Int Aquat Res (2024) 16:195–211
https://doi.org/10.22034/iar.2024.2006079.1593

REVIEW

The contribution of cyanobacteria in the development of nanobiotechnology: a mini-review

Rania Omar . Nabila Shehata . Eman M. Farahat . Sherif Hassan . Ibraheem B.M. Ibraheem . Reham Gamal . Khaled N.M. Elsayed

Received: 18 January 2024 / Accepted: 14 August 2024 / Published online: 23 August 2024

Abstract This review shows how adaptable cyanobacteria are for biotechnological uses; they are potent sources of bioactive substances, biofertilizers, bioplastics, energy, food, and pharmaceuticals. In the last decades, they have been applied to the synthesis of nanoparticles and in the bioremediation process. Diazotrophic cyanobacteria are known for their ability to fix nitrogen which making them important in the global nitrogen cycle. Cyanobacteria play a key role in the ecosystem by producing oxygen for other organisms. Moreover, they play a crucial role in the environment through their ability to perform photosynthesis, and nitrogen fixation in some species, and release important organic compounds. Their metabolic activities also contribute to the formation of a sizable portion of the world's limestone through the development of travertine and stromatolites. One of the notable features of some cyanobacteria is their filamentous growth habit; others are unicellular, which can range from unicellular to quasi-multicellular. The distribution of cyanobacteria is influenced by several factors, including environmental conditions, nutrient availability, and biotic interactions. Cyanobacteria have been found to interact with several types of metal nanoparticles (NPs), leading to the discovery of new potential uses and applications for these NPs. The interaction between cyanobacteria and metal NPs has been studied in different fields such as medicine, environmental protection, and industrial production, showing promising results in terms of anti-pathogenic, cytotoxicity, and antioxidant properties. To conclude, different strains of cyanobacteria and various types of metal NPs they interact with have a wide range of potential applications.

Keywords Cyanobacteria . Green nanotechnology . Biotechnology . Applications . Nanoparticles

Cyanobacteria and its applications: an overview

Cyanobacteria have a broad range of purposes in medicine, pharmacy, biotechnology, and renewable energy as they can be utilized in a variety of items, including cosmetics, detergents, soaps, toothpaste, shampoos, and bioenergy (Zahra et al. 2020). Utilizing cyanobacteria in nanoparticle biosynthesis was chosen for various reasons, including ease of culturing, quick generation time, and ability to withstand mild pH, temperature, and pressure conditions (Elsayed 2017; Hussein et al. 2022). It was discovered that cyano-

---

Rania Omar . Eman M. Farahat . Sherif Hassan . Ibraheem B. M. Ibraheem . Khaled N. M. Elsayed (✉)
Botany and Microbiology Department, Faculty of Science, Beni-Suef University 62511, Egypt
e-mail: k.elsayed@science.bsu.edu.eg

Nabila Shehata
Environmental Science and Industrial Development Department, Faculty of Postgraduate Studies for Advanced Sciences, Beni-Suef University, Beni-Suef, 62511, Egypt

Nabila Shehata
Renewable Energy Science and Engineering Department, Faculty of Postgraduate Studies for Advanced Sciences, Beni-Suef University, Beni-Suef, 62511, Egypt

Reham Gamal
National Institute of Oceanography and Fisheries (Niof), Cairo, Egypt

bacteria can produce natural bioactive substances such as phenolic compounds, which have antioxidant, anti-inflammatory, and anti-microbial properties (Komárek 2013). The following sections discuss in more detail the production, characteristics, and main applications of cyanobacteria.

Isolation and purification of cyanobacteria

Diazotrophic cyanobacteria are known for their ability to fix nitrogen that is making them important in the global nitrogen cycle. One common method for isolating cyanobacteria is the utilization of enrichment culture techniques (Hotos et al. 2023). This involves growing the organisms in a medium specifically designed to promote the target organism's growth while inhibiting other microorganisms' growth (Reeve et al. 2023). For cyanobacteria, this can involve the use of media that is high in nitrogen, such as ammonium or nitrate, and low in phosphorus (Markou and Georgakakis 2011). Another method for isolating cyanobacteria is the use of dilution plating (Rippka 1988). This involves spreading a known amount of a mixed culture onto a solid medium and then diluting the culture by spreading a known amount of the diluted culture onto new plates. This process is repeated until a single colony is obtained. This method is particularly useful for isolating rare or difficult-to-grow strains of cyanobacteria. A third method for isolating cyanobacteria is with filtration. This involves passing a sample through a filter with a known pore size to capture the target organism while removing other microorganisms (Nnadozie et al. 2015).

Overview of cyanobacteria

Cyanobacteria are a diverse group of microorganisms that come in various shapes, such as unicellular, filamentous, and colonial forms. They can be found in a wide range of environments, including hot and cold temperatures, alkaline and acidic conditions, and freshwater, marine, saline, and terrestrial habitats (Sanchez-Baracaldo et al. 2005). Cyanobacteria play a key role in the ecosystem by producing oxygen for other organisms. They possess a primitive nucleus, gas vesicles, and thylakoids that are loosely distributed, along with hexagonal carboxysomes, phycobilisomes, ribosomes, and numerous storage granules (Gallardo 2014). They are characterized by the presence of chlorophyll, accessory pigments, and the PSII reaction center. The diazotrophic cyanobacteria can utilize inorganic nitrogen via permeases and fix nitrogen using nitrogenase enzymes as in diazotrophic, utilizing photosystem I to create adenosine triphosphate (ATP). They hold potential as natural biofertilizers (Glazer 1977; Kalyanasundaram et al. 2020), but their effectiveness can be limited by physiological changes and variations in inoculum depending on the ecological zone.

Importance of cyanobacteria

Cyanobacteria play a crucial role in the environment through their ability to perform photosynthesis, fix nitrogen in some species, and release important organic compounds. Their metabolic activities also contribute to the formation of a significant portion of the world's limestone through the development of travertine and stromatolites (Shridhar 2012). As primary producers in both aquatic and terrestrial ecosystems, cyanobacteria make up a significant portion of the biomass in many aquatic environments (Gladyshev et al. 2013). Additionally, they are important for health and industry as they can produce a variety of valuable natural compounds (Saranraj and Sivasakthi 2014). Furthermore, their role in ecology is notable, particularly in rice-growing countries, where they act as natural biofertilizers through their nitrogen-fixing abilities (Mishra and Pabbi 2004).

Main characters of cyanobacteria

Cyanobacteria are a diverse group of microorganisms that can be classified into five major sub-groups based on their morphological and physiological characteristics. This classification system is based on the dichotomous key presented in the second edition of Bergey's Manual of Systematic Bacteriology, which takes into account factors such as the type of cell division, the presence of differentiated cells, and the morphotype of the organism (Pinevich 2008). One important feature of some cyanobacteria is their filamentous growth habit; others are unicellular, which can range from unicellular to quasi-multicellular. The color of cyanobacterial cultures can vary from blue-green to brown. The shape and size of vegetative cells can vary depending on the species, with some having barrel-shaped cells and others having ovoid cells. The size of vegetative cells can range from 2.5-5.5 micrometers in diameter and 4.0-7.0 micrometers in length. Another essential feature of some filamentous cyanobacteria is the presence of specialized cells called heterocysts, which participate in nitrogen fixation.

Heterocyst is typically ovoid, with diameters ranging from 3.0-6.0 micrometers in width and 3.5-6.5 micrometers in length. They can be found in both internal and terminal positions within the filament. Some cyanobacteria also possess another specialized cell called akinetes, which are used for survival during adverse conditions. Akinetes are usually ovoid and vary from 4.0-6.0 micrometers in width and 5.0-10.0 micrometers in length (Brito 2015). Cyanobacteria are traditionally classified by phycologists based on their morphological and physiological characteristics. However, recent advances in molecular biology have allowed for the use of molecular markers in the classification of cyanobacteria. These markers can be used to differentiate between different strains and species of cyanobacteria. Overall, the classification of cyanobacteria is a complex process that requires the use of multiple criteria and techniques (Prasanna et al. 2006).

Factors that affect the distribution of cyanobacteria

Cyanobacteria are found in a wide range of environments, including freshwater, marine, and terrestrial habitats (Kultschar and Llewellyn 2018). The distribution of cyanobacteria is influenced by several factors, including environmental conditions, nutrient availability, and biotic interactions (Schulte et al. 2022). One of the primary factors that affect the distribution of cyanobacteria is the availability of light. Cyanobacteria are photosynthetic organisms that require light for growth and survival (Mischke 2003). Therefore, they are typically found in environments where light penetration is high, such as in clear water bodies or terrestrial habitats with low canopy cover. Additionally, certain species of cyanobacteria have adaptations, such as pigments that allow them to tolerate low light conditions resulting in surviving in environments with limited light penetration (Havens et al. 1998). Another key factor that affects the distribution of cyanobacteria is nutrient availability.

Cyanobacteria are known to be able to tolerate a wide range of nutrient conditions, but they typically thrive in environments where nutrient levels are high (Arias et al. 2020). For example, in freshwater systems, cyanobacteria often proliferate in eutrophic (nutrient-rich) environments, where nitrogen and phosphorus levels are elevated. In addition to light and nutrient availability, biotic interactions also play a role in shaping the distribution of cyanobacteria (Paerl and Otten 2013). Competition for resources among different organisms can limit the growth and spread of cyanobacteria. For example, in freshwater systems, cyanobacteria may be outcompeted by other photosynthetic organisms, such as macrophytes or phytoplankton. Climate change is also an important factor affecting the distribution of cyanobacteria (Salmaso 2000). Cyanobacteria can tolerate a wide range of temperatures, but certain species are more tolerant to warmer temperatures than others (Bonilla et al. 2023). As global temperatures increase, it is expected that certain species of cyanobacteria will become more dominant in certain regions, while others may decline. Overall, the distribution of cyanobacteria is influenced by a complex interplay of environmental factors, including light availability, nutrient availability, biotic interactions, and climate change. Understanding these factors is critical for predicting and managing the growth and spread of cyanobacteria in different environments.

Applications of cyanobacteria

Cyanobacteria are surprisingly the most significant class of microbes in the cosmos because they have critical environmental responsibilities, serving as a major source of oxygen, nitrogen, and carbon for the entire planet (Joye and Lee 2004). They are significant producers of biofuels, food additives, and coloring agents (Kumar et al. 2019). Cyanobacteria are utilized in the treatment of water (Svrcek and Smith 2004), the manufacture of bioplastics (Markl et al., 2018), cosmetics (Morone et al. 2019), forestry, animal feed (Grewe and Pulz 2012), biohydrogen, bioethanol, and biogas (Parmar et al. 2011). The following sections explore their applications in different sectors.

Cyanobacteria for nanoparticles biosynthesis

Cyanobacteria are a group of photosynthetic microorganisms that have been found to have the ability to biosynthesize nanoparticles (Doman et al. 2023). This process (Figure 1), known as biogenic synthesis, involves the use of enzymes and other biomolecules present in cyanobacteria to produce nanoparticles with unique properties and potential applications in various fields (Srivastava et al. 2022). One of the key features of cyanobacteria that allows for the biosynthesis of nanoparticles is their ability to produce complex mixtures of polysaccharides, proteins, and lipids; which produce extracellular polymeric substances (EPS) (Huang et al. 2023).

These EPS serve as a template for the formation of nanoparticles and can also provide a protective environment for the particles during their formation. The most widely studied type of nanoparticles biosynthesized by cyanobacteria is the metal nanoparticles, particularly those of silver, gold, and copper. The mechanisms by which these nanoparticles are formed are not fully understood, but it is believed that they involve the reduction of metal ions present in the EPS by enzymes or other biomolecules (Fulaz et al. 2019). In addition to metal nanoparticles, cyanobacteria have also been found to biosynthesize other types of nanoparticles, such as semiconductors and magnetic nanoparticles (Asmathunisha and Kathiresan 2013). The potential applications of these nanoparticles are diverse and include their implementation in medical diagnostics, environmental remediation, and renewable energy (Khan et al. 2022).

Despite the potential of cyanobacteria in the biosynthesis of nanoparticles, there are still some challenges that need to be overcome. For example, the yields of nanoparticles produced by cyanobacteria are often low, and the process can be affected by environmental factors such as pH and temperature (Rahman et al. 2020; Thakkar et al. 2010). In conclusion, cyanobacteria have shown enormous potential in the biosynthesis of nanoparticles. Using these microorganisms, unique nanoparticles with potential applications in various fields can be produced in a sustainable and environmentally friendly route. However, further research is needed to improve yields and optimize the biosynthesis process.

The synthesis of metal nanoparticles, such as silver nanoparticles (AgNPs), can be achieved through both physical and chemical methods (Abou El-Nour et al. 2010). However, these methods often have drawbacks, such as the use of expensive and toxic chemicals, difficulty in achieving mono-dispersion and thermodynamic stability, and high energy consumption with the potential for dangerous by-products (Iravani

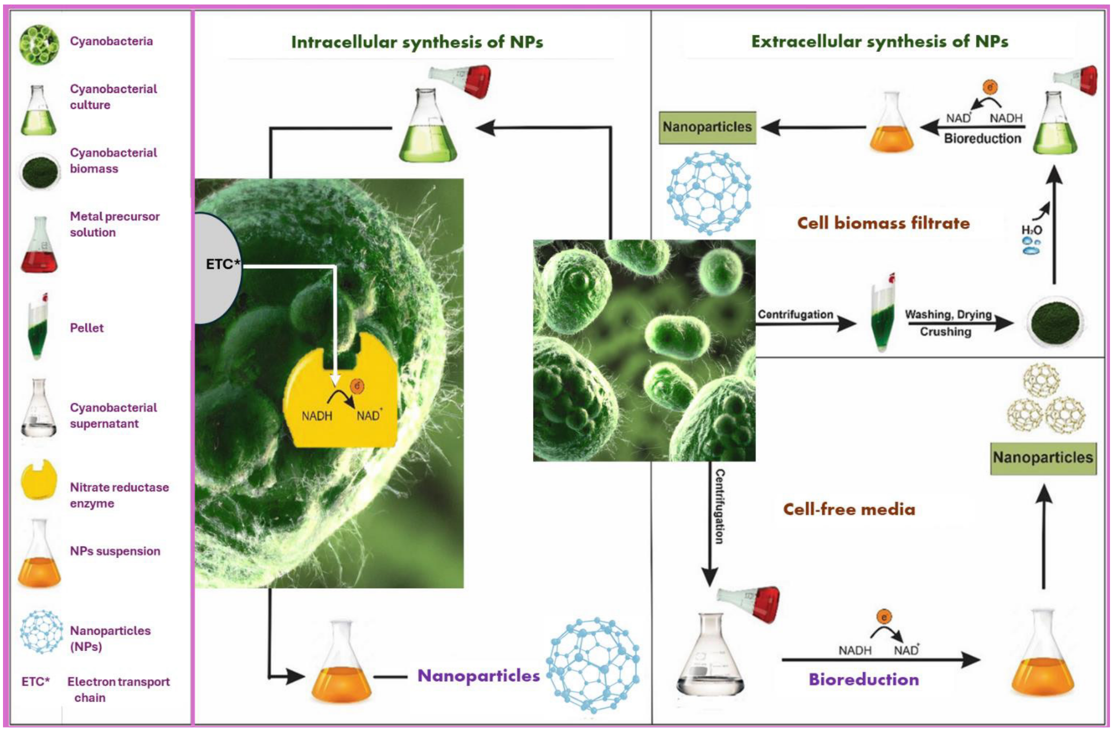

Fig. 1 A schematic flow diagram for the biosynthesis of nanoparticles from cyanobacteria (Javed et al. 2024)

et al. 2014). Green chemistry offers alternative methods for the synthesis of nanoparticles with applications in fields such as drug delivery, sterilization, and catalysis (Albrecht et al. 2006). Silver nanoparticles have strong antimicrobial properties and are commonly used in various consumer products, such as clothing and cosmetics (Mazari et al. 2021). The green method is considered safe, eco-friendly, and capable of large-scale production (Fathy et al. 2020). Additionally, it does not require high energy consumption and can be performed at room temperature under normal conditions (Abdel-Raouf et al. 2019).

The proteins, enzymes, sugars, and lipids present in cyanobacteria act as reducing and capping agents in the conversion of silver ions into nanoparticles (Roy et al. 2019). The hydroxyl group in tyrosine residues and the carboxyl group in aspartic acid and/or glutamic acid residues have been identified as the most active functional groups in this process (Makarov et al. 2014).

Biosynthesis of nanoparticles

Nano-biotechnology is a rapidly growing field within the broader field of nanoscience and technology, and nanoparticles have been shown to possess a wide range of physical, optical, electrical, and chemical characteristics (Jha et al. 2014; Sorbiun et al. 2018). This versatility makes nanoparticles highly attractive for use in biomedical science, including as antimicrobial agents, gene carriers, diagnostic agents, dental resin composites, tissue repair, optical receptors, and electrical batteries (Fathy et al. 2020).

Chemical synthesis of nanoparticles can be challenging, as it requires particular circumstances and has several drawbacks, including chemical toxicity and nanoparticle instability. Physical synthesis methods, while possible, are often energy-intensive and costly (Patel et al. 2015). Although, nanoparticles could be made in one of two approaches: top-down or bottom-up, in most cases, the bottom-up one is exploited in the biological development of nanoparticles (Ibraheem et al. 2016). However, the biological method is superior to the chemical and physical processes since it overcomes the disadvantages of other methods. It has several advantages, including low cost, stability, eco-friendly, and the fact that it does not consume energy (Patel et al. 2015).

Nanoparticles have a size range of 1-100 nm, making the interaction with microbial surfaces much easier, quicker, and more effective than microbes of typical size (Ibraheem et al. 2016). Cyanobacteria with noble metals like silver or metallic elements like copper are used in the biological technique (Hamida et al. 2020b). Bioactive chemicals produced by microorganisms perform a vital role in Ag^+ reduction and nanoparticle stabilization without toxicity or severe circumstances (Cruz et al. 2010; Jeevanandam et al. 2016; Pirtarighat et al. 2019). In general, parameters like the kind of solvent and the reducing agent for silver ions play a big influence on silver nanoparticle production (Ebrahiminezhad et al. 2016). One of the most effective uses of nanoparticles is antimicrobial agents, which can be used in a variety of fields with amazing efficacy, such as pharmaceutical medication production against various microorganisms (Madkour 2017; Zhang et al. 2010).

Characterization of biosynthesized nanoparticles

Characterization is crucial to understanding their properties and potential applications. Several instruments and methods can be used to characterize these nanoparticles, including Transmission Electron Microscopy (TEM); TEM is a widely used technique for imaging and analyzing nanoparticles (Figure 2a). It uses a beam of electrons to produce high-resolution images of the particles, allowing for the determination of their size, shape, and crystalline structure (Wilson and Prud'homme 2021). Scanning electron microscopy (SEM) is another imaging technique that uses a beam of electrons to produce images of the surface of nanoparticles (Figure 2b). It is particularly useful for studying the surface morphology and topography of the particles (Titus et al. 2019). X-ray diffraction (XRD) is a technique that uses X-rays to determine the crystal structure of nanoparticles (Figure 2c). It can be used to identify the crystal phases present in the particles, as well as their size and shape (Bishnoi et al. 2017). UV-visible spectroscopy is another technique that uses light in the ultraviolet and visible range to study the optical properties of nanoparticles. It can be used to determine the absorption and scattering properties of the particles, as well as their size and shape (Shehap and Akil 2016). Dynamic light scattering (DLS) is another technique that uses laser light to study the size and size distribution of nanoparticles in solution. It is a non-destructive method, making it useful for studying the stability of the particles over time (Hoo et al. 2008). Fourier transforms infrared spectroscopy (FTIR) is a technique that uses infrared radiation to study the vibrations of chemical bonds in nanoparticles (Figure 2d, 2e, and 2f). It can be used to identify the chemical composition of the particles and to study their chemical interactions with other molecules (Faghihzadeh et al. 2016). In conclusion, the characterization of biosynthesized nanoparticles is crucial to understanding their properties and potential applications. Although, several instruments and methods can be used to study these particles, including TEM, SEM, XRD, UV-visible spectroscopy, DLS, and FTIR, however, each of these techniques has its limitations, and the choice of technique will depend on the specific questions being asked and the properties of the nanoparticles being studied.

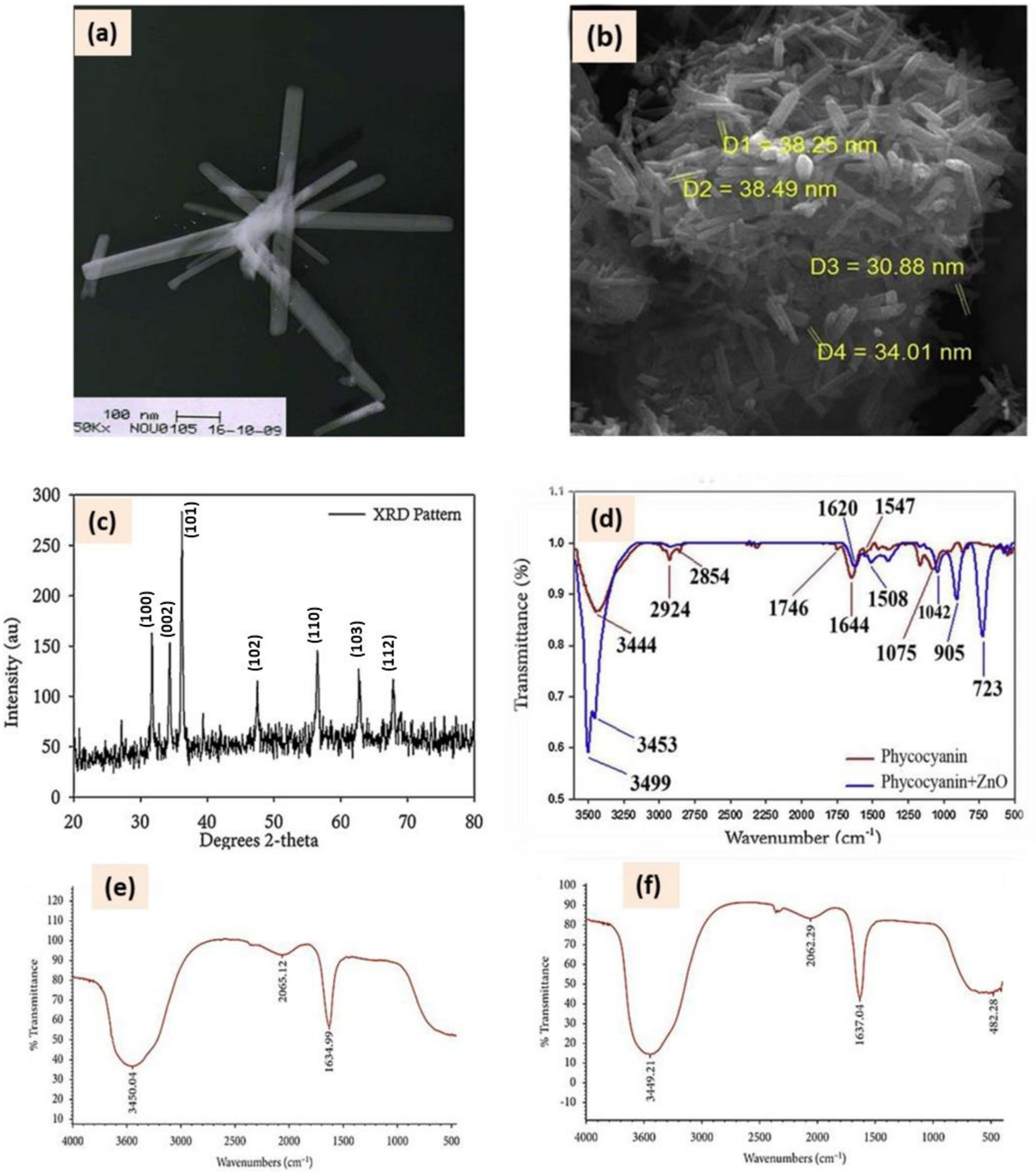

Fig. 2 TEM (a), SEM (b), XRD (c), and FTIR (d) of phycocyanin- ZnO nanorods (Davaeifar et al., 2019) and FTIR spectra of Ag-NPs synthesized extracellularly from *Desertifilum tharense* (e) and *Phormidium ambiguum* (f) (Hanna et al. 2022).

Selectivity of cyanobacteria in the biosynthesis of nanoparticles

Cyanobacteria have been found to interact with various types of metal nanoparticles (NPs), leading to the discovery of new potential uses and applications for these NPs. The interaction between cyanobacteria and metal NPs has been studied in fields such as medicine, environmental protection, and industrial production, showing promising results in terms of anti-pathogenic properties, cytotoxicity, and antioxidant properties. It can be inferred that the different strains of cyanobacteria and the various types of metal NPs they interact with have a wide range of potential applications (Table 1). The data also suggests that certain strains of cyanobacteria have a greater potential for certain applications, such as *Spirulina platensis* for lead uptake and *Anabaena variabilis* for malachite green dye removal.

It is also worth noting that some of the entries in the data have missing or unspecified NP sizes, which could affect the applicability of the findings. In the future perspective, the potential uses and applications of cyanobacteria and metal NPs in various fields such as medicine, environmental protection, and industrial production could be further explored and developed. Further research on the interactions between cyanobacteria and metal NPs, including optimization of NPs size and composition, could lead to the development of new and improved products and technologies.

From the Table interpretation, silver and gold nanoparticles are the most used metals in the biosynthesis of nanoparticles by cyanobacteria. Silver nanoparticles have strong antioxidant and antibacterial properties to kill various types of respiratory tract pathogenic bacteria (Song et al. 2019). They also have the potential to the removal of malachite green dye and suppress pathogenic bacteria growth and cytotoxic effects on cancer cells (Sathiyavimal et al. 2022). Gold nanoparticles, on the other hand, have been found to have various potential applications. They have been found to enhance the transmission of electrons through the cell membrane by absorbing light and increasing the number of photo-excited electrons (Liu and Choi 2021). They also have activities that figureht off free radicals and myocardial infarction. They also have the potential as biocatalysts, bio-selective characters, and biocompatible (Wang et al. 2021). In summary, silver and gold nanoparticles have various potential applications and are commonly used in the biosynthesis of nanoparticles by cyanobacteria. These nanoparticles have promising characteristics in biomedical, environmental, and industrial fields.

Cyanobacterial bioactive compounds

As an abundant source of bioactive chemicals, cyanobacteria have been discovered. The majority of the bioactive substances that have been identified from cyanobacteria are lipopeptides, which are made up of an amino acid fragment and a fatty acid portion. Secondary metabolites extracted from cyanobacteria have a wide spectrum of biological activity, including antibacterial, antifungal, antialgal, anti-protozoan, and antiviral properties

Medical and pharmaceutical biotechnology

Cyanobacteria comprises several secondary metabolites that are useful in the field of medical biotechnology. These microbes have received tremendous attention from researchers because of the generation of bioactive compounds that are incredibly useful in medical settings (Żymańczyk-Duda et al. 2022). Although they generate effective toxins, they also generate various metabolites that are vital in terms of their anticancer (Dash et al. 2023), antibiotic (Saeed et al. 2022), anti-inflammatory (Gómez et al. 2023), immunosuppressant (Polyak and Sukharevich, 2023) and antimicrobial (Frazzini et al. 2022) effects. Cyanobacteria come in a variety of forms, making them a potential source of chemicals with therapeutic potential for malignant diseases including cancer. Different metabolic processes can be combined to produce a wide variety of bioactive substances with enormous biological potential.

Bioplastics and biofuel production

Cyanobacteria are incredibly well-suited for producing biodegradable plastics and biofuels because they

Table 1 A collection of some cyanobacteria used in different nanoparticle biosynthesis.

Cyanobacteria strains	Metal	NP Size (nm)	Applications	Reference
Phormidium tenue	Ca	5	Bio tagging	(MubarakAli et al. 2012)
Cylindrospermum stagnale	Cu	12.21	Effectively inhibit the growth of the pathogens *Candida albicans, Klebsiella pneumoniae, Enterobacter cloacae, Pseudomonas aeruginosa*, and *Escherichia coli*, with minimum inhibitory concentrations of 1.5, 2.4, 1.7, 2.5, and 0.6 mM, respectively. Cytotoxic to the HepG2 cell line and effective against the larvae of *Aedes aegypti, Anopheles subpictus Grassi,* and *Culex quinquefasciatus.*	(Sonbol et al. 2021)
Synechocystis sp. PCC 6803		–	Enhances the transmission of electrons through the cell membrane by absorbing light and increasing the number of photo-excited electrons.	(Liu and Choi 2021)
Lyngbya majuscule		41	Fight off free radicals and myocardial infarction.	(Bakir et al. 2018)
Anabaena cylindrica		< 10	Cyanobacteria have a bioselective character.	(Rochert et al. 2017)
Anabaena laxa		-	Biocatalyst	(Lenartowicz et al. 2017)
Leptolyngbya tenuis *Coleofasciculus chthonoplastes* *Nostoc ellipsosporum*	Au	40	Bio-compatibility	(Parial et al. 2016)
Phormidium willei		25	Antioxidant qualities biolabeling (gold and DNA interaction)	(MubarakAli et al. 2013)
Synechocystis sp. PCC 6803		13 ± 2	Biomolecule sensing	(Focsan et al. 2011)
Spirulina subsalsa		< 20	Bio-recovery of gold	(Chakraborty et al. 2009)
Spirulina plantensis	Pa	10-20	Lead uptake up to 90%	(Sayadi et al. 2018)
Arthrospira (Spirulina) platensis	Se	100-550	Antioxidant Action	(Zinicovscaia et al. 2017)
Nostoc muscorum NCCU 442		30	Strong antioxidant and antibacterial properties. The highest level of antibacterial activity was observed against the pathogen *Staphylococcus aureus* MTCC 902.	(Husain et al. 2021)
Spirulina platensis		13	The ability to kill seven different types of bacteria commonly found in the respiratory tract.	(Ameen et al. 2020)
Anabaena variabilis *Spirulina platensis*		17.9 -26.4	Malachite green dye was removed by 93% using *S. platensis* and 82% using *A. variabilis* AgNPs	(Ismail et al. 2021)
Desertifilum IPPAS B-1220		4.5- 26	Five pathogenic bacteria growth was suppressed Cytotoxic effects on MCF-7, HepG2, and Caco-2 cancer cells with IC50 values of 58, 32, and 90 µg/mL, respectively.	(Hamida et al. 2020a)
Chroococcus minutus		-	The lowest effective dose of 100 mg was found to have the ability to kill pathogenic strains of *E. coli* and *S. pyogenes*, which are responsible for upper respiratory tract infections.	(Sahoo et al. 2020)
Anabaena flos-aquae		5-25	Treatment of T47D cells with AgNPs for 24 h resulted in a 6.21% increase in apoptosis and a 28% increase in necrosis.	(Ebrahimzadeh et al. 2020)
Haloleptolyngbya alcalis KR2005/106	Ag	< 50	Monitoring water quality using ammonia.	(Tomer et al. 2019)
Phormidium sp.		-	Antimicrobial for *P. aeruginosa, E. coli,* and *S. aureus*	(Al Rashed et al. 2018)
Phycocyanin extracted from Nostoc linckia		9-26	Breast cancer cytotoxicity test and antibacterial against *S. aureus, Pseudomonas aeruginosa, E. coli,* and *Klebsiella pneumonia.*	(El-Naggar et al. 2017)
Nostoc sp. strain HKAR-2		51-100	Anti-cancer cytotoxic action in humans MCF-7 cells were discovered to have an IC50 of 27.5 g/mL Antibacterial and antifungal activities.	(Sonker et al. 2017)
Lyngbya majuscule		20-50	Both antibiotic and leukemic	(Roychoudhury et al. 2016)
Synechococcus sp.		430-450	*B. subtilis, E. coli,* and *S. aureus* antibacterial test Degradation of methylene blue	(San Keskin et al. 2016)
Spirulina platensis		-	Use of therapeutic thermostable silver nanoparticles	(Kaliamurthi et al. 2016)
Nostoc commune		15-54	Surface sterilization, antibacterial and antibacterial	(Morsy et al. 2014)
Microcoleus sp.		44-64	Antimicrobial against *Streptococcus sp., B. subtilis, S. aureus, E. coli, P. vulgaris, S. typhi, and V. cholera*	(Sudha et al. 2013)
Spirulina platensis	Ti	17.3	Powerful antioxidant ability	(Hifney and Abdel-Wahab 2019)
Desertifilium sp. EAZ03	Zn	88	Antimicrobial, antibiofilm, and anticancer properties against the pathogens *S. aureus, E. coli,* and *P. aeruginosa.* Anticancer properties against normal lung (MRC-5) cells.	(Ebadi et al. 2022)
Limnothrix sp. KO05		33	Compared to cells treated with ZnONPs, fibroblast L929 was less cytotoxic when exposed to PHY-ZnO NPs	(Davaeifar et al. 2019)
Anabaena sp. L31		80	UV-B-absorbing ZnO nanoparticles combined with the chemical shinorine	(Singh et al. 2014)
Anabaena variabilis	$AgCl_2$	12-20	A new report for utilizing the cyanobacterial species Anabaena variabilis in the nanotechnology field could provide future possible strategies for application in many fields.	(Hamed et al. 2017)

have such remarkable mechanisms for fixing and absorbing atmospheric nitrogen and CO_2 and using them to grow in unfavorable climatic environments, like infertile soils and saline waters (Samadhiya et al. 2022). *Synechocystis*, *Spirulina*, *Anabaena*, and *Nostoc muscorum* are cyanobacteria that can serve as bio-factories to produce biofuel and bioplastic. They have the metabolic capacity to produce, among other copolymers, polyhydroxybutyrate (PHB) and polyhydroxyalkanoates (PHAs); two biopolymers that are both affordable and sustainable (Singh et al., 2017). Polyhydroxyalkanoates (PHA) is a biocompatible substance that is also being researched for use in the biomedical (Ansari et al. 2021) and biopharmaceutical (Elmowafy et al. 2019) industries. It is believed that synthesizing PHA from CO_2 will help developing a carbon-neutral plastic manufacturing method.

The material properties of biopolymeric PHB are similar to those of polypropylene; a common plastic made from petroleum (fossil fuels). PHB is biodegradable compared to normal plastics; therefore using it in place of standard plastics can help mitigate the negative ecological effects of excessive consumption of nonbiodegradable plastics and fossil fuels (Kiran et al., 2014; Klanchui et al. 2017).

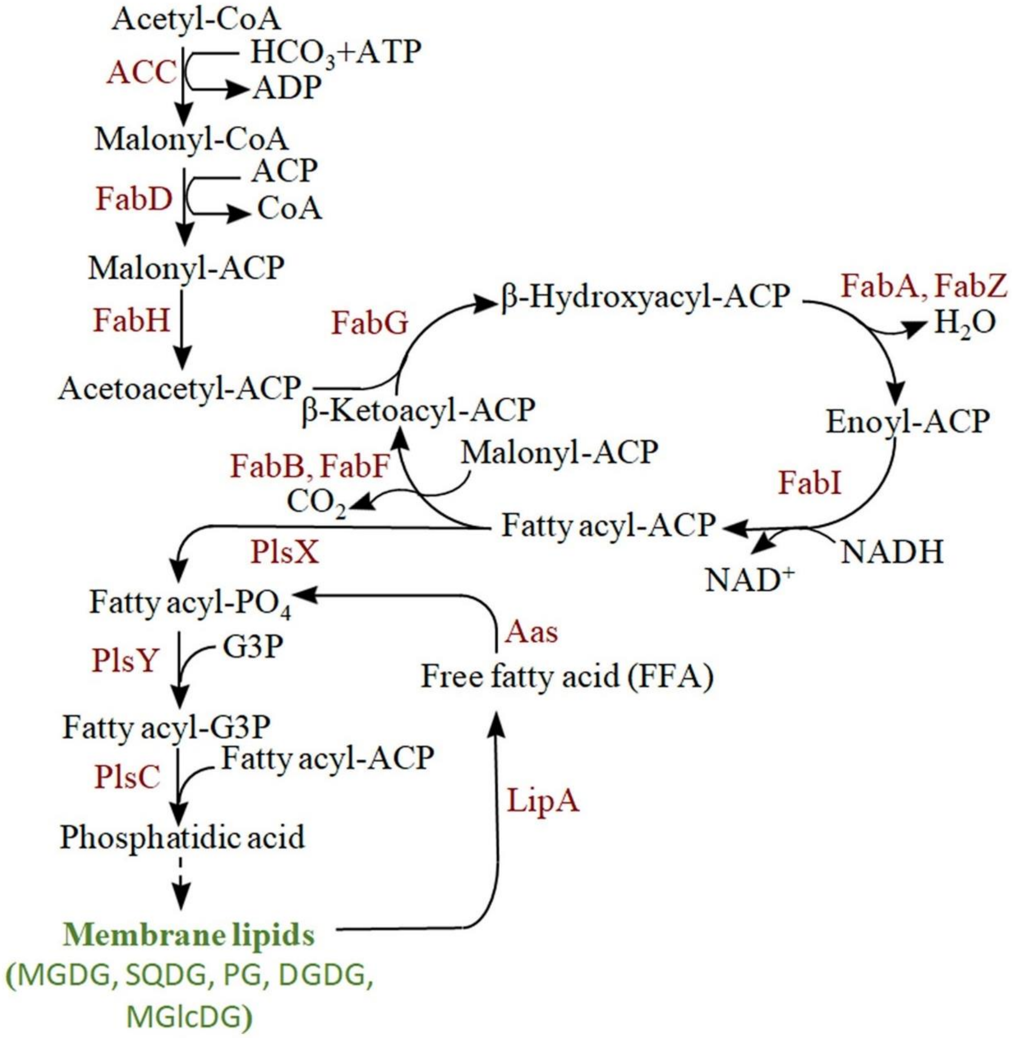

Fig. 3 Metabolism of lipid and fatty acid in cyanobacteria where MGlcDG: monoglucosyldiacylglycerol, MGDG: monogalactosyldiacylglycerol, DGDG: digalactosyldiacylglycerol, PlsC: putative 1-acyl-glycerol-P acyltransferase, PG: phosphotidylglycerol, SQDG: sulfoquinovosyldiacylglycerol, ACC: acetyl-coA carboxylase; ACP: acyl carrier protein. adopted with permission from (Velmurugan and Incharoensakdi 2022).

Bioremediation

Cyanobacteria are known for their remarkable adaptability to a variety of stress circumstances while also being quite resistant to hazardous substances from numerous sources (Rachedi et al. 2020). As a result, these photosynthetic bacteria are pertinent for a variety of bioremediation strategies, such as soil remediation, wastewater treatment, and the degradation of organic contaminants. As a result of anthropogenic activity, including urbanization, industrialization of the environment, as well as agricultural practices, water contamination constitutes a major environmental hazard. It has been demonstrated that brackish aquaculture effluent may be efficiently cleaned from ammonium using the marine *cyanobacterium* and *Synechococcus* sp. (Srimongkol et al. 2019). The usage of a cyanobacterial-bacterial consortium, which relies on the synergistic interaction between photosynthetic microorganisms and heterotrophic bacteria, is an intriguing method of biological wastewater treatment. It should be emphasized that these photosynthetic microbes are well-known for producing exopolysaccharides, which are essential for cyanobacteria to form symbiotic relationships with other organisms (Potnis et al. 2021). Cyanobacterial-bacterial aggregates were shown to be extremely efficient and successfully reduced the amounts of nitrogenous compounds, including nitrate (up to 80%), ammonium (up to 90%), and phosphorus compounds (up to 70%) in crude wastewater. These nitrogenous compounds included nitrate (up to 90%), and ammonium (up to 90%). The number of contaminants removed increased with the addition of an extra wastewater pretreatment stage including electrocoagulation and the use of an electrochemically treated supernatant as a substrate for the culture of microorganisms (Papadopoulos et al. 2020).

Cyanobacteria are a great choice for heavy metal removal due to a few characteristics. For instance, the characteristics of the cell wall, various transportation mechanisms, and the release of EPS (Javed et al. 2024). it has been observed that many cyanobacterial species can sequester heavy metal ions by biosorption, bioaccumulation, or, in many cases, a combination of the two. Certain species use EPS for biosorption to sequester heavy metal ions (Al-Amin et al. 2021). for example; *Anabaena doliolum* (Goswami, Syiem, & Pakshirajan, 2015), *Tolypothrixceytonica*, *Scenedesmus quadricauda* (Harris et al. 1990), *Cyanospira capsulate* and *Nostoc* PCC7936 (De Philippis et al. 2003), *Cyanospiracapsulata* ATCC43193, *Cyanothece* (ET5, TI4, PE14, VI22, CE4) and, *Nostoc* PCC7936 (Colica et al. 2010), *Gloeothece magna (Mohamed, 2001), Limnococcus* sp. (Sen et al. 2018), *Microcystis* sp. (Rai and Tripathi 2007), *Nostocmuscorum* (Roy et al. 2015). Various investigations discovered distinct functional groups in cyanobacterial EPS that are

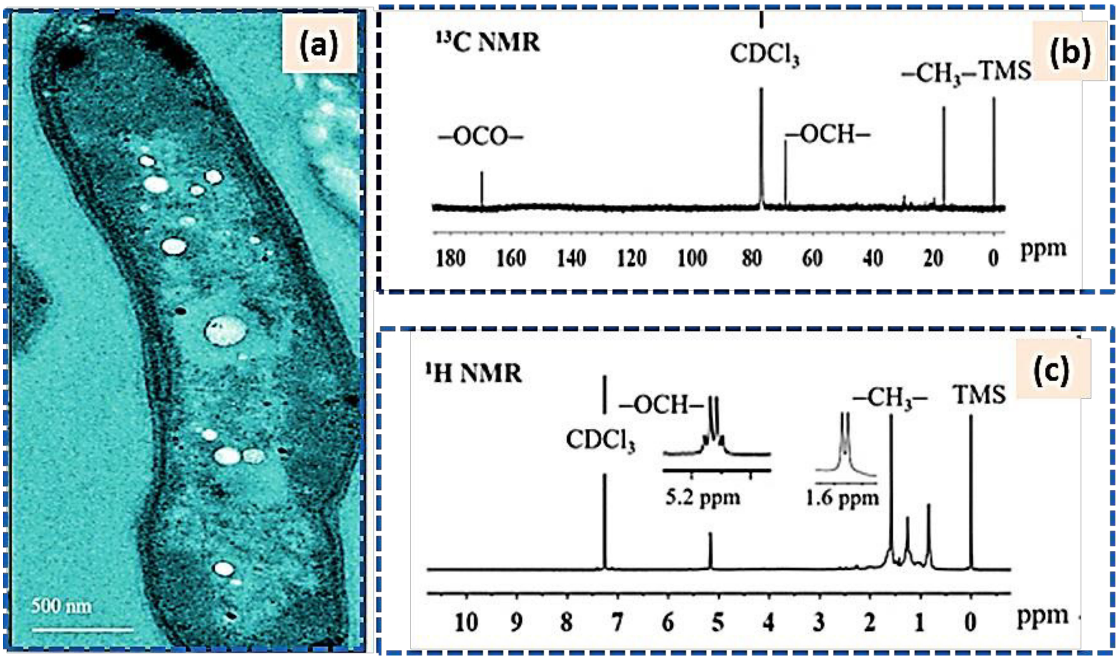

Fig. 4 TEM image (a), ^{13}C NMR (b), and ^{1}H (c) spectra of PLA homopolymer developed inside *S. elongatus* PCC7942. (Tan et al. 2022)

accountable for metal ion sorption. For example, Cu is bound to *Gloeothece* sp. by the carboxyl and amide groups (De Philippis and Micheletti 2017). *Anabaena doliolum*'s carboxyl, sulfate, carbonyl, amide, and hydroxyl groups facilitate the biosorption of copper from water (Goswami et al. 2015). It was discovered that the hydroxyl and amide functional groups of *Synechocystis* sp. PCC6803 (Shen et al. 2021) and *Chlorella miniate* (Han et al. 2008) absorbed Cr(III) and Cr(VI). based on contact time, biosorption and bioaccumulation capacity, multi-metal removal efficiency, and efficiency of heavy metal removal, *Limnococcus* sp. (Sen et al. 2018), *Nostocmuscorum* (Roy et al. 2015), and *Synechococcus* sp. PCC 7942 (Rahman et al. 2011) are among the better prospects for heavy metal removal.

Production of alternative bioenergy

A substitute for the finite supply of fossil fuels in the future, hydrogen gas has been produced by cyanobacteria (Dutta et al. 2005; Milano et al. 2016). The benefits of using biological hydrogen as a fuel include its capacity to be recycled, efficiency, and lack of emissions of carbon dioxide during its manufacture and use. When heterocystous cyanobacteria containing nitrogenase are cultivated under nitrogen-limiting conditions, hydrogen is either produced as a byproduct of nitrogen fixation or by the reversible activity of hydrogenase enzymes in cyanobacteria (Mishra et al. 2019). Because of this, heterocystous cyanobacteria are more effective in producing hydrogen than non-heterocystous varieties (Pinzon-Gamez et al. 2005).

Bio-fertilizers

For their capacity to fix atmospheric nitrogen, heterocystous cyanobacteria and a few non-heterocystous cyanobacteria are well-known (Bhardwaj et al. 2024). Numerous tropical rice field soils' fertility has been largely credited to the presence of nitrogen-fixing cyanobacteria. it was estimated that cyanobacteria contributed 0.23 to 75.5 kg of nitrogen per hectare per year to the soils (Heimann and Cirés 2015). It has been tried and succeeded in injecting cyanobacteria into the soil to boost soil fertility. It was discovered that adding *Azolla* helped soil microorganisms, notably heterotrophic N_2 fixers, proliferate. According to recent reports, nitrogen-fixing cyanobacteria predominate in desert crusts all around the world. It was shown that the addition of *Azolla* promoted the growth of heterotrophic N_2 fixers and other soil microbes. Recent studies claim that cyanobacteria that fix nitrogen predominate in desert crusts all around the world (Garcia-Pichel and Pringault 2001)

Healthy food source

Cyanobacteria are considered one of the richest sources of vitamin B12 and contain more than 60% protein in addition to being high in beta-carotene, thiamine, and riboflavin. Nostoc commune has a high protein and fiber content, making it a valuable nutrient and physiological component of the human diet (Oregon, USA). Zeaxanthin, beta-carotene, canthaxanthin, and astaxanthin, among other cyanobacterial carotenoids, are excellent sources used in food supplements, colorants, food additives, and animal feed. These metabolites are being produced in greater quantities. The dietary supplements can be purchased as tablets, granules, or capsules. For instance, cyanobacteria like Spirulina produce the widely used vitamins alpha-carotene, riboflavin, vitamin B12, and thiamine. As a whole meal or dietary supplement, cyanobacteria are also known to contain minerals, amino acids, proteins, complex sugar, carbohydrates, phycocyanin, active enzymes, vital fatty acids, and chlorophyll (Markou et al. 2021).

Contrary to extracts used in pharmaceutical processes, varieties of nutritional supplements are often made from the biomass of cyanobacterial species (Marsan et al. 2018). For instance, ketocarotenoid (astaxanthin) is regarded as a potent antioxidant in comparison to vitamin A, vitamin C, and other carotenoids that play a critical role in preventing photooxidation-induced cell death in humans. Astaxanthin, a potent protease inhibitor produced by the bacterium Haematococcus pluvialis, has been used to treat several illnesses, including the human immunodeficiency virus disease (the virus that causes AIDS, the terminal stage of HIV disease) (Gregoire et al. 2022; Omatola et al. 2020).

Conclusions and future recommendations

This review has shown that cyanobacteria are potentially useful supplies for several biotechnology applications, particularly nanotechnology. Most of the commercially available chemicals were extracted from freshwater cyanobacteria, demonstrating the biotechnological potential of cyanobacteria. Because photosynthesis diverts the pathway for producing hydrogen, hydrogen productivity tends to decline at greater light intensities; therefore, the light regime needs to be carefully managed. Cyanobacteria have long been researched for their fascinating shape, diversity, and physiology, but groundbreaking work in recent decades has elevated these germs to a level where they are now favorably considered in biotechnology-related domains. Because of this, it is crucial to both comprehend and describe the diversity of cyanobacteria in as-yet unknown habitats as well as to profitably harness them for a range of industrial applications. Taxonomists, molecular biologists, biochemists, engineers, scientists with an interest in industry, and decision-makers in politics must all work together to achieve this. More studies are required on the best ways to use cyanobacteria in conjunction with environmentally friendly technological developments, as well as effective understandings of cyanobacteria applications at bigger scales. To investigate more advantageous uses of cyanobacteria in biotechnology, future research that is likewise promising is required.

Competing interests The authors declare that they have no competing interests. The authors declare that no funds, grants, or other support were received during the preparation of this manuscript.

Authors' contributions All authors contributed to the article and approved the submitted version.

References

Abdel-Raouf N, Al-Enazi NM, Ibraheem IBM, Alharbi RM, Alkhulaifi MM (2019) Biosynthesis of silver nanoparticles by using of the marine brown alga padina pavonia and their characterization. Saudi J Biol Sci 26:1207–1215. DOI: 10.1016/j.sjbs.2018.01.007.

Abou El-Nour KMM, Eftaiha A, Al-Warthan A, Ammar RAA (2010) Synthesis and applications of silver nanoparticles. Arab J Chem 3:135–140. https://doi.org/10.1016/j.arabjc.2010.04.008

Al-Amin A, Parvin F, Chakraborty J Kim Y-I (2021) Cyanobacteria mediated heavy metal removal: A review on mechanism, biosynthesis and removal capability. Environ Technol Rev 10(1):44-57. https://doi.org/10.1080/21622515.2020.1869323

Al Rashed S, Al Shehri S, Moubayed NMS (2018) Extracellular biosynthesis of silver nanoparticles from Cyanobacteria. Biomed Res 29:2859–2862. DOI:10.4066/biomedicalresearch.29-17-3209

Albrecht MA, Evans CW, Raston CL (2006) Green chemistry and the health implications of nanoparticles. Green Chem 8:417–432. https://doi.org/10.1039/B517131H

Ameen F, Abdullah MMS, Al-Homaidan AA, Al-Lohedan HA, Al-Ghanayem AA, Almansob A (2020) Fabrication of silver nanoparticles employing the cyanobacterium *Spirulina platensis* and its bactericidal effect against opportunistic nosocomial pathogens of the respiratory tract. J Mol Struct 1217:128392. DOI:10.1016/j.molstruc.2020.128392

Ansari S, Sami N, Yasin D, Ahmad N, Fatma T (2021) Biomedical applications of environmental friendly poly-hydroxyalkanoates. Int J Biol Macromol 18:549–563. DOI: 10.1016/j.ijbiomac.2021.04.171

Arias DM, García J, Uggetti E (2020) Production of polymers by cyanobacteria grown in wastewater: Current status, challenges and future perspectives. N Biotechnol 55:46–57. DOI: 10.1016/j.nbt.2019.09.001

Asmathunisha N, Kathiresan K (2013) A review on biosynthesis of nanoparticles by marine organisms. Colloids Surfaces B Biointerfaces 103:283–287. https://doi.org/10.1016/j.colsurfb.2012.10.030

Bhardwaj A, Singh P, Gupta N, Bhattacharjee S, Srivastava A, Parida A, Mishra AK (2024) Cyanobacteria: a key player in nutrient cycling. In: *Cyanobacteria* (pp. 579-596): Elsevier. DOI:10.1016/B978-0-443-13231-5.00003-9

Bakir EM, Younis NS, Mohamed ME, El Semary NA (2018) Cyanobacteria as nanogold factories: chemical and anti-myocardial infarction properties of gold nanoparticles synthesized by *Lyngbya majuscula*. Mar Drugs 16:217. https://doi.org/10.3390/md16060217

Bishnoi A, Kumar S, Joshi N (2017) Wide-angle X-ray diffraction (WXRD): technique for characterization of nanomaterials and polymer nanocomposites in: Microscopy Methods in nanomaterials characterization. Elsevier, pp. 313–337. DOI: 10.1016/B978-0-323-46141-2.00009-2

Bonilla S, Aguilera A, Aubriot L, Huszar V, Almanza V, Haakonsson S, Izaguirre I, O'Farrell I, Salazar A, Becker V (2023) Nutrients and not temperature are the key drivers for cyanobacterial biomass in the Americas. Harmful Algae 121:102367. https://doi.org/10.1016/j.hal.2022.102367

Brito ÂMO (2015) Characterization of cyanobacterial strains isolated from the Portuguese coast: diversity and potential to produce bioactive compounds. https://repositorio-aberto.up.pt/handle/10216/101269

Chakraborty N, Banerjee A, Lahiri S, Panda A, Ghosh AN, Pal R (2009) Biorecovery of gold using cyanobacteria and an eukaryotic alga with special reference to nanogold formation–a novel phenomenon. J Appl Phycol 21:145–152. http://dx.doi.org/10.1007/s10811-008-9343-3

Colica G, Mecarozzi PC, De Philippis R (2010) Treatment of Cr (VI)-containing wastewaters with exopolysaccharide-producing cyanobacteria in pilot flow through and batch systems. Appl Micro biotech 87(5):1953-1961. DOI:10.1007/s00253-010-2665-5

Cruz D, Falé PL, Mourato A, Vaz PD, Serralheiro ML, Lino ARL (2010) Preparation and physicochemical characterization of Ag nanoparticles biosynthesized by *Lippia citriodora* (*Lemon Verbena*). Colloids surfaces B biointerfaces 81:67–73. DOI:10.1016/j.

colsurfb.2010.06.025.

Dash S, Pradhan S, Sahoo B, Parida S, Rath B (2023) In vitro study of antioxidant, antimicrobial, and anticancer activities of two selected cyanobacteria found across Odisha coast. India Syst Microbiol Biomanufacturing 1–16. DOI: 10.21203/rs.3.rs-1272821/v1

Davaeifar S, Modarresi M H, Mohammadi M, Hashemi E, Shafiei M, Maleki H, Vali H, Zahiri HS, Noghabi KA (2019) Synthesizing, characterizing and toxicity evaluating of Phycocyanin-ZnO nanorod composites: a back to nature approaches. Colloids Surfaces B Biointerfaces 175:221–230. https://doi.org/10.1016/j.colsurfb.2018.12.002

De Philippis R, Micheletti E (2017) Heavy metal removal with exopolysaccharide-producing cyanobacteria. In Handbook of advanced industrial and hazardous wastes management (pp. 931-964): CRC Press. https://doi.org/10.1201/9781315117423

Roberto De, Raffaella P, Claudio S, Massimo V (2003) Assessment of the metal removal capability of two capsulated cyanobacteria, *Cyanospira capsulata* and Nostoc PCC7936. J Appl Phycol 15:155-161. DOI:10.1023/A: 1023889410912.

Doman KM, Gharieb MM, Abd El-Monem AM, Morsi HH (2023) Synthesis of silver and copper nanoparticle using Spirulina platensis and evaluation of their anticancer activity. Int J Environ Health Res 1–13. DOI: 10.1080/09603123.2022.2163987

Dutta D, De D, Chaudhuri S, Bhattacharya SK (2005) Hydrogen production by cyanobacteria. Microb Cell Fact 4:1–11. https://doi.org/10.1186/1475-2859-4-36

Ebadi M, Zolfaghari MR, Aghaei SS, Zargar M, Noghabi KA (2022) Desertifilum sp. EAZ03 cell extract as a novel natural source for the biosynthesis of zinc oxide nanoparticles and antibacterial, anticancer and antibiofilm characteristics of synthesized zinc oxide nanoparticles. J Appl Microbiol 132:221–236. DOI: 10.1111/jam.15177

Ebrahiminezhad A, Bagheri M, Taghizadeh S M, Berenjian A, Ghasemi Y (2016) Biomimetic synthesis of silver nanoparticles using microalgal secretory carbohydrates as a novel anticancer and antimicrobial. Adv Nat Sci Nanosci Nanotechnol 7:15018. DOI:10.1088/2043-6262/7/1/015018

Ebrahimzadeh Z, Salehzadeh A, Naeemi AS, Jalali A (2020) Silver nanoparticles biosynthesized by *Anabaena* flos-aquae enhance the apoptosis in breast cancer cell line. Bull Mater Sci 43:1–7. DOI:10.1007/s12034-020-2064-1

El-Naggar NEA, Hussein MH, El-Sawah AA (2017) Bio-fabrication of silver nanoparticles by phycocyanin, characterization, in vitro anticancer activity against breast cancer cell line and in vivo cytotxicity. Sci Rep 7:10844. DOI:10.1038/s41598-017-11121-3

Elmowafy E, Abdal-Hay A, Skouras A, Tiboni M, Casettari L, Guarino V (2019) Polyhydroxyalkanoate (PHA): Applications in drug delivery and tissue engineering. Expert Rev Med Devices 16:467–482. DOI: 10.1080/17434440.2019.1615439

Elsayed K (2017) Production of biofuels from microalgae. Doctoral dissertation, IRC-library, information resource center der Jacobs University Bremen

Faghihzadeh F, Anaya NM, Schifman LA, Oyanedel-Craver V (2016) Fourier transform infrared spectroscopy to assess molecular-level changes in microorganisms exposed to nanoparticles. Nanotechnol Environ Eng 1:1–16. DOI:10.1007/s41204-016-0001-8

Fathy W, Elsayed K, Essawy E, Tawfik E, Zaki A, Abdelhameed MS, Hammouda O (2020) Biosynthesis of silver nanoparticles from synechocystis sp to be used as a flocculant agent with different microalgae strains. Curr Nanomater 5:175–187. DOI:10.2174/2468187310999200605161200

Focsan M, Ardelean II, Craciun C, Astilean S (2011) Interplay between gold nanoparticle biosynthesis and metabolic activity of cyanobacterium synechocystis sp. PCC 6803. Nanotechnology 22:485101. DOI:10.1088/0957-4484/22/48/485101

Frazzini S, Scaglia E, Dell'Anno M, Reggi S, Panseri S, Giromini C, Lanzoni D, Rossi CAS, Rossi L (2022) Antioxidant and antimicrobial activity of algal and cyanobacterial extracts: An in vitro study. Antioxidants 11:992. DOI: 10.3390/antiox11050992

Fulaz S, Vitale S, Quinn L, Casey E (2019) Nanoparticle–biofilm interactions: the role of the EPS matrix. Trends Microbiol 27:915–926. DOI: 10.1016/j.tim.2019.07.004

Gallardo T (2014) Marine algae: general aspects (biology, systematics, field and laboratory techniques). DOI:10.1201/b17540-2

Garcia-Pichel F, Pringault O (2001) Cyanobacteria track water in desert soils. Nature 413:380–381. DOI:10.1038/35096640

Gladyshev MI, Sushchik NN, Makhutova ON (2013) Production of EPA and DHA in aquatic ecosystems and their transfer to the land. Prostaglandins Other Lipid Mediat 107:117–126. https://doi.org/10.1016/j.prostaglandins.2013.03.002

Glazer AN (1977) Structure and molecular organization of the photosynthetic accessory pigments of cyanobacteria and red algae. Mol Cell Biochem 18:125–140. https://doi.org/10.1007/BF00280278

Gómez PI, Mayorga J, Flaig D, Castro-Varela P, Jaupi A, Ulloa PA, Soto-Bartierra J, Henríquez V, Rojas V (2023) Looking beyond arthrospira: Comparison of antioxidant and anti-inflammatory properties of ten cyanobacteria strains. Algal Res 103182. DOI:10.1016/j.algal.2023.103182

Goswami S, Syiem MB, Pakshirajan K (2015) Cadmium removal by *Anabaena doliolum* Ind1 isolated from a coal mining area in Meghalaya, India: associated structural and physiological alterations. Environ Eng Res 20(1):41-50. https://doi.org/10.4491/eer.2014.059

Gregoire E, Pirotte BF, Moerman F, Altdorfer A, Gaspard L, Firre E, Moonen M, Darcis G (2022) *Mycobacterium avium* complex and *Cryptococcus neoformans* co-infection in a patient with acquired immunodeficiency syndrome: a case report. Acta Clin Belg 77:679–684. DOI: 10.1080/17843286.2021.1919845

Grewe CB, Pulz O (2012)The biotechnology of cyanobacteria, in: Ecology of Cyanobacteria II: Their diversity in space and time. Springer pp. 707–739. https://doi.org/10.1007/978-94-007-3855-3_26.

Hamed SM, Abdel-Alim MM, Abdel-Raouf N, Ibraheem IB (2017) Biosynthesis of silver chloride nanoparticles using the cyanobacterium *Anabaena variabilis*. Life Sci J 14(6):25–30

Hamida RS, Abdelmeguid NE, Ali MA, Bin-Meferij MM, Khalil MI (2020a) Synthesis of silver nanoparticles using a novel *Cyanobacteria desertifilum* sp. extract: Their antibacterial and cytotoxicity effects. Int J Nanomedicine 49–63. https://doi.org/10.2147/IJN.S238575

Hamida RS, Ali MA, Redhwan A, Bin-Meferij MM (2020b) Cyanobacteria–a promising platform in green nanotechnology: a review on nanoparticles fabrication and their prospective applications. Int J Nanomedicine 6033–6066. DOI:10.2147/IJN.S256134

Han X, Wong YS, Wong MH, Tam NFY (2008) Feasibility of using microalgal biomass cultured in domestic wastewater for the removal of chromium pollutants. Wat Environ Res 80(7):647-653. DOI:10.1002/j.1554-7531.2008.tb00351.x

Hanna AL, Hamouda HM, Goda HA, Sadik MW, Moghanm FS, Ghoneim AM, Alenezi MA, Alnomasy SF, Alam P, Elsayed TR (2022) Biosynthesis and characterization of silver nanoparticles produced by *Phormidium ambiguum* and *Desertifilum tharense* cyanobacteria. Bioinorg Chem Appl 2022. DOI:10.1155/2022/9072508

Harris PO, Ramelow GJ (1990) Binding of metal ions by particulate biomass derived from *Chlorella vulgaris* and *Scenedesmus quadricauda*. Environ Sci and Technol 24(2):220-228. http://dx.doi.org/10.1021/es00072a011

Havens KE, Phlips EJ, Cichra MF, Li B (1998) Light availability as a possible regulator of cyanobacteria species composition in a shallow subtropical lake. Freshw Biol 39:547–556. DOI:10.1046/j.1365-2427.1998.00308.x

Heimann K, Cirés S (2015) N2-fixing cyanobacteria: ecology and biotechnological applications, in: Handbook of Marine Microalgae. Elsevier pp. 501–515. DOI:10.1016/B978-0-12-800776-1.00033-9

Hifney AF, Abdel-Wahab DA (2019) Phyco-based synthesis of TiO 2 nanoparticles and their influence on morphology, cyto-ultrastructure and metabolism of *Spirulina platensis*. Rend Lincei Sci Fis Nat 30:185–195. DOI:10.1007/s12210-019-00770-3

Hoo CM, Starostin N, West P, Mecartney ML (2008) A comparison of atomic force microscopy (AFM) and dynamic light scattering (DLS) methods to characterize nanoparticle size distributions. J Nanoparticle Res 10:89–96. DOI:10.1007/s11051-008-9435-7

Hotos G, Avramidou D, Mastropetros SG, Tsigkou K, Kouvara K, Makridis P, Kornaros M (2023) Isolation, identification, and chemical composition analysis of nine microalgal and cyanobacterial species isolated in lagoons of Western Greece. Algal Res 69:102935. https://doi.org/10.1016/j.algal.2022.102935

Huang R, Han Z, Ma C, Liu H, Huangfu X (2023) Stability and mobility of zinc oxide nanoparticles in aquatic environment: Influence of extracellular polymeric substances from cyanobacteria and microalgae. J Environ Chem Eng 11:109069. DOI:10.1016/j.jece.2022.109069

Husain S, Verma SK, Azam M, Sardar M, Haq QMR, Fatma T (2021) Antibacterial efficacy of facile cyanobacterial silver nanoparticles inferred by antioxidant mechanism. Mater Sci Eng C 122:111888. DOI: 10.1016/j.msec.2021.111888

Hussein M, Zaki A, Abdel-Raouf N, Alsamhary K, Fathy W, Abdelhameed M, Elsayed K (2022) Flocculation of microalgae using calcium oxide nanoparticles; process optimization and characterization. Int Aquat Res 14:63. ttps://doi.org/10.22034/IAR.2022.1943339.1206

Ibraheem IBM, Abd-Elaziz BEE, Saad WF, Fathy WA (2016) Green biosynthesis of silver nanoparticles using marine Red Algae *Acanthophora specifera* and its antimicrobial activity. J Nanomed Nanotechnol 7:1–4. DOI:10.4172/2157-7439.1000409

Iravani S, Korbekandi H, Mirmohammadi SV, Zolfaghari B (2014) Synthesis of silver nanoparticles: chemical, physical and biological methods. Res Pharm Sci 9:385

Ismail GA, Allam NG, El-Gemizy WM, Salem MA (2021) The role of silver nanoparticles biosynthesized by Anabaena variabilis and *Spirulina platensis* cyanobacteria for malachite green removal from wastewater. Environ Technol 42:4475–4489. DOI: 10.1080/09593330.2020.1766576

Javed M R, Perver N, Anwar A, tul Zahra F, Shafiq S, Abd Allah E F, Salman M (2024) Cyanobacteria-based green synthesis of nanoparticles for industrial applications. In pharmaceutical and nutraceutical potential of cyanobacteria (pp. 195-213): Springer. DOI:10.1007/978-3-031-45523-0_8

Jeevanandam J, Chan YS, Danquah MK (2016) Biosynthesis of metal and metal oxide nanoparticles. Chem Bio Eng Rev 3:55–67. DOI:10.1002/cben.201500018

Jha RK, Jha PK, Chaudhury K, Rana SVS, Guha SK (2014) An emerging interface between life science and nanotechnology: present status and prospects of reproductive healthcare aided by nano-biotechnology. Nano Rev 5:22762. https://doi.org/10.3402/nano.v5.22762

Joye SB, Lee RY (2004) Benthic microbial mats: important sources of fixed nitrogen and carbon to the twin cays, belize ecosystem. Atoll Res Bull. https://doi.org/10.5479/si.00775630.528.1

Kaliamurthi S, Selvaraj G, Çakmak ZE, Çakmak T (2016) Production and characterization of spherical thermostable silver nanoparticles from *Spirulina platensis* (Cyanophyceae). Phycologia 55:568–576. https://doi.org/10.2216/15-98.1

Kalyanasundaram GT, Ramasamy A, Rakesh S, Subburamu K (2020) Microalgae and cyanobacteria: Role and applications in agriculture. Appl Algal Biotechnol Nov Sci Publ. Hauppauge, NY, USA

Khan Y, Sadia H, Ali Shah SZ, Khan MN, Shah AA, Ullah N, Ullah MF, Bibi H, Bafakeeh OT, Khedher N Ben (2022) Classification, synthetic, and characterization approaches to nanoparticles, and their applications in various fields of nanotechnology: A review. Catalysts 12(11):1386. https://doi.org/10.3390/catal12111386

Kiran B, Kumar R, Deshmukh D (2014) Perspectives of microalgal biofuels as a renewable source of energy. Energy Convers Manag 88:1228–1244. https://doi.org/10.1016/j.enconman.2014.06.022

Klanchui A, Raethong N, Prommeenate P, Vongsangnak W, Meechai A (2017) Cyanobacterial biofuels: strategies and developments on network and modeling. Adv Biochem Eng Biotechnol 160:75–102. DOI: 10.1007/10_2016_42

Komárek J (2013) Cyanoprokaryota: 3rd Part: Heterocystous Genera. In: Büdel, B., Gärtner, G., Krienitz, L. and Schagerl, M., Eds., Süßwasserflora von Mitteleuropa, Bd. 19(3), Springer Spektrum, Berlin, Heidelberg, 1-1130

Kultschar B, Llewellyn C (2018) Secondary metabolites in cyanobacteria. In: Secondary metabolites - sources and applications. DOI: 10.5772/intechopen.75648

Kumar J, Singh D, Tyagi MB, Kumar A (2019) Cyanobacteria: applications in biotechnology, in: Cyanobacteria. Elsevier, pp. 327–346. https://doi.org/10.1016/B978-0-12-814667-5.00016-7

Lenartowicz M, Marek PH, Madura ID, Lipok J (2017) Formation of variously shaped gold nanoparticles by *Anabaena laxa*. J Clust Sci 28:3035–3055. DOI: 10.1007/s10876-017-1275-0

Liu L, Choi S (2021) Enhanced biophotoelectricity generation in cyanobacterial biophotovoltaics with intracellularly biosynthesized gold nanoparticles. J Power Sources 506:230251. https://doi.org/10.1016/j.jpowsour.2021.230251

Madkour LH (2017) Ecofriendly green biosynthesized of metallic nanoparticles: bio-reduction mechanism, characterization and pharmaceutical applications in biotechnology industry. Drugs Ther 3:1–11. DOI: 10.15761/GDT.1000144

Makarov VV, Love AJ, Sinitsyna OV, Makarova SS, Yaminsky IV, Taliansky ME, Kalinina NO (2014) “Green” nanotechnologies: synthesis of metal nanoparticles using plants. Acta Naturae 6:35–44. PMID: 24772325; PMCID: PMC3999464

Markl E, Grünbichler H, Lackner M (2018) Cyanobacteria for PHB bioplastics production: A review. In: Algae. DOI:10.5772/intechopen.81536

Markou G, Chentir I, Tzovenis I (2021) Microalgae and cyanobacteria as food: Legislative and safety aspects, In: Cultured Microalgae for the Food Industry. Academic Press, pp. 249–264. https://doi.org/https://doi.org/10.1016/B978-0-12-821080-2.00003-4

Markou G, Georgakakis D (2011) Cultivation of filamentous cyanobacteria (blue-green algae) in agro-industrial wastes and wastewaters: A review. Appl Energy 88:3389–3401. https://doi.org/10.1016/j.apenergy.2010.12.042

Marsan DW, Conrad SM, Stutts WL, Parker CH, Deeds JR (2018) Evaluation of microcystin contamination in blue-green algal dietary supplements using a protein phosphatase inhibition-based test kit. Heliyon 4. DOI: 10.1016/j.heliyon.2018.e00573

Mazari SA, Ali E, Abro R, Khan FSA, Ahmed I, Ahmed M, Nizamuddin S, Siddiqui TH, Hossain N, Mubarak NM, Shah A (2021) Nanomaterials: Applications, waste-handling, environmental toxicities, and future challenges–A review. J Environ Chem Eng 9:105028. https://doi.org/10.1016/j.jece.2021.105028

Milano J, Ong HC, Masjuki H, Chong W, Lam M K, Loh P K, Vellayan V(2016). Microalgae biofuels as an alternative to fossil fuel for power generation. Renew Sust Energ Rev 58:180-197. https://doi.org/10.1016/j.rser.2015.12.150

Mischke U (2003) Cyanobacteria associations in shallow polytrophic lakes: influence of environmental factors. Acta Oecologica 24:S11–S23. https://doi.org/10.1016/S1146-609X(03)00003-1

Mishra A K, Kaushik MS, Tiwari DN (2019) Nitrogenase and hydrogenase: enzymes for nitrogen fixation and hydrogen production in cyanobacteria. In: *Cyanobacteria*, 173-191. https://doi.org/10.1016/b978-0-12-814667-5.00008-8

Mishra U, Pabbi S (2004) Cyanobacteria: a potential biofertilizer for rice. Resonance 9:6–10. https://doi.org/10.1007/BF02839213

Mohamed ZA (2001) Removal of cadmium and manganese by a non-toxic strain of the fresh water cyanobacterium *Gloeothece magna*.Wat Res 35(18):4405-4409. DOI: 10.1016/s0043-1354(01)00160-9

Morone J, Alfeus A, Vasconcelos V, Martins R (2019) Revealing the potential of cyanobacteria in cosmetics and cosmeceuticals—A new bioactive approach. Algal Res 41:101541. https://doi.org/10.1016/j.algal.2019.101541

Morsy FM, Nafady NA, Abd-Alla MH, Elhady DA (2014) Green synthesis of silver nanoparticles by water soluble fraction of the extracellular polysaccharides/matrix of the cyanobacterium nostoc commune and its application as a potent fungal surface sterilizing agent of seed crops. Univ J Microbiol Res 2:36–43. DOI: 10.13189/ujmr.2014.020303

MubarakAli D, Arunkumar J, Nag KH, SheikSyedIshack KA, Baldev E, Pandiaraj D, Thajuddin N (2013) Gold nanoparticles from Pro and eukaryotic photosynthetic microorganisms—Comparative studies on synthesis and its application on biolabelling. Colloids Surfaces B Biointerfaces 103:166–173. https://doi.org/10.1016/j.colsurfb.2012.10.014

MubarakAli D, Gopinath V, Rameshbabu N, Thajuddin N (2012) Synthesis and characterization of CdS nanoparticles using C-phycoerythrin from the marine cyanobacteria. Mater Lett 74:8–11. https://doi.org/10.1016/j.matlet.2012.01.026

Nnadozie CF, Lin J, Govinden R (2015) Selective isolation of bacteria for metagenomic analysis: impact of membrane characteristics on bacterial filterability. Biotechnol Prog 31(4):853–866. DOI 10.1002/btpr.2109

Omatola CA, Okolo L-MO, Adaji DM, Mofolorunsho CK, Oyiguh JA, Zige DV, Akpala NS, Samson SO (2020) Coinfection of human immunodeficiency virus-infected patients with hepatitis B virus in Lokoja, North Central Nigeria. Viral Immunol 33:391–395. DOI: 10.1089/vim.2019.0157

Paerl HW, Otten TG (2013) Harmful cyanobacterial blooms: causes, consequences, and controls. Microb Ecol 65:995–1010. DOI: 10.1007/s00248-012-0159-y

Papadopoulos KP, Economou CN, Tekerlekopoulou AG, Vayenas DV (2020) Two-step treatment of brewery wastewater using electrocoagulation and cyanobacteria-based cultivation. J Environ Manage 265:110543. https://doi.org/10.1016/j.jenvman.2020.110543

Parial D, Gopal PK, Paul S, Pal R (2016) Gold (III) bioreduction by cyanobacteria with special reference to in vitro biosafety assay of gold nanoparticles. J Appl Phycol 28:3395–3406. DOI:10.1007/s10811-016-0880-x

Parmar A, Singh NK, Pandey A, Gnansounou E, Madamwar D (2011) Cyanobacteria and microalgae: a positive prospect for biofuels. Bioresour Technol 102:10163–10172. https://doi.org/10.1016/j.biortech.2011.08.030

Patel P, Agarwal P, Kanawaria S, Kachhwaha S, Kothari SL (2015) Plant-based synthesis of silver nanoparticles and their characterization. In: Nanotechnology and Plant Sciences (pp.271-288). DOI:10.1007/978-3-319-14502-0_13

Pinevich AV (2008) Paradoxes of biodiversity, phylogeny and taxonomy of cyanobacteria. Moscow Univ Biol Sci Bull 63:21–24. https://doi.org/10.1007/s11966-008-1004-x

Pinzon-Gamez NM, Sundaram S, Ju L-K (2005) Heterocyst differentiation and H2 production in N2-fixing cyanobacteria. AIChE Annual Meeting Conference, American Institute of Chemical Engineers

Pirtarighat S, Ghannadnia M, Baghshahi S (2019) Biosynthesis of silver nanoparticles using *Ocimum basilicum* cultured under controlled conditions for bactericidal application. Mater Sci Eng C 98:250–255. DOI: 10.1016/j.msec.2018.12.090

Polyak YM, Sukharevich VI (2023) Problems and prospects of applications of cyanobacteria (Review). Inl Water Biol 16:62–69. DOI:10.1134/s1995082923010121

Potnis AA, Raghavan PS, Rajaram H (2021) Overview on cyanobacterial exopolysaccharides and biofilms: Role in bioremediation. Rev Environ Sci Biotechnol 20:781–794. DOI:10.1007/s11157-021-09586-w

Prasanna R, Kumar R, Sood A, Prasanna BM, Singh PK (2006) Morphological, physiochemical and molecular characterization of Anabaena strains. Microbiol Res 161:187–202. https://doi.org/10.1016/j.micres.2005.08.001

Quesada A, Leganés F, Fernández-Valiente E (1997) Environmental factors controlling N2 fixation in mediterranean rice fields. Microb Ecol 34:39–48. DOI: 10.1007/s002489900032

Rachedi R, Foglino M, Latifi A (2020) Stress signaling in cyanobacteria: A mechanistic overview. Life 10(12):312. DOI: 10.3390/life10120312

Rahman A, Kumar S, Nawaz T (2020) Biosynthesis of nanomaterials using algae. in book: Microalgae cultivation for biofuels production. Elsevier, pp. 265–279. DOI:10.1016/B978-0-12-817536-1.00017-5

Rahman MA, Soumya K, Tripathi A, Sundaram S, Singh S, Gupta A (2011) Evaluation and sensitivity of cyanobacteria, *Nostoc muscorum* and *Synechococcus PCC 7942* for heavy metals stress–a step toward biosensor. Toxicol Environ Chem 93(10):1982–1990. https://doi.org/10.1080/02772248.2011.606110

Rai PK, Tripathi BD (2007) Removal of heavy metals by the nuisance cyanobacteria *Microcystis* in continuous cultures: an eco-sustainable technology. Environ Sci 4(1):53-59. https://doi.org/10.1080/15693430601164956

Rastogi A, Singh P, Haraz FA, Barhoum A (2018) Biological synthesis of nanoparticles: An environmentally benign approach, in: Fundamentals of nanoparticles. Elsevier, pp. 571–604. DOI:10.1016/B978-0-323-51255-8.00023-9

Reeve S, Palmer B, Cobb P, Pietrasiak N, Lipson DA (2023) Facilitating restoration of degraded biological soil crusts using mixed culture inoculation. J Arid Environ 208:104876. DOI:10.1016/j.jaridenv.2022.104876

Rippka R (1988) Isolation and purification of cyanobacteria. Methods Enzymol 167:3–27. https://doi.org/10.1016/0076-

6879(88)67004-2

Rochert AS, Rösken LM, Fischer CB, Schönleber A, Ecker D, van Smaalen S, Geimer S, Wehner S (2017) Bioselective synthesis of gold nanoparticles from diluted mixed Au, Ir, and Rh ion solution by Anabaena cylindrica. J Nanoparticle Res 19:1–15. DOI:10.1007/s11051-017-4039-8

Roy A, Bulut O, Some S, Mandal AK, Yilmaz MD (2019) Green synthesis of silver nanoparticles: biomolecule-nanoparticle organizations targeting antimicrobial activity. RSC Adv 9:2673–2702. DOI:10.1039/c8ra08982e

Roy AS, Hazarika J, Manikandan NA, Pakshirajan K, Syiem MB (2015) Heavy metal removal from multicomponent system by the cyanobacterium *Nostoc muscorum*: kinetics and interaction study. Appl Biochem Biotechnol 175:3863-3874. DOI: 10.1007/s12010-015-1553-y

Roychoudhury P, Gopal PK, Paul S, Pal R (2016) Cyanobacteria assisted biosynthesis of silver nanoparticles—a potential antileukemic agent. J Appl Phycol 28:3387–3394.DOI: 10.1007/s10811-016-0852-1

Saeed MU, Hussain N, Shahbaz A, Hameed T, Iqbal HMN, Bilal M (2022) Bioprospecting microalgae and cyanobacteria for biopharmaceutical applications. J Basic Microbiol 62:1110–1124. DOI:10.1002/jobm.202100445

Sahoo CR, Maharana S, Mandhata CP, Bishoyi AK, Paidesetty SK, Padhy RN (2020) Biogenic silver nanoparticle synthesis with cyanobacterium *Chroococcus minutus* isolated from Baliharachandi sea-mouth, Odisha and in vitro antibacterial activity. Saudi J Biol Sci 27:1580–1586. DOI: 10.1016/j.sjbs.2020.03.020

Salmaso N (2000) Factors affecting the seasonality and distribution of cyanobacteria and chlorophytes: a case study from the large lakes south of the Alps, with special reference to Lake Garda. Hydrobiologia 438:43–63. https://doi.org/10.1023/A:1004157828049

Samadhiya K, Sangtani R, Nogueira R, Bala K (2022) Insightful advancement and opportunities for microbial bioplastic production. Front Microbiol 12:674864. DOI:10.3389/fmicb.2021.674864

San Keskin NO, Kılıç, NK, Dönmez G, Tekinay T (2016) Green synthesis of silver nanoparticles using cyanobacteria and evaluation of their photocatalytic and antimicrobial activity. J Nano Res 40:120–127. DOI:10.4028/www.scientific.net/JNanoR.40.120

Sanchez-Baracaldo P, Hayes PK, Blank CE (2005) Morphological and habitat evolution in the Cyanobacteria using a compartmentalization approach. Geobiology 3:145–165. DOI:10.1111/j.1472-4669.2005.00050.x

Saranraj P, Sivasakthi S (2014) *Spirulina platensis*–food for future: a review. Asian J Pharm Sci Technol 4:26–33

Sathiyavimal S, Durán-Lara EF, Vasantharaj S, Saravanan M, Sabour A, Alshiekheid, M, Chi NTL, Brindhadevi K, Pugazhendhi A (2022) Green synthesis of copper oxide nanoparticles using *Abutilon indicum* leaves extract and their evaluation of antibacterial, anticancer in human A549 lung and MDA-MB-231 breast cancer cells. Food Chem Toxicol 168:113330. DOI: 10.1016/j.fct.2022.113330

Sayadi MH, Salmani N, Heidari A, Rezaei MR (2018) Bio-synthesis of palladium nanoparticle using *Spirulina platensis* alga extract and its application as adsorbent. Surf Interfaces 10:136–143. DOI:10.1016/j.surfin.2018.01.002

Schulte NO, Carlisle DM, Spaulding SA (2022) Natural and anthropogenic influences on benthic cyanobacteria in streams of the northeastern United States. Sci Total Environ 826:154241. DOI:10.1016/j.scitotenv.2022.154241

Sen G, Sen S, Thakurta SG, Chakrabarty J, Dutta S (2018) Bioremediation of Cr (VI) using live cyanobacteria: experimentation and kinetic modeling. J Enviro Eng 144(9). DOI:10.1061/(ASCE)EE.1943-7870.0001425

Shehap AM, Akil DS (2016) Structural and optical properties of TiO 2 nanoparticles/PVA for different composites thin films. Int J Nanoelectron Mater 9:17-36

Shen L, Chen R, Wang J, Fan L, Cui L, Zhang Y, Jinju C, Wu X, Li J, Zeng W(2021) Biosorption behavior and mechanism of cadmium from aqueous solutions by *Synechocystis sp*. PCC6803. RSC Adv 11(30):18637-18650. DOI:10.1039/D1RA02366G

Bagali SS (2012) Nitrogen fixing microorganisms. Int J Microbiol Res 3:46–52. DOI:10.5829/idosi.ijmr.2012.3.1.61103

Singh G, Babele PK, Kumar A, Srivastava A, Sinha RP, Tyagi MB (2014) Synthesis of ZnO nanoparticles using the cell extract of the *cyanobacterium*, *Anabaena* strain L31 and its conjugation with UV-B absorbing compound shinorine. J Photochem Photobiol B Biol 138:55–62. DOI:10.1016/j.jphotobiol.2014.04.030

Singh R, Parihar P, Singh M, Bajguz A, Kumar J, Singh S, Singh VP, Prasad SM (2017) Uncovering potential applications of cyanobacteria and algal metabolites in biology, agriculture and medicine: current status and future prospects. Front Microbiol 8:515. DOI:10.3389/fmicb.2017.00515

Sonbol H, AlYahya S, Ameen F, Alsamhary K, Alwakeel S, Al-Otaibi S, Korany S (2021) Bioinspired synthesize of CuO nanoparticles using *Cylindrospermum stagnale* for antibacterial, anticancer and larvicidal applications. Appl Nanosci 1–11. DOI:10.1007/s13204-021-01940-2

Song Z, Wu Y, Wang H, Han H (2019) Synergistic antibacterial effects of curcumin modified silver nanoparticles through ROS-mediated pathways. Mater Sci Eng C 99:255–263. DOI:10.1016/j.msec.2018.12.053

Sonker AS, Pathak J, Kannaujiya VK, Sinha RP (2017) Characterization and in vitro antitumor, antibacterial and antifungal activities of green synthesized silver nanoparticles using cell extract of *Nostoc sp*. strain HKAR-2. Can J Biotechnol 1(1):26. DOI:10.24870/cjb.2017-000103

Sorbiun M, Mehr ES, Ramazani A, Malekzadeh AM (2018) Biosynthesis of metallic nanoparticles using plant extracts and evaluation of their antibacterial properties. Nanochemistry Res 3:1–16. DOI: 10.22036/ncr.2018.01.001

Srimongkol P, Thongchul N, Phunpruch S, Karnchanatat A (2019) Ability of marine cyanobacterium *Synechococcus sp*. VDW to remove ammonium from brackish aquaculture wastewater. Agric Wat Manag 212:155–161. https://doi.org/10.1016/j.agwat.2018.09.006

Srivastava S, Fuentes F, Bhargava A (2022) Algal Synthesis of gold nanoparticles: Applications in bioenergy. In: Technological advancement in algal biofuels production. Springer, 109–127. DOI:10.1007/978-981-19-6806-8_4

Sudha SS, Rajamanickam K, Rengaramanujam J (2013) Microalgae mediated synthesis of silver nanoparticles and their antibacterial activity against pathogenic bacteria. Ind J Exp Biol 51(5):393-9

Svrcek C, Smith DW (2004) Cyanobacteria toxins and the current state of knowledge on water treatment options: a review. J Environ Eng Sci 3(3):155–185. DOI:10.1139/s04-010

Tan C, Tao F, Xu P (2022) Direct carbon capture for the production of high-performance biodegradable plastics by cyanobacterial cell factories. Green Chem 24:4470–4483. https://doi.org/10.1039/D1GC04188F

Thakkar KN, Mhatre SS, Parikh RY (2010) Biological synthesis of metallic nanoparticles. Nanomedicine nanotechnology. Biol Med

6:257–262. https://doi.org/10.1016/j.nano.2009.07.002

Tomer AK, RahiT, Neelam DK, Dadheech PK (2019) Cyanobacterial extract-mediated synthesis of silver nanoparticles and their application in ammonia sensing. Int Microbiol 22:49–58. https://doi.org/10.1007/s10123-018-0026-x

Velmurugan R, Incharoensakdi A (2022) Metabolic transformation of cyanobacteria for biofuel production. Chemosphere 299:134342. https://doi.org/10.1016/j.chemosphere.2022.134342

Wang L, Zhu B, Deng Y, Li T, Tian Q, Yuan Z, Ma L, Cheng C, Guo Q, Qiu L (2021) Biocatalytic and antioxidant nanostructures for ROS scavenging and biotherapeutics. Adv Funct Mater 31:2101804. https://doi.org/10.1002/adfm.202101804

Wilson BK, Prud'homme RK(2021) Nanoparticle size distribution quantification from transmission electron microscopy (TEM) of ruthenium tetroxide stained polymeric nanoparticles. J Colloid Interface Sci 604:208–220. DOI: 10.1016/j.jcis.2021.04.081

Zahra Z, Choo DH, Lee H, Parveen A (2020) Cyanobacteria: Review of current potentials and applications. Environments 7:13. https://doi.org/10.3390/environments7020013

Zhang L, Pornpattananangkul D, Hu CM, Huang CM (2010) Development of nanoparticles for antimicrobial drug delivery. Curr Med Chem 17:585–594. DOI: 10.2174/092986710790416290

Zinicovscaia I, Chiriac T, Cepoi L, Rudi L, Culicov O, Frontasyeva M, Rudic V (2017) Selenium uptake and assessment of the biochemical changes in *Arthrospira* (*Spirulina*) *platensis* biomass during the synthesis of selenium nanoparticles. Can J Microbiol 63:27–34. DOI: 10.1139/cjm-2016-0339

Żymańczyk-Duda E, Samson SO, Brzezińska-Rodak M, Klimek-Ochab M (2022) Versatile applications of cyanobacteria in biotechnology. Microorganisms 10:2318. DOI: 10.3390/microorganisms10122318

Publisher's Note