynthesis of MAAs was present only in *A. variabilis* PCC 7937, and not in the other three species. Moreover, during the phylogenetic analysis, the present study revealed evidence of horizontal gene transfer from cyanobacteria to dinoflagellates and from there to metazoa, which suggests the evolution of these genes from cyanobacteria to other organisms through the plastidic line.

**2.2 Stress avoidance mechanisms**

During pioneer establishment on earth, they might have evaded stress conditions initially through avoidance mechanisms rather than resisting it. Phototaxis and gliding movement, the formation of microbial mat, individual thallus separation within algal mat are few stress avoidance mechanisms exhibited by the majority of cyanobacteria in the order Oscillatoriales.

*2.2.1Phototaxis and gliding movement*

Cyanobacteria are capable of phototaxis. *Synechocystis* sp. PCC6803 has a captivating phototaxis mechanism. They exhibit positive phototaxis movement towards light source whereas negative phototaxis away from deleterious ultraviolet light (Chau et al., 2015; Kim, 2017)driven by type IV Pili (Z. Chen et al., 2020) and further assessment of physiology or evolution behind phototaxis have pointed out either it may be changed in the direction of gliding movement as in *Phormidium uncinatum* Gomont ex Gomont 1892 (Carlos Tamulonis, 2011) or an inherent ability of all cells in the trichome to sense light like *Anabaena variabilis* Kutzing ex Bornet and Flahault 1886 which bend their trichome to U-shape in the direction of sunlight.(G. Choi et al., 2012)

Locomotion of cyanobacteria those lacking the flagella is confusing! Though flagellar movement is impossible, instead they glide on the surface. The fact that gliding rate could be influenced by wavelength (Kim, 2017) and the direction of light (J. S. Choi et al., 1999) calls into question the mechanism of gliding. This mechanism in *Oscillatoria princeps* Vaucher ex Gomont 1892 that “gliding is produced by unidirectional waves of bending which act against substrate thus displacing trichome” (Halfen Lawrence & Castenholz, 1970)whereas one school of thought is polysaccharide extrusion through junctional pore is responsible for this movement in *Phormidium uncinatum* Gomont ex Gomont 1892 and *Anabaena variablis* Kutzing ex Bornet and Flahault 1886(Hoiczyk & Baumeister, 1995)

*2.2.2 Biofilim or Microbial sheath*

One of the common stress avoidance mechanisms is communal living of members of different taxa into a microbial film or mat usually appear as certain laminated structures, few of their reports in extreme climatic conditions are Arctic (Quesada et al., 1999), saline (Sorensen et al., 2005b) and rice field (Sinha & Hader, 1996). Microbial mat of unicellular algae is reported in hypolithic rocks and caves (Stal, 2012) but filamentous colonial form like *Microcoleus chthonoplastes* Thuret ex Gomont 1892 become dense entangled mass on intertidal zone (Stal et al., 1985). Microbial mat manifest them firmly on exposed surface in spite of wave energy. Similarly, *Crinalium epipsammum* Winder, Stal & Mur 1992, a terrestrial cyanobacteria of filamentous habit, is reported from moving sand and sand dune. Microbial crust of *C.epipsammum* safeguard sand dune from erosion; (Mikhailyuk et al., 2019). In *Rivularia periodica* obenluneschloss,1991 shows tan coloured laminations on rocks, their crust contributes to biologically introduced calcification. The extra polymeric substances and sheath morphology changes with climate, so variation in calcification pattern observed in different climates (Willmer & Rasser, 2022).

Cyanobacterial members have their own preferred niches in this mat. For example, algal mat from mangrove sandy soil, in which a top layer of brownish coloured *Lyngbya aestuarii* Liebman ex Gomont 1892 and lower layer inhabited by *Microcoleus chthonoplastes* Thruet ex Gomont 1892, where former produce ultraviolet (UV) absorbing pigment that is scytonemin and latter get protected by virtue of overlying thallus (Karsten et al., 1998). Individualist thallus separation also observed in algal mat of Mc Murdo Iceshelf Antartica, *Oscillatoria priestleyi* West and G.S.West 1911, may be regarded as stress avoiders owing to their gliding locomotion even to low concentration of ultraviolet (UV) A and ultraviolet (UV) B and they may migrate to depth of mat. *Phormidium murrayi* (West ad G.S.West) Anagnostidis & Komarek 1988 are reported in the upper layers of this algal mat. They are nonmotile but nevertheless they are resistant to high energy radiation (Quesada & Vincent, 1997). In short, cyanobacteria in terrestrial habitat evolved to be in microbial mat for evading desiccation, ultraviolet (UV) light and so on.

**2.3 Morphological and biochemical adaptation**

*2.3.1 Adaptation in the cell envelop*

May be before the evolution of oxygenic photosynthesis, the absence of ozone layer might have forced cyanobacteria to adapt extreme ultraviolet (UV) radiation by making up a unique cell envelop. Even today, sustenance of these adaptations has contributed in withstanding the ultraviolet (UV) radiation on the terrestrial habitat where tolerance to desiccation is the only mean to survive. The colonization of terrestrial algae involves frequent encounter to harsh environment so thicker the envelop they produce better their adaptation to desiccation

Cell wall characteristics of both gram-positive and gram-negative envelope meld together in cyanobacterial envelop (Bertocchi et al., 1990). According to (Hoiczyk & Baumeister, 1995), cell wall of gram-positive bacteria is multi layered with thickness ranging from 20 to 40 nm where as in gram- negative bacteria peptidoglycan layer is relatively thin ranging from 2 to 6 nm. The *Phormidium uncinatum* Gomont ex Gomont 1892 cell envelop thickness ranges from 15 to 35 nm and *Oscillatoria princeps* Vaucher ex Gomont 1892 has a diameter of more than 700 nm. Even though cyanobacteria possess cell wall thickness similar to gram positive bacteria, the former has a composition which is similar to gram-negative bacteria as it possesses an outer membrane and also lacks a typical component of gram-positive bacteria, that is the teichoic acid (Silhavy et al., 2010); (Hoiczyk & Hansel, 2000).

Lipopolysaccharide outer membrane, a unique feature of gram-negative bacteria is found in cyanobacteria. It is a straight double track structure with uniform width of 6 to 8 nm in *Phormidium uncinatum* Gomont ex Gomont 1892 (Hoiczyk, 1998). In addition to cyanobacterial o antigen, *Synechococcus* PCC6716 they also contain carotenoids, unusual fatty acids such as beta hydroxy palmitic acid which are anchored to underlying peptidoglycan (Schrader et al., 1981). Carotenoids protect cyanobacterial cell from high light intensity, particularly ultra violet (UV) range.

Cyanobacteria synthesis diverse external carbohydrate structures in response to different environment stimuli to retain cellular water. (Plude et al., 1991)) reported pectin like polymer composed of 83% galacturonic acid synthesized by *Microcystis flos-aquae* C3-40. Similarly, *Phormidium uncinatum* Gomont ex Gomont 1892 and *Nostoc commune* Vaucher ex Bornet& Flahault,1886 sheath contain cellulose like homoglucan fibrils cross linked by minor monosaccharides (Hoiczyk, 1998); (Inoue-Sakamoto et al., 2017). Occurrence of different extra cell wall layers with specific function had reported in *Phormidium uncinatum* Gomont ex Gomont 1892*.* Cyanobacteria has an adaptation in switching their polysaccharide biosynthesis to different environment stimuli.

In *Nostoc commune* Vaucher ex Bornet & Flahault,1886 production of scytonemin and an oligosaccharide happens on differential exposure to UV Aand UV-B (Ehling-Schulz et al., 1997). ultraviolet (UV) A induces scytonemin biosynthesis whereas ultraviolet B induces Oligosaccharide mycosporine like amino acids so they suggest the existence of distinct photoreceptors that signals biosynthesis of these two pigments. Cell envelop of *Nostoc carneum* C.Agardh ex Bornet & Flahault 1886 possess reducing or antioxidant activity (Hussein et al., 2015). *N.commune* which contain aromatic pigments like scytonemin (Proteau et al., 1993) and oligosaccharide mycosporine like amino acids in the external smooth layer (Nazifi et al., 2015).

Scytonemin also has sun screening action in blue green algae (Rozema et al., 2002), and is isolated exclusively from extracellular sheath of cyanobacteria (Wada et al., 2013). Scytonemin is produced from intermediate compounds of shikimate pathway so this protective compound most likely to be appeared later in evolution (Derikvand et al., 2017); (Simeonov & Michaelian, 2019). *N.commune* colonies can be desiccated even for 87 years (Cameron, 1962) and those attached on sun-exposed faces of rocks are darker in colour because of scytonemin. The pigment profile of cyanobacterial crust isolated from desert samples reported that scytonemin concentration was elevated 2 to 6 times than chlorophyll *a* and lutein was also higher than chlorophyll *a* (Abed et al., 2010). In cyanobacteria, ultraviolet A radiation and scytonemin production are not distinct events, rather both of them occurred as a single cascade of events (Soule et al., 2016); (Pathak et al., 2019). Efficacy of scytonemin present in *Chlorogloeopsis* sp. strain 0-89-cgs is proven after photobleaching it with high ultraviolet-A radiation. Though radiation inhibited photosynthesis and detained growth in this terrestrial cyanobacterium, deposition of scytonemin on cyanobacterial sheath accustomed photosynthesis and growth, thus becoming resistant to photobleaching in due course(Garcia‐Pichel et al., 1992).

*2.3.2 Salinity and Osmotic stress*

Blue green algae are diverse with respect to the mechanism they evolved in stress condition especially under salinity and the accompanying osmotic stress. Halophilic archaea and bacteria adapt to saline condition by salt in strategy that is accumulation of large number of inorganic ions in the cytoplasm (Rodriguez-Valera, 1993). Biomolecules of these evolved strains are resistant to denaturation and they carry out their physiological function even under high ion concentration (Bayley & Morton, 1978)(Muller & Oren, 2003)

Most organism including cyanophyceae evolved salt out strategy. This strategy has got different interpretations. One of the explanations is that they accumulate osmo-protectant initially and in the latter phase inorganic ions are transported across electrochemical gradients into cytoplasm (Pade & Hagemann, 2015). Other explanation is that, the excess ions in the cytoplasm are excluded by dint of Na+ Cl- pumb, Na+ H+ antiporters, Cl-/H+ antiporters and Na+ ATPases. In *Aphanotheca halophytica* Fremy 1993, *Synechocystis* sp.PCC 6803, *A. marina* justify exclusion of ions from blue green algal cells (Fukaya et al., 2009)(Elanskaya et al., 2002) ;(Tsunekawa et al., 2009) ;(Wang et al., 2002)(Brown, 1976; Weinisch et al., 2018). Regarding salt out strategy, cyanobacteria exclude salt ions from the cytoplasm prior phase and simultaneously accumulate compatible solute.

The Compatible solute concept was proposed by Brown (Brown, 1976). These low molecular compounds can be considered as the chemical chaperone of cells under multiple stress factors such as ultraviolet (UV) radiation, dehydration, high and low temperature, salt and pH. Cyanobacteria under saline stress in accordance with their compatible solutes had been assembled into three groups(Reed et al., 1986): low salt tolerant species such as *Nostoc* sp. PCC 7120 accumulating sucrose and or trehalose, moderate salt tolerant species similar to *Synechocystis* sp. PCC 6803 which synthesis glucosyl glycerol and third halophilic strains like *A. halophytica* which prefers glycine betaine (Erdmann, 1983); (Erdmann et al., 1992); (Pade & Hagemann, 2015) (Fulda et al., 1999).

Sucrose and trehalose considered as a general osmo-protectant to desiccation and salinity, in *N. muscorum* on the top of sucrose and trehalose, proline over accumulation enhanced salt tolerance (A. K. Singh et al., 1996), in hyper saline species in addition to glycine betaine, secondary compatible solute such as glutamate betaine reported (Mackay et al., 1984). Generally, genes which codes for the enzyme that synthesise these compatible solutes have been identified however none of the genes which codes for trehalose and glucosyl glycerol have detected in *Microcystis aeruginosa* and *Prochlorococcus* sp. (Klahn et al., 2010); (Pade & Hagemann, 2015). We presume either there may be some multifunctional enzyme that exhibit pleiotropy under salt stress or else there may be some receptors like phytochrome, cryptochrome or bicomponent signalling to initiate biosynthesis of compactable solutes not included in the genome.

There seems an immense disparity between *Synechococcus* and *Synechocystis* species in terms of osmo protectant and adaptation to stress condition though both of them are unicellular cyanobacteria. *Synechocystis* accumulate glucosyl glycerol and is halotolerant (Marin et al., 1998) can with stand elevated concentration of salinity whereas *Synechococcus* accumulate proline and is regarded as salt shocked strain (Fulda et al., 1999). Under majority of the stress condition *Synechoccus* up-regulate the respiratory genes and down-regulate the photosynthetic one. On the contrary, both set of genes are downregulated in the latter (Billis et al., 2014).Physiology and adaptation of cyanobacteria varies with species. In real sense compatible solutes has a cascade of action that varies with species.

**3. Conclusion**

The ability of cyanobacteria to transform the Earth's atmosphere through the production of oxygen is a remarkable feat that has paved the way for the evolution of life as we know it. Moreover, the study of cyanobacteria can potentially provide insights into the possibility of life beyond Earth. Through research and experimentation, it has been shown that some strains of cyanobacteria are capable of surviving in extreme conditions similar to those found on other planets. The potential application of cyanobacteria in terraforming other planets and supporting life in space exploration further highlights their significance in the field of astrobiology. Overall, the study of cyanobacteria and their adaptations provides an interesting avenue for both biotechnology and space exploration**.**

**4. Discussion**

The study of cyanobacteria has been limited due to the lack of resources available for the analysis of their phylogenetic evolution. With only 35 completely sequenced genomes out of approximately 2,500 species, more exploration into genome-level analysis is necessary to identify significant genes that result in the distinct shikimate pathway and mutant development (Nicolaisen et al., 2010). However, bioinformatics applications have the potential to facilitate this research and provide insight into the metabolic processes of cyanobacteria.

The ability of cyanobacteria to thrive in outer space has significant implications for the search for extraterrestrial life. The first EXPOSE-E mission demonstrated the viability of vegetative cells of Chroococcidiopsis sp. under space vacuum and extra-terrestrial ultraviolet spectrum (Cockell et al., 2011; Billi et al., 2011). Further research has been conducted on the desert strain of Chroococcidiopsis in simulated Mars conditions on Earth (Warren-Rhodes et al., 2006) and in the Biofilm Organisms Surfing Space (BOSS) and Biology and Mars Experiment (BIOMEX) of the EXPOSE-R2 mission of Russia (Baque et al., 2013). These developments suggest that interplanetary transport and settlement of life beyond Earth may be possible through the lithopanspermia theory. However, further research is needed to understand the climate of other planets and how algal biotechnology can contribute mutant strains of microalgae that can survive in these conditions.

In addition to facilitating the search for extra-terrestrial life, the study of cyanobacteria also has practical applications. Genome-scale metabolic models can be constructed with a completely annotated genome sequence of cyanobacteria, providing insight into all the possible biosynthesis that occurs within the species (Ducat et al., 2011). Mathematical models can then be used to predict metabolic rates and behaviour, allowing for the development of more efficient and effective biotechnological applications of cyanobacteria.

In conclusion, the study of cyanobacteria has the potential to significantly impact both our understanding of life beyond Earth and our ability to develop practical applications in biotechnology. With further exploration of genome-level analysis and the use of bioinformatics, we can gain insight into the metabolic processes of cyanobacteria and develop models that predict their behaviour. This information can then be used to develop more efficient and effective biotechnological applications of cyanobacteria.

**5.Competing interest**

Authors declare that we have no direct and indirect financial or non-financial interest related to this work.

**6.Conflict of interest**

Authors declare that we have no conflict of interest

**7. Funding Declaration**

Authors declare that we haven’t received no specific grant from any funding agency.

**8. Author Contribution**

Conceptualisation-Merin Ann Ninan and Binoy Thundiyathu Thomas

Writing- Merin Ann Ninan

Concept development

1st session: Merin Ann Ninan

2nd session: Merin Grace Jiji

3rd Session: Merin Ann Ninan and Sabu Thomas

Conclusion and Future Perspective: Merin Ann Ninan and Binoy Thundiyathu Thomas

Final revision- Sabu Thomas

Review & Editing- Thomas Valukkattil Ponnachen, Merin Grace Jiji

**9. References**

Abed, R. M. M., Al Kharusi, S., Schramm, A., & Robinson, M. D. (2010). Bacterial diversity, pigments and nitrogen fixation of biological desert crusts from the Sultanate of Oman. *FEMS Microbiology Ecology*, *72*(3), 418–428. https://doi.org/10.1111/j.1574-6941.2010.00854.x

Airs, R. L., Temperton, B., Sambles, C., Farnham, G., Skill, S. C., & Llewellyn, C. A. (2014). Chlorophyll f and chlorophyll d are produced in the cyanobacterium Chlorogloeopsis fritschii when cultured under natural light and near-infrared radiation. *FEBS Letters*, *588*(20), 3770–3777. https://doi.org/10.1016/j.febslet.2014.08.026

Allakhverdiev, S. I., Kreslavski, V. D., Zharmukhamedov, S. K., Voloshin, R. A., Korol’kova, D. V., Tomo, T., & Shen, J. R. (2016). Chlorophylls d and f and their role in primary photosynthetic processes of cyanobacteria. *Biochemistry (Moscow)*, *81*(3), 201–212. https://doi.org/10.1134/S0006297916030020

Arnold, G. L., Anbar, A. D., Barling, J., & Lyons, T. W. (2004). Molybdenum Isotope Evidence for Widespread Anoxia in Mid-Proterozoic Oceans. *Science*, *304*(May), 87–90. https://doi.org/10.1126/science.1091785

Baque, M., De Vera, J. P., Rettberg, P., & Billi, D. (2013). The BOSS and BIOMEX space experiments on the EXPOSE-R2 mission: Endurance of the desert cyanobacterium Chroococcidiopsis under simulated space vacuum, Martian atmosphere, UVC radiation and temperature extremes. *Acta Astronautica*, *91*(2013), 180–186. https://doi.org/10.1016/j.actaastro.2013.05.015

Bayley, S. T., & Morton, R. A. (1978). Recent developments in the molecular biology of extremely halophilic bacteria. *Critical Reviews in Microbiology*, *6*, 151–205. https://doi.org/10.1007/978-1-4419-1069-1\_8

Bertocchi, C., Navarini, L., & Cesaro, A. (1990). Polysaccharides from Cyanobacteria. *Carbohydrate Polymers*, *12*(2), 127–153. https://doi.org/10.1016/0144-8617(90)90015-K

Bhakta, S., Das, S. K., & Adhikary, S. P. (2016). Algal Diversity in Hot Springs of Odisha. *Nelumbo*, *58*(2016), 157–173. https://doi.org/10.20324/nelumbo/v58/2016/105914

Billi, D., Baque, M., Verseux, C., Rothschild, L., & De Vera, J.-P. (2017). Desert Cyanobacteria: Potential for Space and Earth Applications. In H.Stan-Lotter & S.Fendrihan (Eds.), *Adaption of Microbial Life to Environmental Extremes: Novel Research Results and Application, Second Edition* (Issue March, pp. 1–342). Springer International Publishing AG 2017. https://doi.org/10.1007/978-3-319-48327-6

Billi, D., Viaggiu, E., Cockell, C. S., Rabbow, E., Horneck, G., & Onofri, S. (2011). Damage escape and repair in dried chroococcidiopsis spp. from hot and cold deserts exposed to simulated space and martian conditions. *Astrobiology*, *11*(1), 65–73. https://doi.org/10.1089/ast.2009.0430

Billis, K., Billini, M., Tripp, J. H., Kyrpides, N. C., & Mavromatis, K. (2014). Comparative transcriptomics between synechococcus PCC7942 and synechocystis PCC 6803 Provide Insights into Mechanisms of Stress Acclimation. *PLoS ONE*, *9*(10), 1–10.

Blankenship, R. E., & Hartman, H. (1998). The origin and evolution of oxygenic photosynthesis. *Trends in Biochemical Sciences*, *23*(1991), 94–97. https://doi.org/10.1016/S0968-0004(98)01186-4

Brown, A. D. (1976). Microbial water stress. *Bacteriological Reviews*, *40*(4), 803–846. https://doi.org/10.1128/mmbr.40.4.803-846.1976

Cameron, R. E. (1962). Species of Nostoc Vaucher Occurring in the Sonoran Desert in Arizona. *Transactions of the American Microscopical Society*, *81*(4), 379–384. https://doi.org/10.2307/3223790

Carlos Tamulonis, M. P. and J. K. (2011). *modellin filamentous cyanobaceria reveals avantage of long and fast trichome.pdf* (pp. 1–12).

Chau, R. M. W., Ursell, T., Wang, S., Huang, K. C., & Bhaya, D. (2015). Article Maintenance of Motility Bias during Cyanobacterial Phototaxis. *Biophysical*, *108*(7), 1623–1632. https://doi.org/10.1016/j.bpj.2015.01.042

Chen, M., Li, Y., Birch, D., & Willows, R. D. (2012). A cyanobacterium that contains chlorophyll f - A red-absorbing photopigment. *FEBS Letters*, *586*(19), 3249–3254. https://doi.org/10.1016/j.febslet.2012.06.045

Chen, Min., Schliep, Martin., Willows, R. D., Cai, Z.-Li., Neilan, B. A., & Scheer, Hugo. (2010). A Red-Shifted Chlorophyll. *Science*, *329*(5997), 1318–1319. https://doi.org/10.1126/science.1191127

Chen, Z., Li, X., Tan, X., Zhang, Y., & Wang, B. (2020). Recent Advances in Biological Functions of Thick Pili in the Cyanobacterium Synechocystis sp. PCC 6803. *Frontiers in Plant Science*, *11*(241), 1–10. https://doi.org/10.3389/fpls.2020.00241

Choi, G., Yoon, S., Kim, H., Ahn, C., & Oh, H. (2012). Morphological and Molecular Analyses of Anabaena variabilis and Trichormus variabilis ( Cyanobacteria ) from Korea. *Korean Journal Environmental Biology*, *30*(1), 54–63.

Choi, J. S., Chung, Y. H., Moon, Y. J., Kim, C., Watanabe, M., Song, P. S., Joe, C. O., Bogorad, L., & Park, Y. M. (1999). Photomovement of the gliding cyanobacterium Synechocystis sp. PCC 6803. *Photochemistry and Photobiology*, *70*(1), 95–102. https://doi.org/10.1111/j.1751-1097.1999.tb01954.x

Cockell, C. S., Rettberg, P., Rabbow, E., & Olsson-Francis, K. (2011). Exposure of phototrophs to 548 days in low Earth orbit: Microbial selection pressures in outer space and on early earth. *ISME Journal*, *5*(10), 1671–1682. https://doi.org/10.1038/ismej.2011.46

Derikvand, P., Llewellyn, C. A., & Purton, S. (2017). Cyanobacterial metabolites as a source of sunscreens and moisturizers: a comparison with current synthetic compounds. In *European Journal of Phycology* (Vol. 52, Issue 1, pp. 43–56). https://doi.org/10.1080/09670262.2016.1214882

Drews, G. (2011). The evolution of Cyanobacteria and Photosynthesis. In G. A. Peschek, C. Obinger, & G. Renger (Eds.), *Bioenergetic Processes of Cyanobacteria* (Issue May 2011, pp. 265–284). Springer Science+Business Media. https://doi.org/10.1007/978-94-007-0388-9\_11

Ehling-Schulz, M., Bilger, W., & Scherer, S. (1997). UV-B-induced synthesis of photoprotective pigments and extracellular polysaccharides in the terrestrial cyanobacterium Nostoc commune. *Journal of Bacteriology*, *179*(6), 1940–1945. https://doi.org/10.1128/jb.179.6.1940-1945.1997

Elanskaya, I. V., Karandashova, I. V., Bogachev, A. V., & Hagemann, M. (2002). Functional analysis of the Na+/H+ antiporter encoding genes of the cyanobacterium Synechocystis PCC 6803. *Biochemistry (Moscow)*, *67*(4), 432–440. https://doi.org/10.1023/A:1015281906254

Erdmann, N. (1983). Organic Osmoregulatory Solutes in Blue-green Algae. *Zeitschrift Für Pflanzenphysiologie*, *110*(2), 147–155. https://doi.org/10.1016/s0044-328x(83)80161-5

Erdmann, N., Fulda, S., & Hagemann, M. (1992). Glucosylglycerol accumulation during salt acclimation of two unicellular cyanobacteria. *Journal of General Microbiology*, *138*(2), 363–368. https://doi.org/10.1099/00221287-138-2-363

Fritsch, F. E. (1922). The Terrestrial Alga. *The Journal of Ecology*, *10*(2), 220–236. https://doi.org/10.2307/2255743

Fukaya, F., Promden, W., Hibino, T., Tanaka, Y., Nakamura, T., & Takabe, T. (2009). An Mrp-like cluster in the halotolerant cyanobacterium Aphanothece halophytica functions as a Na+/H+ Antiporter. *Applied and Environmental Microbiology*, *75*(20), 6626–6629. https://doi.org/10.1128/AEM.01387-09

Fulda, S., Huckauf, J., Schoor, A., & Hagemann, M. (1999). Analysis of stress responses in the cyanobacterial strains Synechococcus sp. PCC 7942, Synechocystis sp. PCC 6803, and Synechococcus sp. PCC 7418: Osmolyte accumulation and Stress Protein Synthesis. *Journal of Plant Physiology*, *154*(2), 240–249. https://doi.org/10.1016/S0176-1617(99)80215-6

Gan, F., Shen, G., & Bryant, D. A. (2015). Occurrence of Far-Red Light Photoacclimation (FaRLiP) in Diverse Cyanobacteria. *Life*, *5*(1), 4–24. https://doi.org/10.3390/life5010004

Garcia‐Pichel, F., Sherry, N. D., & Castenholz, R. W. (1992). Evidence for an ultraviolet sunscreen role of the extracellular pigment Scytonemin in the terrestrial cyanobacterium Chlorogloeopsis sp. *Photochemistry and Photobiology*, *56*(1), 17–23. https://doi.org/10.1111/j.1751-1097.1992.tb09596.x

Gudel, M. (2007). The sun in time: Activity and environment. *Living Reviews in Solar Physics*, *4*(3), 1–137. https://doi.org/10.12942/lrsp-2007-3

Halder, N. (2017). Note on taxonomy of Chlorogloeopsis fritschii (Mitra) Mitra et Pandey with soil analysis, collected from a rice field in West Bengal, India. *Our Nature*, *14*(1), 92–98. https://doi.org/10.3126/on.v14i1.16445

Halfen Lawrence, & Castenholz, R. W. (1970). Gliding in a Blue-Green algae; a possible mechanism. *Nature*, *225*(5238), 726–734.

Halliday A, & Canup R. (2023). Accretion of planet Earth. *Nature Reviews Earth & Environment*, *4*, 19–35. https://doi.org/10.1098/rsta.2008.0101

Hallsworth, J. E., Udaondo, Z., Pedrós-Alió, C., Höfer, J., Benison, K. C., Lloyd, K. G., Cordero, R. J. B., de Campos, C. B. L., Yakimov, M. M., & Amils, R. (2023). Scientific novelty beyond the experiment. *Microbial Biotechnology*, *January*, 1–43. https://doi.org/10.1111/1751-7915.14222

Hoiczyk, E. (1998). Structural and biochemical analysis of the sheath of Phormidium uncinatum. *Journal of Bacteriology*, *180*(15), 3923–3932. https://doi.org/10.1128/jb.180.15.3923-3932.1998

Hoiczyk, E., & Baumeister, W. (1995). Envelope structure of Four Gliding filamentous Cyanobacteria. *Journal of Bacteriology*, *177*(9), 2387–2395. https://doi.org/10.1128/jb.177.9.2387-2395.1995

Hoiczyk, E., & Hansel, A. (2000). Cyanobacterial cell walls: News from an unusual prokaryotic envelope. *Journal of Bacteriology*, *182*(5), 1191–1199. https://doi.org/10.1128/JB.182.5.1191-1199.2000

Hu, Q., Zhou, Y., Wu, S., Wu, W., Deng, Y., & Shao, A. (2020). Molecular hydrogen: A potential radioprotective agent. *Biomedicine and Pharmacotherapy*, *130*(110589), 1–8. https://doi.org/10.1016/j.biopha.2020.110589

Hussein, M. H., Abou-Elwafa, G. S., Shaaban-Dessuuki, S. A., & Hassan, N. I. (2015). Characterization and antioxidant activity of exopolysaccharide secreted by nostoc carneum. *International Journal of Pharmacology*, *11*(5), 432–439. https://doi.org/10.3923/ijp.2015.432.439

Inoue-Sakamoto, K., Nazifi, E., Tsuji, C., Asano, T., Nishiuchi, T., Matsugo, S., Ishihara, K., Kanesaki, Y., Yoshikawa, H., & Sakamoto, T. (2017). Characterization of mycosporine-like amino acids in the cyanobacterium Nostoc verrucosum. *Journal of General and Applied Microbiology*, *64*(5), 203–211. https://doi.org/10.2323/jgam.2017.12.003

Jorgensen, B. B., Cohen, Y., & Revsbech, N. P. (1986). Transition from Anoxygenic to Oxygenic Photosynthesis in a Microcoleus chthonoplastes Cyanobacterial Mat. *Applied and Environmental Microbiology*, *51*(2), 408–417. https://doi.org/10.1128/aem.51.2.408-417.1986

Karsten, U., Maier, J., & Gracia-Pichel, F. (1998). Seasonality in UV-absorbing compounds of cyanobacterial mat communities from an intertidal mangrove flat. *Aquatic Microbial Ecology*, *16*, 37–44. https://doi.org/doi:10.3354/ame016037

Kashiyama, Y., Miyashita, H., Ohkubo, S., Ogawa, N. O., Chikaraishi, Y., Takano, Y., Suga, H., Toyofuku, T., Nomaki, H., Kitazato, H., Nagata, T., & Ohkouchi, N. (2008). Evidence of global chlorophyll d. *Science*, *321*(5889), 658. https://doi.org/10.1126/science.1158761

Kim, M. (2017). Phototaxis of cyanobacteria under complex light environments. *MBio*, *8*(2), 8–10. https://doi.org/10.1128/mBio.00498-17

Klahn, S., Steglich, C., Hess, W. R., & Hagemann, M. (2010). Glucosylglycerate: A secondary compatible solute common to marine cyanobacteria from nitrogen-poor environments. *Environmental Microbiology*, *12*(1), 83–94. https://doi.org/10.1111/j.1462-2920.2009.02045.x

Knoll, A. H., & Golubic, S. (1979). Anatomy and Taphonomy of a Precambrian Algal Stromatolite. *Precambrian Research*, *10*(1–2), 115–151. https://doi.org/10.1016/0301-9268(79)90022-6

Koizumi, H., Itoh, Y., Hosoda, S., Akiyama, M., Hoshino, T., Shiraiwa, Y., & Kobayashi, M. (2005). Serendipitous discovery of Chl d formation from Chl a with papain. *Science and Technology of Advanced Materials*, *6*(6), 551–557. https://doi.org/10.1016/j.stam.2005.06.022

Kulasooriya, S. A. (2011). Cyanobacteria: Pioneers of Planet Earth. *Ceylon Journal of Science (Biological Sciences)*, *40*(2), 71–88. https://doi.org/10.4038/cjsbs.v40i2.3925

Kump, L. R. (2008). The rise of atmospheric oxygen. *Nature*, *451*(7176), 277–278. https://doi.org/10.1038/nature06587

Lal, M. A. (2018). Photosynthesis. In *Plant Physiology, Development and Metabolism* (pp. 159–226). Springer. https://doi.org/10.1007/978-981-13-2023-1\_5

Loughlin, P., Lin, Y., & Chen, M. (2013). Chlorophyll d and Acaryochloris marina: Current status. *Photosynthesis Research*, *116*(2–3), 277–293. https://doi.org/10.1007/s11120-013-9829-y

Lyons Timothy W, Reinhard Christopher T, & Planavsky Noah J. (2014). The rise of oxygen in Earth’s early ocean and atmosphere. *Nature*, *506*(7488), 307–315.

Mackay, M. A., Norton, R. S., & Borowitzka, L. J. (1984). Organic osmoregulatory solutes in Cyanobacteria. *Journal of General Microbiology*, *130*(9), 2177–2191. https://doi.org/10.1099/00221287-130-9-2177

Makhalanyane, T. P., Valverde, A., Velázquez, D., Gunnigle, E., Van Goethem, M. W., Quesada, A., & Cowan, D. A. (2015). Ecology and biogeochemistry of cyanobacteria in soils, permafrost, aquatic and cryptic polar habitats. In *Biodiversity Conservation* (Vol. 24, Issue 4, pp. 819–840). Springer Science+Business Media. https://doi.org/10.1007/s10531-015-0902-z

Marin, K., Zuther, E., Kerstan, T., Kunert, A., & Hagemann, M. (1998). The ggpS Gene from Synechocystis sp. Strain PCC 6803 encoding glucosyl- glycerol-phosphate synthase is involved in osmolyte synthesis. *Journal of Bacteriology*, *180*(18), 4843–4849. https://doi.org/10.1128/jb.180.18.4843-4849.1998

Mikhailyuk, T., Vinogradova, O., Holzinger, A., & Glaser, K. (2019). *New record of the rare genus Crinalium Crow (Oscillatoriales, Cyanobacteria) from sand dunes of the Baltic Sea, Germany: epitypification and emendation of Crinalium magnum Fritsch et John based on an integrative approach*. *400*(3), 165–179.

Miyashita, H., Ohkubo, S., Komatsu, H., Sorimachi, Y., Fukayama, D., Fujinuma, D., Akutsu, S., & Kobayashi, M. (2014). Discovery of Chlorophyll d in Acaryochloris marina and Chlorophyll f in a a unicellular Cyanobacterium,Strain KC1, isolated from Lake Biwa. *Journal of Physical Chemistry and Biophysics*, *4*(4), 1–9. https://doi.org/10.4172/2161-0398.1000149

Muller, V., & Oren, A. (2003). Metabolism of chloride in halophilic prokaryotes. *Extremophiles*, *7*(4), 261–266. https://doi.org/10.1007/s00792-003-0332-9

Murakami, A., Miyashita, H., Iseki, M., Adachi, K., & Mimuro, M. (2004). Chlorophyll d in an Epiphytic Cyanobacterium of Red Algae. *Science*, *303*(5664), 1633. https://doi.org/10.1126/science.1095459

Nazifi, E., Wada, N., Asano, T., Nishiuchi, T., Iwamuro, Y., Chinaka, S., Matsugo, S., & Sakamoto, T. (2015). Characterization of the chemical diversity of glycosylated mycosporine-like amino acids in the terrestrial cyanobacterium Nostoc commune. *Journal of Photochemistry and Photobiology B: Biology*, *142*, 154–168. https://doi.org/10.1016/j.jphotobiol.2014.12.008

NdrewKnoll, H. A. (2008). Cyanobacteria and Earth History. In F. Antonia, Herrero and Enrique (Ed.), *The Cyanobacteria: Molecular Biology, Genomics & Evolution.* (Issue June, pp. 1–19). Caister Academic Press, U.K. https://doi.org/https://doi.org/10.21775/9781913652531

Nienow, J. A. (2009). Extremophiles : Dry Environments ( including Cryptoendoliths ). In M. Schaechter (Ed.), *Encyclopedia of Microbiology* (pp. 159–173). Elsevier Inc. https://doi.org/10.1016/B978-012373944-5.00277-7

Nurnberg, D. J., Morton, J., Santabarbara, S., Telfer, A., Joliot, P., Antonaru, L. A., Ruban, A. H., Cardona, T., Krausz, E., Boussac, A., Fantuzzi, A., & Rutherford, W. A. (2018). Photochemistry beyond the red-limit in chlorophyll f -photosystems. *Science*, *360*(6394), 1210–1213. https://doi.org/10.1126/science.aar8313

Pade, N., & Hagemann, M. (2015). Salt acclimation of Cyanobacteria and Their Application in Biotechnology. *Life*, *5*(1), 25–49. https://doi.org/10.3390/life5010025

Parikh, A., Shah, V., & Madamwar, D. (2006). Cyanobacterial flora from polluted industrial effluents. *Environmental Monitoring and Assessment*, *116*(1–3), 91–102. https://doi.org/10.1007/s10661-006-7229-x

Pathak, J., Pandey, A., Maurya, P. K., Rajneesh, R., Sinha, R. P., & Singh, S. P. (2019). Cyanobacterial Secondary Metabolite Scytonemin : A Potential Photoprotective and Pharmaceutical Compound. *Proceedings of the National Academy of Sciences, India Section B: Biological Sciences*. https://doi.org/10.1007/s40011-019-01134-5

Pavlov, A. A., & Kasting, J. F. (2002). Mass-Independent Fractionation of Sulfur Isotopes in Archean Sediments: Strong Evidence for an Anoxic Archean Atmosphere. *Astrobiology*, *2*(1).

Plude, J. L., Parker, D. L., Schommer, O. J., Timmerman, R. J., Hagstrom, S. A., Joers, J. M., & Hnasko, R. (1991). Chemical characterization of polysaccharide from the slime layer of the cyanobacterium Microcystis flos-aquae C3-40. *Applied and Environmental Microbiology*, *57*(6), 1696–1700. https://doi.org/10.1128/aem.57.6.1696-1700.1991

Portwich, A., & Garcia-Pichel, F. (1999). Ultraviolet and osmotic stresses induce and regulate the synthesis of mycosporines in the cyanobacterium Chlorogloeopsis PCC 6912. *Archives of Microbiology*, *172*(4), 187–192. https://doi.org/10.1007/s002030050759

Proteau, P. J., Gerwick, W. H., Garcia-Pichel, F., & Castenholz, R. (1993). The structure of scytonemin, an ultraviolet sunscreen pigment from the sheaths of cyanobacteria. *Experientia*, *49*(9), 825–829. https://doi.org/10.1007/BF01923559

Quesada, A., & Vincent, W. F. (1997). Strategies of adaptation by antarctic cyanobacteria to ultraviolet radiation. *European Journal of Phycology*, *32*(4), 335–342. https://doi.org/10.1080/09670269710001737269

Quesada, A., & Vincent, W. F. (2012). Cyanobacteria in the Cryosphere:Snow,Ice and Extreme Cold. In B. A. Whitton (Ed.), *Ecology of Cyanobacteria II: Their Diversity in Space and Time* (Vol. 9789400738, pp. 387–399). Springer. https://doi.org/10.1007/978-94-007-3855-3

Quesada, A., Vincent, W. F., & Lean, D. R. S. (1999). Community and pigment structure of Arctic cyanobacterial assemblages: the occurrence and distribution of UV-absorbing compounds. *FEMS Microbiology Ecology*, *28*(4), 315–323. https://doi.org/10.1111/j.1574-6941.1999.tb00586.x

Reed, R. H., Borowitzka, L. J., Mackay, M. A., Chudek, J. A., Foster, R., Warr, S. R. C., Moore, D. J., & Stewart, W. D. P. (1986). Organic solute accumulation in osmotically stressed cyanobacteria. *FEMS Microbiology Reviews*, *39*(1–2), 51–56. https://doi.org/10.1016/0378-1097(86)90060-1

Rindi, F. (2011). Terrestrial green algae: Systematics, biogeography and expected responses to climate change. In Trevor R Hodkinso, M. B. Jones, S. Waldren, & John A. N. Parnell (Eds.), *Climate Change, Ecology and Systematics* (pp. 201–228). Cambridge University Press. https://doi.org/10.1017/CBO9780511974540.010

Rodriguez-Valera, F. (1993). Introduction to saline environments. In R. H. Vreeland & L. I. Hochstein (Eds.), *The biology of halophilic bacteria* (Taylor & Fra, Issue September, pp. 1–78). CRC Press Taylor and Francis Group. https://doi.org/10.1201/9781003069140

Rothman, D. H. (2017). Thresholds of catastrophe in the Earth system. In *Science Advances* (Vol. 3, Issue 9, pp. 1–12). https://doi.org/10.1126/sciadv.1700906

Rozema, J., Bjorn, L. O., Bornman, J. F., Gaberscik, A., Hader, D. P., Trost, T., Germ, M., Klisch, M., Groniger, A., Sinha, R. P., Lebert, M., He, Y. Y., Buffoni-Hall, R., De Bakker, N. V. J., Staaij, V. D. J., & Meijkamp, B. B. (2002). The role of UV-B radiation in aquatic and terrestrial ecosystems-An experimental and functional analysis of the evolution of UV-absorbing compounds. *Journal of Photochemistry and Photobiology B: Biology*, *66*(1), 2–12. https://doi.org/10.1016/S1011-1344(01)00269-X

Schiller R. (2022). *A non-traditional guide to physical chemistry : insights using hydrogen | Formats and Editions*. https://www.worldcat.org/formats-editions/1341586991

Schopf, W. J. (2000). The fossil record:Tracing the roots of cyanobacterial lineage. In B. A. W. M.Potts (Ed.), *The Ecology of Cyanobacteria* (pp. 13–35). Kluwer Academic Publishers.

Schrader, M., Drews, G., & Weckesser, J. (1981). Chemical analyses on cell wall constituents of the thermophilic cyanobacterium Synechococcus PCC6716. *FEMS Microbiology Letters*, *11*(1), 37–40. https://doi.org/10.1111/j.1574-6968.1981.tb06930.x

Silhavy, T. J., Kahne, D., & Walker, S. (2010). The bacterial cell envelope. *Philosophical Transactions of the Royal Society B: Biological Sciences*, *370*(1679), 1–17. https://doi.org/10.1098/rstb.2015.0019

Simeonov, A., & Michaelian, K. (2019). Properties of cyanobacterial UV-absorbing pigments suggest their evolution was driven by optimizing photon dissipation rather than photoprotection. *Biological Physics*, *V3*, 1–37.

Singh, A. K., Chakravarthy, D., Singh, T. P. K., & Singh, H. N. (1996). Evidence for a role for L-proline as a salinity protectant in the cyanobacterium Nostoc muscorum. *Plant, Cell and Environment*, *19*(4), 490–494. https://doi.org/10.1111/j.1365-3040.1996.tb00342.x

Singh, S. P., Klisch, M., Sinha, R. P., & Hader, D. P. (2010). Genome mining of mycosporine-like amino acid (MAA) synthesizing and non-synthesizing cyanobacteria: A bioinformatics study. *Genomics*, *95*(2), 120–128. https://doi.org/10.1016/j.ygeno.2009.10.002

Sinha, R. P., & Hader, D. P. (1996). Photobiology and Ecophysiology of Rice Field Cyanobacteria. *Photochemistry and Photobiology*, *64*(6), 887–896. https://doi.org/10.1111/j.1751-1097.1996.tb01852.x

Sinha, R. P., Singh, N., Kumar, A., Kumar, H. D., Hader, M., & Hader, D. P. (1996). Effects of UV irradiation on certain physiological and biochemical processes in cyanobacteria. *Jornal of Photochemistry and Photobiology B:*, *32*(1–2), 107–113.

Sorensen, K. B., Canfield, D. E., Teske, A. P., & Oren, A. (2005a). Community composition of a hypersaline endoevaporitic microbial mat. *Applied and Environmental Microbiology*, *71*(11), 7352–7365. https://doi.org/10.1128/AEM.71.11.7352-7365.2005

Sorensen, K. B., Canfield, D. E., Teske, A. P., & Oren, A. (2005b). Community composition of a hypersaline endoevaporitic microbial mat. *Applied and Environmental Microbiology*, *71*(11), 7352–7365. https://doi.org/10.1128/AEM.71.11.7352-7365.2005

Soule, T., Shipe, D., & Lothamer, J. (2016). Extracellular Polysaccharide Production in a Scytonemin-Deficient Mutant of Nostoc punctiforme Under UVA and Oxidative Stress. *Current Microbiology*, *73*(4), 455–462. https://doi.org/10.1007/s00284-016-1084-y

Stal, L. J. (2012). Cyanobacterial Mats and Stromatolites. In Brian. A. Whitton (Ed.), *Ecology of Cyanobacteria II: Their Diversity in Space and Time* (pp. 1–760). Springer Science+Business Media. https://doi.org/10.1007/978-94-007-3855-3

Stal, L. J., van Gemerden, H., & Krumbein, W. E. (1985). Structure and development of a benthic marine microbial mat. *FEMS Microbiology Ecology*, *31*(2), 111–125. https://doi.org/10.1016/0378-1097(85)90007-2

Tamagnini, P., Axelsson, R., Lindberg, P., Oxelfelt, F., Wünschiers, R., & Lindblad, P. (2002). Hydrogenases and Hydrogen Metabolism of Cyanobacteria. *Microbiology and Molecular Biology Reviews*, *66*(1), 1–20. https://doi.org/10.1128/mmbr.66.1.1-20.2002

Trampe, E., Mosshammer, M., Johnson, M., Larkum, A. W. D., Frigaard, N., & Koren, K. (2020). *Substantial near-infrared radiation-driven photosynthesis of chlorophyll f -containing cyanobacteria in a natural habitat*. 1–15.

Tsunekawa, K., Shijuku, T., Hayashimoto, M., Kojima, Y., Onai, K., Morishita, M., Ishiura, M., Kuroda, T., Nakamura, T., Kobayashi, H., Sato, M., Toyooka, K., Matsuoka, K., Omata, T., & Uozumi, N. (2009). Identification and characterization of the Na+/H+ antiporter NhaS3 from the thylakoid membrane of Synechocystis sp. PCC 6803. *Journal of Biological Chemistry*, *284*(24), 16513–16521. https://doi.org/10.1074/jbc.M109.001875

Vincent, W. F. (2000). Cyanobacterial Dominance in the Polar Regions. In B. A. Whitton & P. M. (Eds.), *The Ecology of Cyanobacteria* (pp. 321–340). Kluwer Academic Publishers. https://doi.org/10.1007/0-306-46855-7\_12

Vincent, W. F., & Quesada, A. (1994). Ultraviolet radiation effects on cyanobacteria: Implications for Antarctic microbial ecosystems. In C. S. Weiler & P. A. Penhale (Eds.), *Ultraviolet radiation in Antarctica: Measurements and Biological effects Antarctic Research Series* (Vol. 62, pp. 111–124). American Geophysical Union. https://doi.org/10.1029/AR062

Wada, N., Sakamoto, T., & Matsugo, S. (2013). Multiple roles of photosynthetic and sunscreen pigments in cyanobacteria focusing on the oxidative stress. *Metabolites*, *3*(2), 463–483. https://doi.org/10.3390/metabo3020463

Wang, H., Postier, B. L., & Burnap, R. L. (2002). Polymerase chain reaction-based mutageneses identify key transporters belonging to multigene families involved in Na + and pH homeostasis of Synechocystis sp . PCC 6803. *Molecular Microbiology*, *44*(6), 1493–1506.

Warren-Rhodes, K. A., Rhodes, K. L., Pointing, S. B., Ewing, S. A., Lacap, D. C., Gómez-Silva, B., Amundson, R., Friedmann, E. I., & McKay, C. P. (2006). Hypolithic cyanobacteria, Dry limit of photosynthesis, and Microbial Ecology in the Hyperarid Atacama Desert. *Microbial Ecology*, *52*(3), 389–398. https://doi.org/10.1007/s00248-006-9055-7

Watanabe, Y., Farquhar, J., & Ohmoto, H. (2009). Anomalous Fractionations of Sulfur. *Science*, *324*(April), 370–373. https://doi.org/10.1126/science.1169289 www.sciencemag.org

Weinisch, L., Ku, S., Roth, R., Grimm, M., Roth, T., Daili, J., Netz, A., Pierik, A. J., & Filker, S. (2018). *Identification of osmoadaptive strategies in the halophile , heterotrophic ciliate Schmidingerothrix salinarum*. 1–29.

Willmer, B. J., & Rasser, M. W. (2022). Calcification patterns of Rivularia-type cyanobacteria: examples from the Miocene of the North Alpine Foreland Basin. *Facies*, *68*(4), 1–21. https://doi.org/10.1007/s10347-022-00654-3

Zahnle, K., Claire, M., & Catling, D. (2006). The loss of mass-independent fractionation in sulfur due to a Palaeoproterozoic collapse of atmospheric methane. *Geobiology*, *4*(4), 271–283. https://doi.org/10.1111/j.1472-4669.2006.00085.x

**Figure caption**

Cyanobacteria;In the course of Evolution- Factors which lead to evolution of life in the hydrogen coated cyanobacteria of initial molten earth