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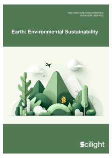

Review

Cyanobacteria: Can They Serve as Natural Sponges for Environmental Contaminants?

Anastasiia Bolshakova †, Gaurav Bhardwaj †, Khyati Joshi †, Ratul Kumar Das and Satinder Kaur Brar *

Department of Civil Engineering, Lassonde School of Engineering, York University, North York, Toronto, ON M3J 1P3, Canada
* Correspondence: Satinder.Brar@lassonde.yorku.ca
† These authors contributed equally to this work.

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Abstract: Cyanobacteria are highly effective microorganisms with strong potential for remediation of a wide range of contaminants, including heavy metals, pharmaceuticals and personal care products (PPCPs), synthetic dyes, polycyclic aromatic hydrocarbons (PAHs), per- and polyfluoroalkyl substances (PFAS), polychlorinated biphenyls (PCBs), and other organic pollutants, commonly found across aquatic environments. This review critically discusses cyanobacteria as natural absorbents ("sponges") and examines related mechanisms of bioremediation: biosorption, bioaccumulation, and biodegradation, while exploring sustainable approaches for resource recovery and biomass valorization. Various bioreactor configurations have also been discussed for optimizing growth and pollutant removal efficiency. This review brings together current knowledge on cyanobacteria-based remediation and outlines key directions needed to move these approaches toward reliable, real-world implementation.

Keywords: cyanobacteria; emerging contaminants; bioremediation; circular bioeconomy; bioreactor systems

1. Introduction

Cyanobacteria are among the oldest and most ubiquitous photosynthetic microorganisms on Earth, thriving across a wide range of aquatic and terrestrial environments, including freshwater lakes, rivers, marine systems, and wastewater streams [1]. Beyond their established roles in global carbon and nitrogen cycling, cyanobacteria are most prominently recognized for their ability to form cyanobacterial harmful algal blooms (HABs), which have increased in frequency, intensity, and geographic extent due to nutrient enrichment and climate-driven changes in aquatic systems [2]. These blooms are widely associated with deteriorated water quality, hypoxia, and the production of cyanotoxins, posing risks to ecosystems and human health [2]. However, the physiological traits that enable bloom formation, such as rapid growth, extensive extracellular polymeric substance (EPS) production, and metabolic flexibility, also influence the fate and behavior of environmental contaminants in aquatic systems [3,4].

In recent years, cyanobacteria have emerged as key biological agents capable of accumulating, transforming, and sequestering a wide range of contaminants of emerging concern (CECs), effectively acting as natural "sinks" or "biological sponges" in aquatic ecosystems [5–7]. These contaminants include heavy metals, microplastics, pharmaceuticals and personal care products (PPCPs), per- and polyfluoroalkyl substances (PFAS), polycyclic aromatic hydrocarbons (PAHs), and polychlorinated biphenyls (PCBs) [6–12]. In many aquatic systems, cyanobacteria coexist with these pollutants, particularly in eutrophic waters and wastewater-impacted environments, where nutrient enrichment and contaminant loading overlap, creating conditions that enhance microbial-pollutant interactions [13] (Figure 1).

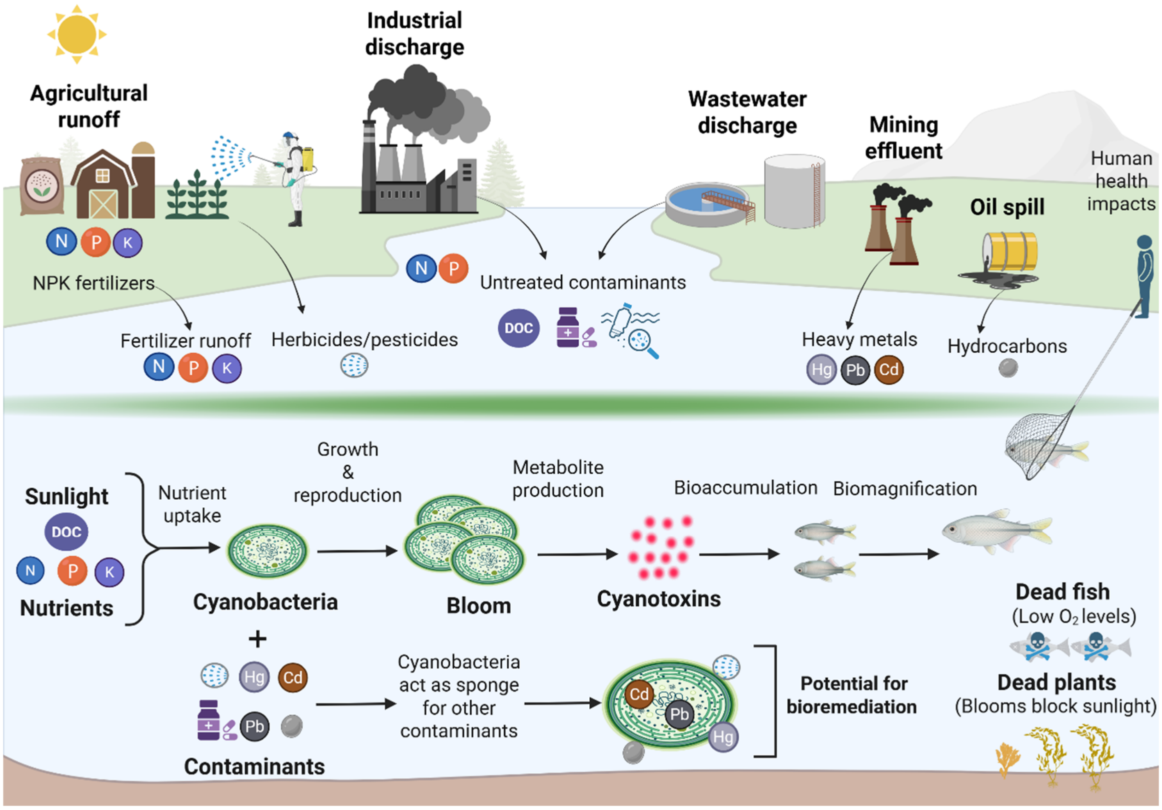


Figure 1. Schematic overview of cyanobacterial growth, reproduction, ecological effects, and potential for bioremediation.

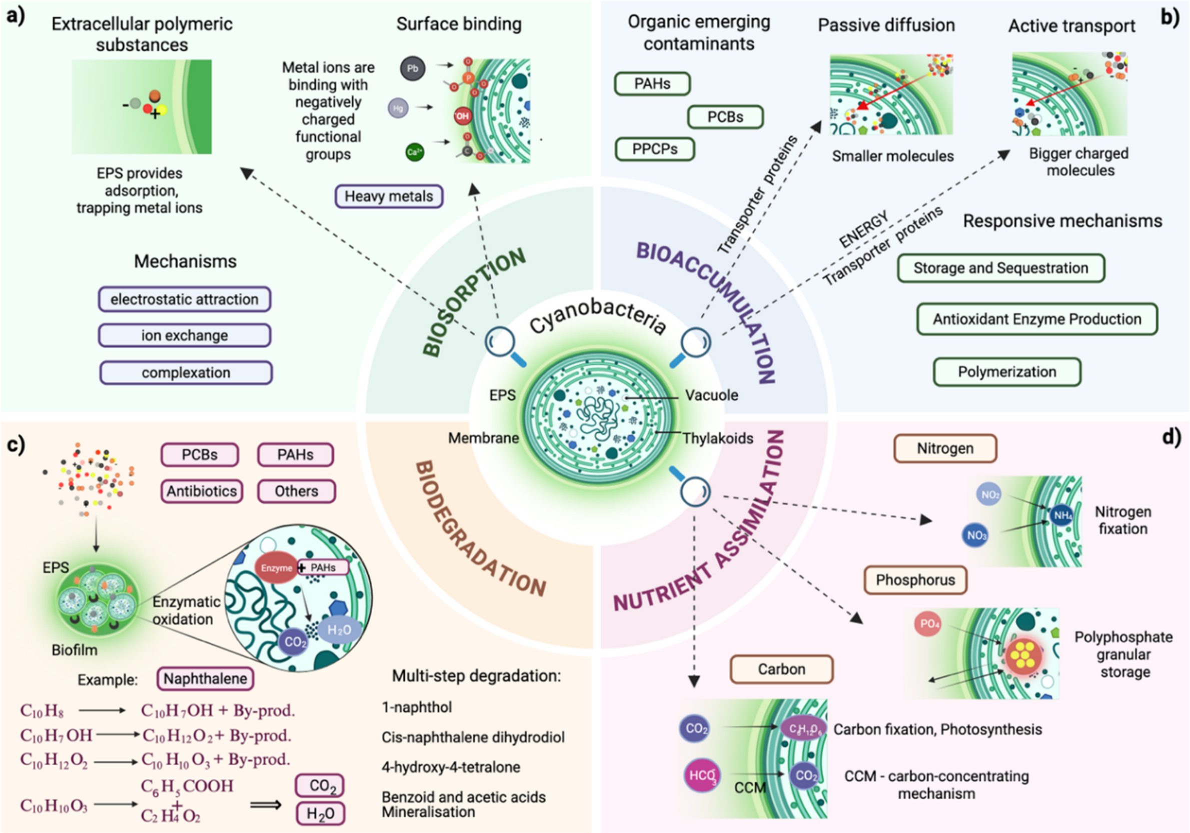
The ability of cyanobacteria to interact with contaminants is rooted in their unique cellular and extracellular structure. Cyanobacterial cell surfaces are coated with extracellular polymeric substances (EPS) rich in functional groups, such as carboxyl, hydroxyl, phosphate, and amine moieties. The EPS matrix provides numerous active sites for the binding and retention of metals and organic pollutants, while also facilitating the colonization of microplastics to form biofilms [13–15]. These structural and chemical features, combined with metabolic versatility, highlight the multiple physicochemical and biological mechanisms through which cyanobacteria interact with and modulate environmental contaminants [14].

In addition, several cyanobacterial species are capable of bioaccumulation, actively transporting contaminants into the cell, where they may be sequestered, transformed, or detoxified [16–18]. Beyond passive uptake, cyanobacteria exhibit metabolic pathways that facilitate biodegradation or biotransformation of complex organic contaminants, including PAHs and various PPCPs, through enzymatic oxidation, reduction, or co-metabolic processes [9,11]. Simultaneously, their inherent capacity for nutrient assimilation (e.g., nitrogen and phosphorus) enables integration of contaminant removal with eutrophication control [19,20].

Given these multifaceted interactions, cyanobacteria have emerged as promising candidates for biotechnological applications in environmental remediation [21–24]. Their use has been explored in diverse reactor configurations, including open ponds, photobioreactors, biofilm-based systems, and hybrid algal–bacterial reactors, targeting contaminant removal from wastewater, industrial effluents, and polluted surface waters [25–27]. This review critically examines the potential of cyanobacteria as natural sponges for environmental contaminants. It explores their co-occurrence with multiple pollutant classes, discusses the underlying mechanisms of contaminant uptake and transformation, evaluates circular economy and valorization aspects of cyanoremediation, and reviews reactor systems employed for cyanobacteria-based remediation. By analyzing recent advances and identifying critical knowledge gaps, this review evaluates the potential of cyanobacteria to be strategically harnessed as sustainable tools for contaminant removal in complex environmental matrices.

2. Mechanisms of Contaminant Uptake by Cyanobacteria

Cyanobacterial strains have unique chemical characteristics that distinguish them from other microorganisms [28]. These distinct properties, particularly the structure of the cell surface, enhance their ability to interact with and adsorb various substances using four main mechanisms, including biosorption, bioaccumulation, biodegradation, and nutrient assimilation (Figure 2). Blue-green algae are primary producers in freshwaters and marine environments, which makes them significant contributors to global CO_2 fixation [6]. Cyanobacteria have developed a special carbon-concentrating mechanism (CCM), which takes carbon from their surroundings into the cell and converts it into a usable form [29]. Blue-green algae are also capable of nitrogen fixation, converting atmospheric nitrogen into ammonia [30]. Some cyanobacteria species can store phosphorus in the form of polyphosphate granules, allowing them to mobilize it in phosphorus-limited conditions and release the excess in the surrounding environment under nutrient-limited conditions [31].



$C_{10}H_8 \longrightarrow C_{10}H_7OH + \text{By-prod.}$
$C_{10}H_7OH \longrightarrow C_{10}H_{12}O_2 + \text{By-prod.}$
$C_{10}H_{12}O_2 \longrightarrow C_{10}H_{10}O_3 + \text{By-prod.}$
$C_{10}H_{10}O_3 \longrightarrow C_6H_5COOH + C_2H_4O_2 \Longrightarrow \boxed{CO_2}\ \boxed{H_2O}$

Figure 2. Mechanisms of Contaminant Uptake in Cyanobacteria: (**a**) Biosorption; (**b**) Bioaccumulation; (**c**) Biodegradation; (**d**) Nutrient Assimilation.

The specific chemical groups on the cyanobacterial cell surface, such as polysaccharides, proteins, and lipids, contribute to these mechanisms by providing active sites for binding pollutants or nutrients and accumulating them within the cell [32]. Hence, the unique surface qualities of cyanobacteria are crucial in adsorption processes, facilitating interactions with environmental contaminants and making them highly effective in bioremediation practices (phycoremediation). Blue-green algae can store toxic organic, inorganic, and radioactive substances in their cells, significantly aiding in the self-purification of various wastewater types, including municipal, industrial, and agro-industrial effluents [33]. Cyanobacteria have been studied in the context of the removal of various types of water pollutants, including heavy metals [34], microplastics [35], organic pollutants, i.e., PHAs [36], PCBs [37], and pesticides [38]. Moreover, there has been growing interest in the interactions and potential remediation of PFAS, PPCPs and other CECs by certain cyanobacteria species.

2.1. Biosorption and Bioaccumulation

2.1.1. Heavy Metals

Cyanobacteria have shown promising results in heavy metal removal through biosorption [34]. The presence of proton-active functional groups in the cell wall, along with polymeric substances in the extracellular polysaccharide (EPS) layer, enables cyanobacteria to effectively adsorb and absorb positively charged metal ions (Figure 2A) [28]. EPS contains different biomolecular components (proteins, lipids, etc.) with a broad spectrum of negatively charged functional groups (carboxylate, sulfhydryl, sulphate, amide, amine, and uronic acid), which provide surface binding for metal ions [39]. The mechanisms involved in the biosorption of heavy metals by cyanobacteria mainly include ion exchange, electrostatic attraction, chelation, complexation, and microprecipitation [6]. For those processes, environmental conditions play a critical role. Factors such as biomass type and concentration, presence of other cations and anions in the matrix, and most importantly, pH directly impact the biosorption process [40]. Changes in pH can affect the protonation and the biosorbent's binding sites, which affects their affinity for metal ions; this mechanism can also be used to induce desorption for the recovery of metals and biosorbent [40]. After heavy metals are adsorbed onto the surface of cyanobacteria cells, they can be transported and stored within different parts of the cell via bioaccumulation [29]. Although both processes are interconnected, their effectiveness in interacting with heavy metals varies among different cyanobacteria species, in some cases even within the same species. For example, a study on cyanobacteria *Nostoc sp*. showed that it had the highest bioaccumulation potential for Lead and Copper, while it was the most effective for biosorption of Cadmium [17]. This study highlighted the differences in removal mechanisms for other heavy metals, with living cells showing a higher affinity for Zinc, and dry biomass being more effective for Nickel [17].

2.1.2. Organic CECs

Electrostatic attraction and complexation mechanisms on the cyanobacteria's cell surface are not only involved in the adsorption and accumulation of heavy metals, but also for the organic contaminants of emerging concern, i.e., PAHs, PCBs, PFAS, PPCPs, and pesticides. In the context of bioremediation of organic pollutants, bioaccumulation within the blue-green algae cell plays a critical role as a transitional step to the biodegradation. Metabolic activity (extracellular or intercellular bioaccumulation) often occurs through two main transport mechanisms- active transport and passive diffusion [32,34]. With the help of transport proteins (channels, secondary carriers, and primary active transporters), organic (and inorganic) pollutants get transported into the cyanobacteria cell and can accumulate in the vacuole, thylakoids, or other cell compartments. In response to it, cyanobacteria have developed special stress mechanisms, i.e., pollutant storage, antioxidant enzyme production, and polymerization [29]. Planktonic algae comprising multiple species, including cyanobacteria (*Cyanophyta*), *Bacillariophyta*, and *Chlorophyta*, were found to primarily bioaccumulate low-ring PAHs [41]. The same study emphasized the importance of the eutrophication levels, which influenced phytoplankton composition and their PAH accumulation patterns, with planktonic algae accumulating significantly more PAHs compared to sediments [41].

Examining a different organic substance, *Anabaena* sp. was exposed to 40 PCB congeners in a bioaccumulation experiment [42]. The study discussed bioaccumulation factors (BAFs), which indicate the extent of compound accumulation in an organism compared to its environment [42]. They found a BAF correlation with PCBs with lower hydrophobicity, but it wasn't observed for the more hydrophobic PCBs [42]. For *Anabaena* sp., adjusting BAFs based on phospholipid content decreased the variation in bioaccumulation of highly hydrophobic PCBs, proposing that membrane permeability restricts the entry of these compounds into the cells [42]. Another study examining antibiotic (Tetracycline) remediation found cyanobacteria *Microcystis aeruginosa* (*M. aeruginosa*) more effective compared to widely used green algae *Chlorella pyrenoidosa*, due to stronger uptake mechanisms, such as rapid biosorption and bioaccumulation [43]. In addition, studies have proven the efficiency of cyanobacteria to bioaccumulate pesticides. A Mesotrione (herbicide) was shown to accumulate readily in *Microcystis* sp. during 7-day exposure [44]. Cyanobacteria exhibited reduced photosynthetic activity but showed higher tolerance compared to the green microalgae *Scenedesmus quadricauda,* which contributed to the rapid removal of Mesotrione from the medium [44].

2.2. Biodegradation

The removal rate and biodegradation of pollutants by cyanobacteria depend on various factors, including algae species, biomass, metabolic activity, and environmental conditions [33]. Selected species can degrade various types of contaminants, i.e., antibiotics, high-molecular-weight organic matter, pesticides, PAHs, synthetic dyes, and PCBs, partially transforming them into less harmful and toxic components and, in some cases, facilitating their mineralization (Table 1) [33]. Redox enzymes released by cyanobacteria (laccase, azoreductase, and polyphenol oxidase) play a key role in biodegradation via increasing the hydrophilicity of pollutants through oxidation, reduction, or hydrolysis, by adding or unmasking hydroxyl groups [33,45]. Similar to bioaccumulation, the biodegradation process can occur extra- or intracellularly, or in a combination of both, first extracellular initial degradation, and then intracellular product breakdown [46,47].

Table 1. Bioremediation by selected cyanobacterial species.

Cyanobacterial Species	Contaminants	Bioremediation	Reference
Oscillatoria sp.	Pyrene (PAH)	95%	[48]
Fischerella sp.	Phenanthrene (PAH)	92%	[49]
A. variabilis	o-nitrophenol (ONP)	100% (light conditions)	[33]

Table 1. *Cont.*

Cyanobacterial Species	Contaminants	Bioremediation	Reference
Synechocystis sp.	Perfluorooctanoic acid (PFOA) Perfluorooctane sulfonate (PFOS)	37% 88%	[50]
Anabaena sp. *PD-1 strain*	PCB-Aroclor 1254 PCB169	84.4% 68%	[37]
M. aeruginosa	Tetracycline (PPCP)	98%	[43]
Phormidium lucidum; Oscillatoria subbrevis	LDPE MPs	30%	[51]
Nostoc linckia	Azo dye (methyl red)	81.97%	[52]
Lyngbya lagerlerimi	Azo dye (Orange II)	47%	[52]
Oscillatoria rubescens	Azo dye (Basic cationic)	85%	[52]
Gloeocapsa pleurocapsoides and *Phormidium ceylanicum*	Azo dyes	>80%	[53]
Oscillatoria quadripunctulata	Dissolved salts from petrochemical waste	40%	[54]

2.2.1. PAHs

Previous research showed that the cyanobacterium *Oscillatoria* sp. successfully degraded 95% of a high molecular weight PAH–pyrene [48]. Authors indicated that changes in dry weight, chlorophyll, and carotenoid levels demonstrate the cyanobacterium's adaptation to pyrene as a carbon source [48]. On the other hand, a microbial consortium dominated by the cyanobacterium *Fischerella* sp. has achieved 92% degradation of phenanthrene, a tricyclic aromatic hydrocarbon [49]. The metabolic pathway involves the enzymatic oxidation of phenanthrene to dihydroxy transitional compounds, which are broken down into metabolites such as 1-hydroxy-2-naphthoic acid to enter central metabolic cycles, e.g., the Krebs cycle [49]. Another study discussed the process of degradation of organic hydrocarbon (naphthalene) (Figure 2C) [33]. With the complex enzyme oxidation process, naphthalene (PAH) can be broken down into four major compounds at non-toxic concentrations, mainly 1-naphthol, cis-naphthalene dihydrodiol, 4-hydroxy-4-tetralone, and trans-naphthalene dihydrodiol, which can further be degraded to simple compounds such as water and carbon dioxide [33].

2.2.2. PFAS

Synechocystis sp. demonstrated tolerance to PFOS and PFOA, with partial removal of these compounds observed over time [50]. Respirometry tests showed no short-term toxicity and indicated a possible metabolic shift between respiration and photosynthesis, as suggested by increased oxygen evolution [50]. *Synechocystis* sp. removed 37% of PFOA from the external medium, with 3.6% detected in the lysate, suggesting metabolic transformation, while 88% of PFOS was removed, with 51% found in the lysate, and the rest likely adsorbed to membranes, suggesting both internalization and membrane binding [50]. Preliminary bioinformatic analysis identified proteins that may facilitate PFOS uptake, and enzymes similar to laccases and dehalogenases involved in PFAS degradation [50]. These findings suggest a promising foundation for exploration of *Synechocystis* sp. as a self-sufficient agent for PFAS phycoremediation, although its complete degradation capabilities require further research.

2.2.3. PCBs

Cyanobacteria strain *Anabaena PD-1* demonstrated strong resistance and effective degradation of various PCB congeners—e.g., 84.4% degradation of Aroclor 1254 [37]. This strain preferentially degraded less chlorinated PCBs, with higher degradation rates for congeners with fewer ortho-chlorines, as meta- and para-chlorines are more readily dechlorinated [37]. Highly chlorinated PCBs (hexachlorobiphenyls and heptachlorobiphenyls) showed less consistent degradation patterns. Notably, *Anabaena PD-1* could tolerate and degrade toxic dioxin-like PCBs, achieving up to 68% biodegradation of PCB169 within 7 days [37]. These findings highlight great potential for PCB bioremediation; however, the authors emphasized that the key enzymes and metabolic pathways require further understanding.

2.2.4. PPCPs

M. aeruginosa, a harmful algal bloom (HAB) species, demonstrated notable ability to remove high concentrations of Tetracycline from wastewater, achieving 98% removal within 2 days [43]. Kinetic study indicated that bioremediation (a combination of biosorption, bioaccumulation, and biodegradation) accounted for 71.6%

of antibiotic removal by *M. aeruginosa* as compared to the 20.5% by the microalgae *Chlorella pyrenoidosa* [43]. Biodegradation primarily occurred through two mechanisms: biochemical transformation involving modification of functional groups and ring-opening reactions, and photocatalysis reactions facilitated by extracellular organic matter (EOMs) and ferric ion interactions [43]. Seven major by-products were identified, many of which are known from advanced oxidation processes and show a greatly reduced level of toxicity [43]. *M. aeruginosa* maintained high biomass stability under tetracycline stress and released low levels of microcystin-LR toxin, which makes it an environmentally sustainable agent for antibiotic biodegradation and wastewater treatment [43].

2.2.5. Synthetic Dyes

The cyanobacteria species *Nostoc lincki*, *Oscillatoria rubescens*, and *Lyngbya lagerlerimi* showed notable degradation and decolorization of various synthetic dyes [52]. Up to 82% of methyl red was removed by *Nostoc lincki* and *Oscillatoria rubescens,* and up to 35% by *Lyngbya lagerlerim* [52]. More complex dyes (orange II and G-Red) were less effectively removed, up to 47 and 14%, respectively [52]. This study indicated that dye removal involved enzymatic biodegradation (azo dye reductase induction) in addition to adsorption [52]. Selected cyanobacteria species are effective in degrading water-insoluble vat dyes as well [55]. *Anabaena* sp. and *Phormidium* sp. demonstrated 71% and 91% remediation of indigo dye, respectively [55]. The study reveals dye removal mechanisms associated with combined biosorption and biodegradation [55]. After 19 days, full decolorization was observed; however, full mineralization was not achieved [55]. Analysis revealed the formation of intermediate products such as anthranilic acid and isatin**,** revealing a partial biodegradation path [55].

2.3. The Role of Phycosphere-Associated Microorganisms

Phycosphere-associated microorganisms are defined as diverse microbial communities surrounding phytoplankton cells (including cyanobacterial cells) [56]. They coexist within an EPS-rich mucilage, forming a metabolically active microenvironment that provides biochemical interactions and nutrient exchange [57]. The phycosphere may enhance contaminant removal with complementary metabolic functions, including co-metabolism with cyanobacteria and even enzymatic degradation [58]. For example, bacterial communities associated with *Microcystis* sp. demonstrated active degradation of toxic cyanobacterial metabolites from *M. aeruginosa* within the phycosphere [57]. Additionally, the phycosphere microorganisms can provide nutrient acquisition, i.e., phosphonate mineralization and organic carbon exchange, which indirectly contribute to the uptake capacity of cyanobacterial cells [59,60]. *Microcystis* phycosphere showed strong spatial structuring of bacterial communities across aggregate sizes, which promotes cooperative breakdown of complex compounds, demonstrating coordinated metabolic activity [61].

Several experimental studies demonstrated the importance of phycosphere-associated microorganisms in the context of emerging contaminant removal. For PPCPs, the mixed cyanobacteria–bacteria consortia, which may exist in the phycosphere, showed enhanced removal compared to the axenic cyanobacteria system [62]. *Synechococcus* sp. demonstrated high removal efficiencies for the mix of multiple antibiotics (amoxicillin, sulfadiazine, tetracycline, ciprofloxacin, and erythromycin), attributed to cyanobacteria–bacteria interactions and bacterial metabolic activity [62]. Another study showed that the phycosphere of *Desmodesmus* sp. facilitates microbial colonisation on microplastic, leading to chemical transformation and polymer deformation, supporting biodegradation strategies [63]. Collectively, these studies indicate that phycosphere-associated microorganisms enhance co-metabolism and transformation of complex contaminants by cyanobacteria, promoting bacterial growth and EPS production, thereby increasing pollutant uptake and supporting all three main mechanisms – biosorption, bioaccumulation, and biodegradation.

2.4. Cyanobacterial Responses to Emerging Contaminants

Exposure to emerging contaminants triggers dose-dependent toxicity in cyanobacteria, may alter growth dynamics, species composition, and bloom succession. Studies on *Microcystis aeruginosa* have shown that at higher concentrations, sulfamethoxazole (an antibiotic) induces strong oxidative stress responses, which affect photosynthetic efficiency and cellular growth, damage cell structure, and disrupt pigment content [64,65]. In addition, in the sulfamethoxazole remediation study, the associated microbial community structure changed, activating multiple bacterial degradation pathways [58]. Similar effects on *Microcystis aeruginosa* were observed under long-term exposure to amoxicillin [66]. This study revealed the cyanobacterial growth stimulation, altered photosynthetic activity, and increased microcystin (cyanotoxin) production [66]. Combined exposure to antibiotics spiramycin and amoxicillin on the same species showed antagonistic and synergistic effects depending on concentrations and mixing ratios [67]. Results showed that at environmental concentrations, growth and photosynthesis-related gene expression are negatively correlated with increased proportion of the more toxic antibiotic (spiramycin) [67]. Certain mixing ratios increased the expression of toxin-related genes [67].

Another experimental study on the combined exposure of a mixture of antibiotics and pesticide (glyphosate) has shown consistent effects on *Microcystis aeruginosa,* simulating photosynthetic activity at low concentrations due to hormesis (with no effect when exposed individually) [65]. All studies mentioned above have reported increased microcystin production, linked to the activation of the toxin synthesis pathways [66,67]. Beyond direct toxicity, antibiotics can restructure the phycosphere microbial community associated with cyanobacteria and shift metabolic activity [68]. Furthermore, exposure to organically contaminated (with sertraline and simazine) microplastics (polyethylene) caused similar cellular stress responses in cyanobacteria (growth, photosynthesis) linked to contaminant type [69]. However, while photosynthetic activity was reduced, microcystin production was reported to decline, indicating changes in toxicity potential [69]. On the other hand, a study on nanoplastics (amino-modified polystyrene) exposure reported induced oxidative stress and reduced organic matter synthesis, as well as enhanced microcystin production [70]. Synthetic dyes have been reported to cause physiological stress**,** reducing growth and pigment content [52]. Collectively, these effects are associated with a change in protein expression and metabolic pathways, leading to increased toxin release and harmful cyanobacterial bloom formation.

3. The Circular Bioeconomy of Cyanoremediation

The economic viability of cyanoremediation is increasingly predicated on the implementation of a Circular Bioeconomy (CBE) framework. In this model, the spent cyanobacterial biomass is not treated as a hazardous waste stream but as a versatile feedstock for a cascading biorefinery. In earlier work, this was conceptualized as a “cradle-to-cradle” system, where the metabolic byproducts of remediation, specifically the intracellular accumulation of carbon and nutrients, are valorised into industrial commodities [71,72]. However, a critical analysis of the literature reveals that the valorization pathway is strictly governed by the contaminant-product compatibility. Valorization is highly influenced by biomass purity. Due to contamination with environmental pollutants, efficiency and final product quality may be compromised. Contamination with synthetic dyes, heavy metals, PPCPs, microplastics, and other substances may alter biochemical composition and significantly reduce chemical purity of the biomass [73–75]. Heavy metals can bind to cyanobacteria cell walls and EPS, which poses toxicity risks for the biomass use in biofertilizers, and may affect thermochemical processes (i.e., hydrothermal liquefaction) through unfavorable char formation [76–78]. Antibiotics and dyes may be partially absorbed, transformed, and persist in the cyanobacterial biomass, leading to contaminated bio-oils and digestates, which would require additional purification [73,79]. Contaminated biomass in an anaerobic reactor can inhibit methanogenesis, which may reduce the biogas yield and overall reactor stability [79]. Similarly, microplastics in cyanobacterial biomass can act as inactive components and release additives, reducing biomass purity and complicating further processing [74,78].

While biomass grown on nutrient-rich wastewater is suitable for agricultural or plastic applications [80], biomass laden with persistent organic pollutants (POPs) or heavy metals faces purity constraints that restrict it to energy recovery [81]. Therefore, we propose a hierarchical valorization strategy that prioritizes high-value low-volume metabolites before converting the residual biomass into high-volume commodity feedstocks, as shown in Table 2.

Table 2. Integrated valorization potential of cyanobacterial biomass.

Valorization Pathway	Cyanobacterial Species	Production Strategy/Mode of Action	Performance Outcome/Yield	Reference
High-value pigments	*Synechococcus* sp.	Growth in secondary effluent with semi-continuous operation.	Phycobiliproteins: Up to 214 mg/g DW. Carotenoids: Up to 4 mg/g DW.	[82]
	Pleurocapsa sp.	Cultivation in urban wastewater with pH adjustment (8.0 to 11).	Phycobilins: 102 mg/g DW.	[83]
Bioplastics (PHB/PHBV)	*Aulosira fertilissima*	Nitrogen & Phosphorus deprivation supplemented with Acetate/Citrate.	85% dry cell weight (PHB)	[84]
	Nostoc muscorum Agardh	Nitrogen limitation supplemented with Glucose, Acetate, and Valerate.	78% dry cell weight (PHBV)	[85]
	Synechococcus sp. MA19	Phosphorus deprivation under inorganic conditions.	55% dry cell weight (PHB)	[86]
	Synechocystis sp. PCC6803 (Mutant)	Mixotrophic cultivation with Acetate supplementation.	35% dry cell weight (PHB)	[87]
Agricultural Bio-effectors	*Synechococcus mundulus*	Mobilization of insoluble iron (Fe^{3+}) in the rhizosphere.	Enhanced Fe uptake and chlorosis prevention in Maize (*In vitro*).	[88]
	Anabaena vaginicola ISB42	Synthesis of auxins/cytokinins facilitating nutrient uptake.	Increased essential oil yield and biomass in *Mentha* (Greenhouse).	[89]
	Nostoc sp.	Biological Nitrogen Fixation (BNF) combined with P/K/Zn solubilization.	Significant growth stimulation in Wheat and Rice systems.	[90]
	Arthrospira platensis	Production of bioactive compounds supporting nutrient acquisition.	Improved nutritional status in Chia (*Salvia hispanica*) cultivation.	[91]

3.1. Pigments and Bioactive Compounds

The extraction of intracellular pigments represents the most lucrative tier of the biorefinery, potentially subsidizing the high operational costs associated with harvesting microscopic biomass [82]. Previous studies emphasize that freshwater cyanobacteria, particularly bloom-forming species, are rich sources of phycocyanin [92], a thermally stable blue pigment with a global market value estimated at over $87 million in 2016 and projected to reach $114.8 million by 2022 [93]. The extraction of such bioactive compounds must serve as the primary step in the cascade; however, this pathway is highly sensitive to the initial water quality. Although, recent evidence suggests that the "sponge" nature of cyanobacteria does not compromise the quality of these intracellular products, confirming that wastewater-grown biomass can compete directly with synthetic cultures. Recently, the viability of this pathway was confirmed, demonstrating that *Synechococcus* sp. grown in secondary effluent achieved phycobiliprotein contents of 214 mg/g-DW, a yield comparable to that of cultures grown in optimized synthetic media [82]. However, the "sponge" nature of the biomass presents a critical quality control boundary. While most wastewater contaminants are effectively separated during extraction, the co-sequestration of heavy metals or persistent organic pollutants (POPs) precludes the use of these pigments in food or cosmetic applications. In such scenarios, the high-value pigment pathway is rendered non-viable, relegating the biomass to non-food industrial applications or alternative valorization routes where purity is less critical.

3.2. Bioplastics (Polyhydroxyalkanoates)

Following the extraction of high-value metabolites, or in scenarios where biomass purity is compromised, the production of biodegradable plastics offers a robust valorization pathway that synergizes mechanistically with the remediation process itself [94,95]. Cyanobacteria naturally synthesize Polyhydroxyalkanoates (PHAs), specifically Polyhydroxybutyrate (PHB), as intracellular carbon storage granules. This accumulation is triggered by a specific physiological stress state, an imbalance in the Carbon-to-Nitrogen (C:N) ratio, which occurs naturally during the final polishing stages of wastewater treatment when nitrogen and phosphorus are depleted but organic carbon remains available [96].

The metabolic mechanism relies on the redirection of Acetyl-CoA; under nutrient-sufficient conditions, Acetyl-CoA feeds the TCA cycle for growth, but under the nutrient stress typical of tertiary wastewater treatment, it is diverted toward the PHA synthase pathway for polymer accumulation [97]. This metabolic plasticity allows specific strains to function as "bioplastic factories" directly within the treatment infrastructure. The efficiency of this pathway is highly strain-dependent and significantly enhanced by mixotrophic conditions. For instance, while model strains typically accumulate lower PHA fractions, robust species such as *Aulosira fertilissima* have been documented to accumulate up to 85% of their dry cell weight (DCW) as PHB under optimized mixotrophic conditions with nutrient deprivation, while *Nostoc muscorum* has reached 78% DCW [84,85].

Economically, the integration of PHA production into cyanoremediation surmounts the primary barrier to commercialization, feedstock costs, by substituting expensive carbon substrates with wastewater, effectively nullifying up to 50% of production expenses. Ultimately, this transforms the remediation process from a waste management obligation into a value-added manufacturing step, incentivizing extended biomass retention to ensure deeper nutrient removal while maximizing intracellular polymer yields.

3.3. Biofertilizers and Agricultural Bio-Stimulants

For cyanobacterial biomass that has primarily sequestered nutrients without significant loads of toxic contaminants, agricultural application remains the most direct and volume-efficient valorization strategy. This approach transitions the biomass from a passive nutrient carrier to an active bio-effector known as a biofertilizer. Unlike synthetic fertilizers, which are prone to rapid leaching and volatilization, cyanobacterial biomass functions as a slow-release matrix that synchronizes nutrient mineralization with crop demand [80]. The value of this application extends beyond simple NPK stoichiometry to include active biological nitrogen fixation (BNF) and mineral solubilization [98]. Studies emphasize that re-inoculating soils with cyanobacterial isolates creates a "living fertilizer" system. Heterocystous species such as *Anabaena* and *Nostoc* possess the *nifH* gene complex, allowing them to convert atmospheric N_2 into ammonium (NH_4^+) [89]. In rice paddy ecosystems, this natural fertilization has been documented to increase plant length by 127% and significantly enhance grain weight, effectively reducing the dependency on synthetic urea [99]. Furthermore, the spent sponge addresses soil mineral lock-up through the secretion of organic acids and phosphatases, which solubilize insoluble tricalcium phosphates and mobilize potassium from silicate minerals, rendering them bioavailable for root uptake.

Beyond direct nutrient supply, the biomass functions as a potent bio stimulant, enhancing plant vigor and stress resilience through the secretion of bioactive metabolites. This non-nutrient enhancement is driven by the synthesis of phytohormones, including auxins, cytokinins, and gibberellins, by genera such as *Calothrix* and *Anabaena*, which directly stimulate seed germination and lateral root development [100,101]. The bio stimulant effect is further amplified by specific stress-mitigation mechanisms; for instance, species like *Synechococcus nidulans* secrete high-affinity siderophores that mobilize ferric iron in the rhizosphere, preventing chlorosis in alkaline soils [102]. In abiotic stress scenarios, such as salinity or drought, the biomass secretes EPS and antioxidants that buffer the plant against oxidative damage. This physiological support extends to modern soil-less systems, where co-cultivation with microalgae can elevate dissolved oxygen levels, preventing root anaerobiosis and significantly boosting crop productivity, thus demonstrating a closed-loop potential where the remediator becomes a critical physiological enhancer [103].

3.4. Bioenergy

Finally, when the biomass is laden with complex organic pollutants or heavy metals that preclude agricultural or material use, energy recovery serves as the universal safety valve of the circular economy. Anaerobic digestion (AD) allows for the conversion of the bulk biomass into methane while stabilizing the hazardous constituents. Anaerobic digestion of freshwater cyanobacterial biomass was reported to yield methane volumes exceeding 60% of the total biogas produced [104], with specific yields up to 400 L/kg of volatile solids [105]. While the economic return of biogas is lower than that of pigments or bioplastics, this pathway ensures the thermal or biological degradation of organic contaminants, preventing their re-entry into the ecosystem. Furthermore, co-digestion with other organic substrates has been shown to double the specific methane yield, suggesting that spent remediation biomass should be integrated into existing municipal waste-to-energy infrastructures rather than treated in isolation.

The integration of cyanoremediation within a Circular Bioeconomy framework signifies a paradigm shift from simple pollutant removal to sustainable resource recovery. By adopting a cascading biorefinery approach, operators can maximize economic returns through the extraction of high-value metabolites and biopolymers when biomass purity permits, while retaining robust bioenergy and agricultural pathways for lower-quality streams. This strategic flexibility, governed by strict contaminant-product compatibility, ensures that every fraction of the harvested "sponge" contributes to a closed-loop system, effectively decoupling environmental protection from economic liability.

4. Reactor Systems for Cyanobacteria Growth and Remediation

Cyanobacteria-based remediation relies on the synergistic action of biomass growth, pollutant uptake, and metabolic transformation to remove organic pollutants (PAHs, PCBs, PPCPs) and heavy metals from contaminated environments [9,11,37]. The choice of reactor system significantly influences these processes by determining biomass density and mass transfer [106]. Over the past decades, various reactor systems, including open ponds, raceway ponds, photobioreactors, and immobilized biofilm reactors, have been developed to maximize cyanobacterial growth while addressing scalability, operational stability, and environmental variability [25–27,107] (Figure 3).

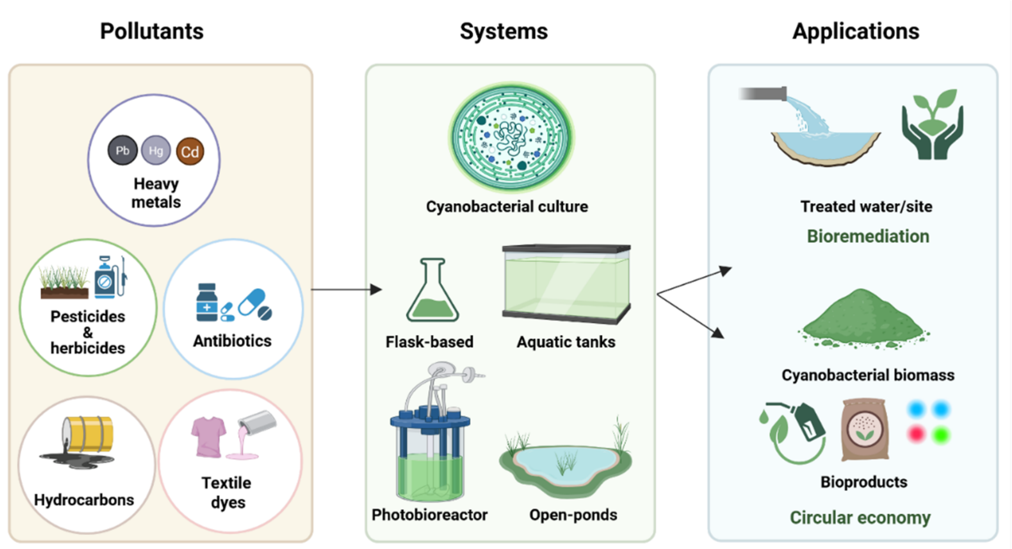


Figure 3. Overview of target pollutants, cyanobacterial reactor systems, and pathways toward bioremediation and circular economy applications.

In this section, the principles, operational characteristics, advantages, limitations, and reported performance of different reactor systems for cyanobacteria-mediated remediation will be discussed, with a focus on their ability to remove organic pollutants and heavy metals from complex effluents.

Open pond systems, including shallow ponds and raceway channels, represent the most cost-effective and historically common approach for large-scale cyanobacterial cultivation, relying on natural sunlight and simple mixing to sustain growth [106,108]. Although primarily used for biomass production, such open systems inherently support cyanobacterial uptake of nutrients and organic matter when wastewater is used as a growth medium [109]. Dry biomass from raceway cultures (e.g., *Arthrospira platensis*) has been shown to achieve high lead adsorption (>90%) in separate biosorption assays, highlighting their potential role in heavy metal uptake [110].

Closed photobioreactors (PBRs), including tubular, flat-panel, and stirred designs, provide controlled light, temperature, and gas transfer, promoting greater cyanobacterial cell densities and enabling more consistent assimilation of organic pollutants and nutrients from wastewater streams [111]. Studies have demonstrated successful selection and cultivation of wastewater-borne cyanobacteria in PBRs with associated nutrient removal, highlighting their utility for integrated treatment and biomass production under defined conditions [112].

Photo-sequencing batch reactors (PSBRs) extend reactor control by cycling fill-react-settle phases under light, enabling dominance of cyanobacteria over competing microalgae and facilitating simultaneous removal of total nitrogen, phosphorus, and organic carbon with tailored hydraulic conditions, as shown in operational studies targeting cyanobacterial enrichment within mixed cultures [112].

In addition to suspended growth systems, biofilm-based configurations and granular aggregates incorporating cyanobacteria (e.g., oxygenic photogranules) are emerging for their enhanced biomass retention and resilience [113,114]. Across these reactor types, cyanobacteria contribute to remediation through mechanisms such as biosorption, bioaccumulation, and biotransformation of heavy metals and organic pollutants, with performance and operational stability varying according to design, control of environmental conditions, and integration with downstream harvesting and valorization processes [16–18].

5. Conclusions and Future Research Recommendations

Cyanobacteria stand out as a powerful tool for ecological restoration by effectively removing pollutants, ranging from heavy metals to pharmaceutical residues and dyes. Mechanisms such as biosorption, bioaccumulation, and biodegradation are proven to be efficient in pollutant removal, making cyanobacteria a possible alternative green treatment due to their widespread availability, versatility, and cost-effectiveness for possible large-scale applications. Moreover, cyanobacterial biomass has strong valorization potential, as it could be recovered and converted into useful products. Depending on the strain and operational approach, it can be used for producing pigments, biopolymers, biofertilizers, and even energy recovery. Cyanobacterial reactor systems such as open and raceway ponds, biofilm-, and photobioreactors have been showing positive developments towards operational stability and environmental variability while ensuring optimal bacterial growth. Furthermore, bioremediation with cyanobacteria can be enhanced by optimizing their metabolism through engineering and environmental manipulations. Despite these advantages, the large-scale application of cyanobacteria in bioremediation remains challenging. Prevention of the production of cyanotoxins, optimization, and constant monitoring of pollutants' uptake, and stabilization are complex processes that require future investigation.

Nevertheless, current research on the mechanisms of pollutant uptake and detoxification, along with advancements in biotechnological applications, has the potential to support more efficient and cost-effective environmental pollution control. Although antibiotics are heavily studied in the context of cyanobacterial remediation and response mechanisms, more experimental studies are required for organic and inorganic emerging contaminants (PAHs, PFAS, etc.) to reveal their bioremediation potential. Phycosphere-associated microorganisms' role in adsorption and cell wall interactions is also often overlooked. Ultimately, further research should focus on improving genetic engineering techniques and integrating new technologies for more effective bioremediation and limiting cyanotoxin release. For example, phyconanotechnology could be a promising approach: heavy metal biosorption by cyanobacteria can be combined with the consecutive valorization of the obtained metal-organic materials to get added-value compounds, including metal nanoparticles. Interdisciplinary approaches combining environmental science, molecular biology, and engineering will be crucial to unlock the full potential of cyanobacteria in bioremediation.

Author Contributions

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Conflicts of Interest

The authors declare no conflict of interest.

Use of AI and AI-Assisted Technologies

No AI tools were utilized for this paper.

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