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Exploring the microscopic eyeball of cyanobacteria: A comprehensive review

Mohammed F Haddad [1], Basima A Abdullah [2], Mustafa F Haddad [3], Ali M Saadi [4*]
[1]Medical Laboratory Techniques Department / Mosul Medical Technical Institute / Northern Technical University/ Mosul/ Iraq
[2]Dept. of Biology /College of Science/University of Mosul/ Mosul/ Iraq
[3] M.Sc. In Microbiology
[4*] Techniques, Mosul Medical Technical Institute, Northern Technical University, Mosul, Iraq

* Corresponding Author: **Ali M Saadi**

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Abstract

Cyanobacteria resemble algae in that they contain chlorophyll and then photosynthesize and oxygen is released as a result. Cyanobacteria resemble bacteria in that they are Gram-negative bacteria and their wall consists of peptidoglycan and contain a primitive nucleus and do not contain chloroplasts but membranes called thylakoids that contain the chlorophyll pigment for photosynthesis. Cyanobacteria produce their own energy through photosynthesis, just like plants. Scientists from America said that they made an "energy generator" using a bottle containing bacteria and sewage, and that the efficiency of these "microbes connected to wires" reached 30%, which is equivalent to the efficiency of the best solar cells currently commercially available. The researchers explained in their study, the results of which were published in the Proceedings of the American Academy of Sciences, that it is still necessary to find a suitable metal to manufacture an important part of this small "generator", which is a cathode, which is the electrode of the electrical circuit where the process of reducing electrons occurs, as an alternative to the silver oxide that they currently use. The idea of using bacteria as a source of energy generation is not new, and through this idea, bacteria that live on natural waste can be exploited and release excess electrons through a complex mechanism of cells during this process that leads to the conversion of chemical energy into an electric current. It is expected that water purification plants will be the place for these microbial generators, as public wastewater is rich in natural materials, in addition to the fact that not only will electricity be produced there, but the water will be purified at the same time, which reduces the operating costs of these stations. However.

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Introduction

Cyanobacteria resemble algae in that they contain chlorophyll and then photosynthesize and oxygen is released as a result. They do not have flagella but move by sliding through a gelatinous layer secreted on the surface of the cell. They contain auxiliary pigments called phycobilins, where the blue color is due to phycocyanin, and allophycocyanin, and the red color is due to phycoerythrin

Phycobilins = Phycocyanin + Allophycocyanin + Phycoerthyrine.

Cyanobacteria resemble bacteria in that they are Gram-negative bacteria and their wall consists of peptidoglycan and contains a primitive nucleus and does not contain chloroplasts but membranes called thylakoids that contain the chlorophyll pigment for photosynthesis.

Cyanobacteria do not undergo mitotic or meiotic divisions and do not reproduce sexually. Cyanobacteria produce their own energy through photosynthesis, just like plants. The cyanobacterial cell contains a large number of ribosomes of RNA and proteins, which consist of the 70s type, and are found free in the cytoplasm, in contrast to their counterparts that are found associated with the endoplasmic reticulum in higher algae and plants. * Plankton have gas vacuoles in the form of red granules. Each vacuole consists of hollow, cylindrical membranes that assemble in the shape of a honeycomb called air vesicles. These membranes are composed of protein that is highly permeable to gases but impermeable to water. The main function of gas vacuoles is related to the process of floating and diving, as they are organized into types that represent aquatic blooms on the surface of the water and secrete harmful toxins, including Microcystis. Cyanophycin granules are large particles consisting of stored protein in the form of polypeptides found in abundance in Akinetes. Their quantity varies according to the growth stage of the algae, as they decrease in the exponential growth stage and are high in the stationary stage. Carboxysome contains the enzyme capable of fixing carbon dioxide. Polyphosphate bodies and Volutin granules represent phosphate stores (Vidal *et al.*, 2021) [37]. They play an important role in the mechanism of detoxification by trapping heavy metals. Polyglucan granules are considered the stored food and are found between the thylakoid membranes and contain 14-16 glucose units and are similar to amylopectin. Nucleoplasm: It is the area where the nuclear material is found in the cell. Cyanobacteria do not contain histones and the composition of the nuclear material base ranges between 37-70% guanine-cytosine, which is similar to that found in prokaryotes. They are found in almost all kinds of ecosystems, such as permanently ice-covered waters, coastal areas, deserts, hot and cold springs, saline and alkaline ecosystems, and hydrated cement surfaces. They have evolved into the most diverse and metabolically versatile group in the bacterial world due to their wide distribution. These unique groups of prokaryotic organisms have existed worldwide for approximately 2.5 billion years (Sánchez-Baracaldo *et al*. 2022 and Dadheech, 2024) [16, 8].

Scientists have made significant progress in the field of generating electrical energy from algae, which represents a breakthrough in the field of green energy technology to combat climate change. The College of Engineering at the University of Colorado said that this technology exploits the photosynthesis process carried out by algae, which are among the most common microorganisms on the planet. A stream of electrons is released naturally during the photosynthesis process, and by using electrodes placed on the plant algae, these electrons can be attracted and converted into electrical energy, a technology that reduces the repercussions of global warming. During the photosynthesis process, algae capture carbon dioxide from the atmosphere, which reduces carbon emissions in the atmosphere in addition to generating clean energy. The researchers added - that within five years, people will be able to charge their smartphones using this energy, and they indicated that it will take more than ten years for algae energy to replace solar energy. The algae electricity technology is environmentally friendly and does not involve the use of any dangerous materials. The new energy requires connecting thin gold electrodes to the algae formations within a device about two centimeters wide. Unlike solar energy, which does not work at night, algae energy works during all hours of the day, day and night. https://p.dw.com/p/1HDa1.

Technology has combined common white fungi, bacteria, and nanotechnology to generate “clean” electricity. By integrating cyanobacteria, which can produce electricity, with nanomaterials that can harvest electrical current, Cyanobacteria’s ability to produce electricity is well known in bioengineering circles. However, researchers have been limited in using these microbes in hydrogen-treated systems because cyanobacteria don’t survive long on biocompatible artificial surfaces. Some species of cyanobacteria have also been found in association with fungal hyphae, especially those that are found submerged in water. Various forms of cyanobacteria are known to occur in puddles and aquarium glass (Yadav *et al*. 2022 and Rachedi *et al.*, 2020) [40, 28].

Cyanobacteria are one of the largest and most important contributors to the processes in different types of global ecosystems. They are present in almost all known environments where sunlight is present, and due to their abundance, they are extremely important to biogeochemical cycles. The habitats they are capable of colonizing range from the hot springs of Yellowstone to the moon. In addition to the known salts, heavy metals, radionuclides, and excess nitrate, there have been a large number of chemicals identified that are toxic to varying degrees to cyanobacteria, mostly occurring as contamination of the water. In addition to causing biosorption to the tailings, it has also been tested for biological remediation purposes against heavy metals and radionuclides. Sherwood *et al*. have shown that the interplay between the water microbiome, especially cyanobacteria in water storage systems, and hydraulic conditions can lead to a reduction in pathogenic communities and, therefore, risk. (Zahra *et al.*, 2020; Cano-Díaz *et al.*, 2020 and Chorus *et al.*, 2021) [44, 4, 37].

Cyanobacteria are amazing oxygenic phototrophic microorganisms that generate the greatest proportion of atmospheric O2 on Earth through an oxygenic photosynthetic apparatus. Because of their genetic and metabolic abilities, the ability to accept or adapt to different niches, and the ability to produce diverse secondary metabolites, they are extraordinary and unique microorganisms. Cyanobacteria are one of the oldest living organisms that originated about 2.5 billion years ago with the onset of oxygen accumulation as a result of photosynthesis activity. In nature, they can occur in distinct forms such as unicellular, colonial, filamentous, branched, and simple multicellular (4 cells), as well as in rich morphological structures, the size of which ranges from extremely small to the largest form (Sánchez-Baracaldo *et al*., 2022 and Dadheech, 2024) [16, 8].

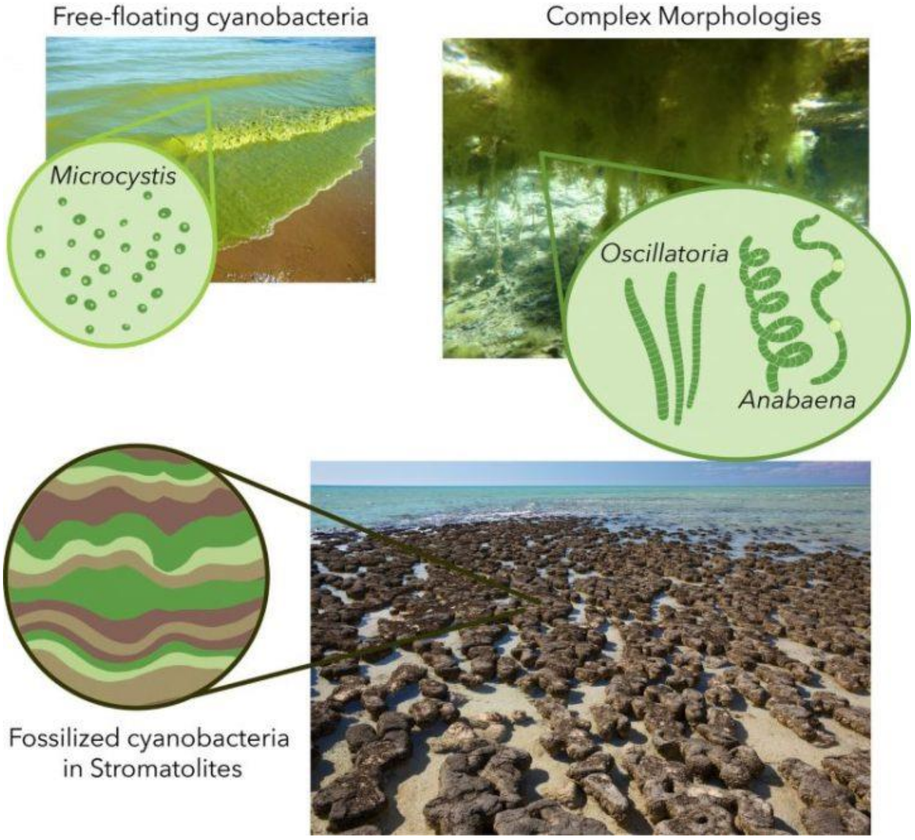

Fig 1: Free-floating cyanobacteria. Complex morphologies and fossilized cyanobacteria in stromtolites

Importance and Ecological Role of Cyanobacteria

With over a billion years of Earth's history, cyanobacteria are the dominant and ubiquitous microorganisms in various environments on Earth. Cyanobacteria not only play significant roles in ecological processes such as primary production and material cycling but also have a molecular phylogenetic relationship with higher plant chloroplasts. Formerly, they were known as blue-green algae due to their characteristic blue-green pigments, phycocyanin and allophycocyanin. However, they are prokaryotes, thus not algae in a strictly taxonomic sense. Additionally, unlike algae, cyanobacteria are capable of fixing CO2 and producing O2, indicating they may facilitate the formation of natural ecosystems by producing O2 from CO2. However, they are responsible for only 25% of the total O2 production on the Earth's surface, while other algal groups produce a combined 75%, with the sea surface contributing to a smaller portion of total oxygen produced than that of the land surface. (Fujita & Uesaka, 2022 and Ma & Wang, 2021) [11, 21].

It is well known that cyanobacteria are the main contributors responsible for a significant portion of primary production and nutrient cycles in marine and freshwater systems; they also play an important role in the biodiversity of coral reefs and lichens. It is also regarded as a major contributor to the global carbon and nitrogen cycles. Many studies have already been reported regarding the ecological importance of cyanobacteria that influence processes happening in terrestrial and aquatic ecosystems, like oxygen production, nitrogen fixation, and nutrient dynamics in aquatic habitats. Many researchers also have stated that cyanobacteria are highly diversified and adapted to colonize various extreme habitats, such as the deepest point of an ice-covered arid desert, the Altiplano, or the Columbia Glacier of Antarctica (Sukharevich & Polyak, 2020) [35].

The Structure and Function of the Microscopic Eyeball

The terminal and transverse gliding motility of cyanobacteria is one of the most striking features. The unicellular cyanobacteria possess a number of strategies to sense the direction of the light source. One of these tools is a microscopic eyeball, which is located at the front. Quite interestingly, these eyes are functionally equivalent to large complex multicellular eyeballs. Moreover, a distinction between the retinal part and the nerve fiber parts has been documented. However, the in-depth review of these microscopic eyeballs is yet to be carried out, which necessitates the present review (Schwabenland *et al*.2024 and Vidal *et al.*, 2021) [31, 37].

The microscopic eyeball in cyanobacteria bears an intricate ultrastructure that harbors a transparent, lens-like structure containing points, a subterminal organic outer coat, and a layer capsule upon the thylakoid layers in the cytoplasm. These photoreceptive systems, each termed as an "eyeball," are capable of varying their length to refine light input and function as a super-resolution lens to make close-ups. The conic form of the microscopic eyeball, the lens-like layer, and the points in the lens make the eyeball completely distinct. The physiological examination of unicellular cyanobacteria shows that when the incident light shifts from the front, ps-I production in the nearest points promotes the transportation of ATP from this area to other neighboring points through the flow of ATP particles. These cytosolic ATP particles in the cytoplasm can transform the alignment of spF complexes in the points, and this transformation has an inverse correlation with the proximity of the points to the front of the cell, enhancing the capability of attraction of tiny energy of light. (Nikkanen *et al.*,2021; Forchhammer & Selim, 2020 and Pandey *et al*.,2022) [23, 10, 26].

Anatomy of the Eyeball of Cyanobacteria

The mollusk's eye is analogous to vertebrates. A point-source camera eye has a sensory epithelium that contains photoreceptor cells located in the innermost layer close to the pigmented sub-epithelial layer, followed by pigmented cells, and additional cellular layers from outward to inward. Similarly, the anatomical structure of the photoreceptive eyespot of cyanobacteria, also called a microscopic eyeball, contains three main parts, i.e., five layers of cells, a cellular clear layer, and a mucilaginous layer that separates the eyeball from the principal cell mass. Here, we present an in-depth review article exploring the structural and functional aspects of this cyanobacteria microscopic eyeball. (Williams, 2022; Yamashita & Baluška, 2022 and Yamashita & Baluška, 2023) [39, 41, 42].

1.1. Microscopic and Macroscopic Eyeballs of Cyanobacteria. Like a point-source ocellus mini-camera eye found on the photoreceptive eyespot of Chlamydomonas reinhardtii and the stomatogastric nervous system, a point-source camera eye does not have a lens, but the camera components are arranged in a posterior-to-anterior orientation. In comparison, the cyanobacteria microscopic eyeball is smaller than animal eyespots or vertebrate and invertebrate camera eyes, and its diameter ranges from 1 µm to 15 µm. Protocells of the eyeball and basal bodies are the underlying photoreceptive receptor cells of the cyanobacteria eyespot. In fact, the retina is supplied with dual-range wavelengths photoreceptor cells that are sensitive to different wavelengths of light. Every structure in the eyespot of photoreceptors is not similar to animals. (Zhou *et al.*, 2023) [45].

Photoreception Mechanisms of Cyanobacteria

Photoreception is one of the special sensory systems in living organisms that provides light intensity, quality, and direction signals to the organism for its optimum growth and sustenance. Photoreception allows organisms to adapt to their light environment and is essential for the initiation of energy conservation and signal transduction processes. Light controls a variety of behaviors in different organisms, ranging from simple orientation or choice of a photosynthetic lifestyle to the development of complex patterns and even photosensitive hyper-rhythmic regulation of flowering under stressful conditions. Photoreceptor proteins absorb light during photosynthesis or rhodopsin processes to absorb light for signaling and are responsible for the perception of light signals for most living systems, including prokaryotes and eukaryotes. (Manoj & Jacob, 2020 and Abbas & Vinberg, 2021) [22, 1].

The prokaryotes, particularly cyanobacteria, are exploiting sunlight by using a better photoreception system. The photoreception machinery of cyanobacteria comprises multiple interrelated physiological processes, such as photoreceptor sensing, signal transduction, phototactic behavior, and gene expression changes. The mechanism of signal photoreception at the cellular or molecular level in cyanobacteria is poorly understood. This section describes the molecular and cellular aspects of photoreception in these tiny microbes (Selim *et al*., 2020) [3].

Photoreceptor: A photoreceptor is a pigment that can transform a light signal into a chemical signal. The photoreceptor is an essential system for sensing and responding to a light signal in most organisms. A variety of photoreceptional pigments are known, which vary in chromophores, tertiary/quaternary structure, signal, and signaling mechanism. The changes in the signal by a photoreception pigment can be transduced to the membrane and membrane-associated transducer proteins or may interact directly (without a signal transducer) with a membrane channel protein to open it. The different photoreception systems elucidated for several organisms include rhodopsin, bacteriochlorophyll, phytochromes, etc. (Lewandowski *et al*., 2022; Palczewski and Kiser 2020 and Yue *et al*., 2021) [19, 25, 43].

Evolutionary Significance of Cyanobacteria

Cyanobacteria photoreception is an ancient but not well-understood field. Lens ocelli are found in the lower trilobite fossils from approximately 500 Myr, suggesting that the evolution of these eyes must have occurred earlier. However, some research estimated the divergence time of Cyanobacteria into the Mesoproterozoic (1.0–1.6 Ga), and the emergence of the stem-group Cyanobacteria was even up to 2.45 Ga, suggesting a longer geological record over 2.5 Ga. With this, it seems logical that the evolution of phototaxis in cyanobacteria might predate Homo sapiens. (Sánchez-Baracaldo *et al.* 2022 and Walters *et al*., 2020) [16, 38].

The origin of photoreception is an important unsolved field in the evolution of photosynthetic microorganisms. The ancestral condition of photoreception remains controversial. It might have first evolved to protect the cell components (inhibition of DNA repair enzymes and tryptophan biosynthetic enzymes) of the cell from the harmful effects of high UV ray exposure, and the visibility of visible light might have been a secondary or an incidental by-product. High light tolerance acquired by the detection of other wavelengths was not rare during the Mesoproterozoic. The accumulation of the carotenoid-protein complex near the chlorophyll and the development of the cell wall are also positive examples of visible light detection before actual photoreception. The phylogenetic study also supports that the molecular evolution pattern of these photosensors arose way before the oxygenation of the atmosphere. Thus, phototaxis might have helped stem-group Cyanobacteria to avoid photodamage against other forms of radiation at the peroxidic or anoxic time, and a modified form of this primitive signal transduction might have led to the later development of high light tolerance by using different photosensors in Cyanobacteria (Chizhov *et al.*2022; Kacar, 2024 and Soni *et al*., 2020) [5, 15, 34].

Origin and Evolution of Photoreception in Cyanobacteria

Cyanobacteria were estimated to have evolved about 3 billion years ago, from early Gram-positive bacteria. The photoreceptive machinery of the contemporary oxygenic photosynthesizers is a legacy of how this pivotal function in microorganisms evolved into the world-shaping thylakoid-based cellular architecture of plants. Another strength of cyanobacteria that makes them attractive for studying the early evolution of photoreception is their extraordinary diversification of potential photoreceptors/light-harvesting proteins (LH) types along a putative continuum of lessening responsiveness to longer (red) wavelengths, namely the evolution of xanthorhodopsin from type-2 proteorhodopsins, followed by 'traditional' rhodopsins and family/pedigree 2 phycobiliproteins on to the more ancient and conserved family/pedigree 1 phycobiliprotein (PBPs). (Dadheech, 2024 and Alexander & Svetlana, 2021) [8, 2].

There is a considerable amount of recent work highlighting the wide diversity of light-sensing, timekeeping, and photoprotective mechanisms found in the contemporary cyanobacterial phylum. This subsection provides an in-depth overview of the origin and evolution of photoreception in cyanobacteria. Photoreception first emerged in prokaryotes, and independently in archaea bacteria with variants of the light-driven ion pumps, rhodopsins. Two routes have been proposed in the establishment of early photoreception in the prokaryotic kingdoms, along with the internal membranes ultimately giving rise to the cyanobacterial thylakoid: through phagocytosis and gene transfer from mitochondria or through endosymbiotic gene transfer from chloroplasts. (Rozenberg *et al*., 2021 and Sephus, 2021) [30, 32].

Applications and Future Directions

The understanding and analysis of photoreception in cyanobacteria and their respective photoreceptive protein complexes and systems can lead to a wide variety of practical applications, including their use as effectors for integrated optogenetic approaches in biotechnology, proteomics, or biosensing. Photoreceptive systems have the potential to be used as powerful tools for numerous scientific applications. As mentioned in this review, photo-sensing and retinal-based light detection have already been established as a useful method of modulating osmolyte transport systems for use in various biotechnological applications, including synthetic biology. However, few, if any, other aspects of cyanobacterial photoreception have been robustly addressed or taken advantage of within relevant industries. (Sivasankari *et al*., 2024; Hudson, 2021 and Datta *et al*. 2023) [33, 14, 9].

The mechanisms of lipoprotein-mediated signal transduction are still rudimentary at best, with many areas that need to be investigated before we can hope to make full use of this knowledge. Indeed, only a few applications of lipoproteins have been explored due to the basic understudied nature of the supposed signal transduction pathway. We know very little about the signaling mechanisms of WLPs due to the various complications and drawbacks relating to their study. Undoubtedly, many more applications will be made possible if we gather a better knowledge of these systems and will importantly have the potential to allow the easy genetic manipulation of photoreceptive systems in responding cells for truly synthetic biological applications. In the case of BLUF domains, they will likely have similar limitations as to how useful they will be, but CO2 fixing enzymes may find use in certain carbon capture applications and modification of tropism and secretion of certain products.

In conclusion, while the consideration of various lipoprotein reaction mechanisms and infection conditions are not fully considered for industrial applications at present, the drive for synthetic biology approaches and biotechnological advances will undoubtedly lead to the discovery of methods to make use of or even exploit such photoreceptive systems. To achieve these goals, numerous research challenges will have to be overcome, including both photoreceptive biosynthesis findings and a mechanistic understanding of relevant intracellular machinery. Exploration of these cellular photoreceptive systems will undoubtedly yield surprising new insights into physiology and the advancement of environmental or green industry biotechnological systems of the future. (Clarke & Kitney, 2020 and Patra *et al*., 2021) [7, 27].

Biotechnological Applications

Besides providing essential functions within the cell, the potential of cyanobacterial photoreception and phototaxis has also been a subject of study for possible biotechnological applications. The increasing knowledge of the possible photoreceptive elements may support the efficient use of these systems as devices. One of the main applications is for enhanced light energy harnessing for both carotenoid- and chlorophyll-based photoreception systems. In the past few years, cyanobacteria have been employed as a biotechnological platform for the synthesis of chemicals using light as an energy source through bioenergy production or coupling bioproduction with energy harnessing via phototaxis. (Żymańczyk-Duda *et al.*, 2022 and López-Hernández *et al.*, 2022) [46, 20].

1. Enhanced Light Energy Harnessing under Light Limitation (Fu *et al.,)* reviewed the natural photon direction-sensing systems such as chlorophyll fluorescence induction in Synechocystis sp. PCC 6803. These natural photoreception systems remain within the original organism. Alternative to the whole cell system, external biosensors may be an option foresaw potential applications of photoproteins in nanotechnology, medical diagnosis, in vivo imaging, and production of solar fuels. They also mentioned the systems used in this review such as the Photoswitchable Carotenoid Protein (SCOPO) used in photoregulation of the enzymatic activity (PHR) coli and for expression controls in OPTIMAGE. (Ogawa *et al*., 2021 and Lakatos *et al*., 2021) [24, 17].
2. Phototaxis towards Efficient Biotechnological Production Khan *et al*. applied phototaxis in processing stained blood films for malaria diagnosis. Madrid system has been prepared by combining phototactic microalgae (C. reinhardtii) and a computer-aided image processing algorithm. AL Mossier patented a device utilizing phototaxis and bioluminescence for marine attractants. Kuchmina *et al.* discussed the use of phototactic cells in biomineralization. Camezán *et al.* reviewed the use of phototaxis in bioprocessing such as for in situ bioremediation of micro- or nano-particles with marine resources—bacteria, microalgae, and zooplankton. Kemler and Melkonian mentioned the possible biotechnological applications of phototactic microalgae for biofuel production. The most promising approach for biofuels is the direct production, not conversion, of biofuels by using engineered or naturally rich oleic microalgae.

Research Challenges and Opportunities

Based on the current advances in studying the molecular composition of cyanobacterial photoreceptor constructs and a physiologically authentic context thereof in situ, three unresolved "big problems" appear to remain, which offer considerable rewards to any researchers capable of overcoming them. A first "big problem" is to determine the stoichiometry and nanoscale distribution of constituent and stoichiometric flavin and bilin synthetases, binding glycosyltransferases, and the final photoreceptor apoproteins, together with two additional holo-phycobiliproteins, in PBSs (Camargo, 2023 and Hou & Allakhverdiev, 2023) [12, 3].

Currently, the existing technologies of resolving the structures of photoreceptor quantum dots adhere to intrinsic limitations, beyond which they fail to reach. Seeking out such a technical "holy grail" for imaging the objects of interest via direct observation is expected to allow for revealing up to 99% more about the organization, operation, and regulatory anatomy of cyano photoreceptor gas factory vital centers. The fact that the atomic imaging of the characteristic bioprotective S Chemerin vibronic quantum sidebands of immobilized-bound red-light photoactivated phytochromes had been obtained from four cautious X-ray article authors a year prior to their parallel publication of the limited PD study speaks fetchingly for itself. But even PD-bullying of X-ray photosniper-helm is insufficient to explain the nature of hydrated or not hydrated PFTs in vibrational quiescence, or of the green-tinted oxy-PD opsin unfolds. Taken together with the need for technologies to quantify PB fluorescence yield, the reading is that any reverse PD investigation presupposing free-floating photoreceptor monomers trapped, e.g., in copolymers, is starry-eyed because it signally misidentifies its subject of study. (Hou & Allakhverdiev, 2023; Camargo, 2023 and Tan *et al.*, 2022) [12, 3, 36].

Conclusion

In this review, we describe the different components of cyanobacterial photoreception, the complete signal transduction chains from the sensors (photoreceptors) to the effectors (mainly the chemoreceptors and the NBC systems), and discuss those that are the core of cellular motility and the related light-inhibited ion flux. A complete state-of-the-art of such a "phototaxis and photoreception chain" in order to offer an extensive and useful guide to all the researchers interested in these problems. Finally, we treat the connections of such a "minimal eyespot" with those pioneering photoreceptors with "real" rhodopsin domains about their common evolutionary origin.

Plenary information derived from the molecular analysis of the different components of the "minimal eyespot" in cyanobacteria shows that they belong to large superfamilies, each of them with members having intense and continuing scientific interest. The signaling mechanisms in these superfamilies and especially the governing light-moderated switches are fundamentally related to those present in Aqua-PSPs and in channelrhodopsins. If, possibly, creations of the first channelrhodopsins on the base of PsB and PpB are excluded, we could agree that the presently known cyanobacteria with PSPs and channelrhodopsin-like rhodopsins (mainly crypto-chlorogloeopsin-like) have eyespots as the earliest relatives of the PSP domain. In addition, the proofs of photomotility and functional phototactic complexes only in the older of the two sub-kingdoms of cyanobacteria, Chroococcidiopsidales, strengthen the importance of the successful evolutionary strategy of chlorophyll/helix-sensing-based photomotility. Given the high number and variation in molecular characteristics of phototaxis genes, AMD probability and velocity in monocellular cyanobacteria could represent a good proxy to explore and discover new microorganism ecologies.

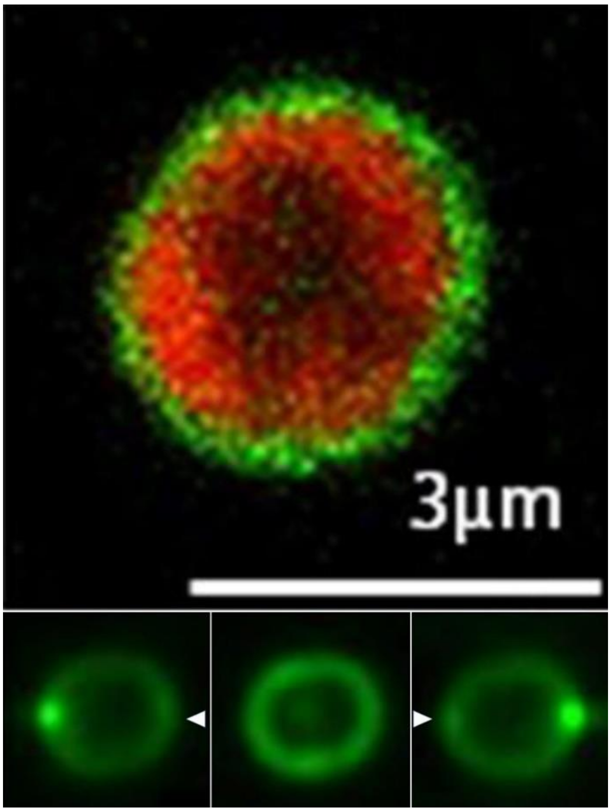

Fig 2: Cyanobacteria ‘See’ Like Microscopic Eyeballs

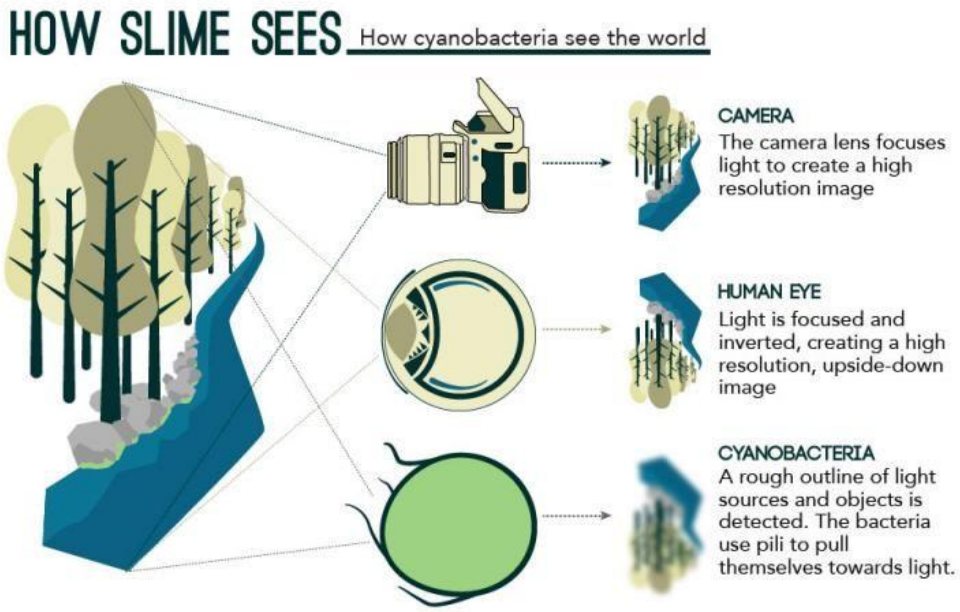

Fig 3: How Cyanobacteria see the World

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