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Review 综 述

蓝细菌对汞耐受机制的研究进展

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摘 要：蓝细菌对不同形态的汞具有很强的耐受和富集能力，能够改变环境中的汞浓度，影响汞的生物地球化学循环。同时，蓝细菌是生态系统中重要的初级生产者，经过蓝细菌富集的汞更容易进入食物链，影响人类健康。本文系统总结了蓝细菌对汞的耐受机制，主要包括：(1) 在细胞壁外合成胶质鞘隔离汞；(2) 通过与自身化合物结合钝化汞的毒性；(3) 利用自身抗氧化机制修复汞对细胞的损伤；(4) 利用自身酶转化汞的形态降低毒性；(5) 与抗汞细菌共生抵御汞。基于此，本文展望了蓝细菌汞耐受机制的进一步研究方向，以及利用蓝细菌进行汞解毒和污染修复的前景。

关键词：蓝细菌；汞；耐受机制；富集

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Advances in the mercury tolerance mechanisms of cyanobacteria

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Abstract: Cyanobacteria have strong capacities of tolerance and accumulation for different speciations of mercury, make the concentrations of different mercury-speciations convert and influence the biogeochemical cycling of mercury. Meanwhile, the various mecury-speciations accumulated by cyanobacteria which are significant primary producers in the ecosystem, are more easily delivered into the food chain, which affects human health. This paper systematically summarized the mechanisms of mercury tolerance of cyanobacteria, which included: (1) synthesizing a colloidal sheath outside the cell wall to isolate mercury; (2) mercury stabilization by combining with their own compounds; (3) using their own antioxidant mechanisms to repair the damage of mercury to cells; (4) using their own enzymes to transform the form of mercury to reduce toxicity; (5) symbiosis with mercury-resistant bacteria to resist mercury. On the basis of the above, this paper gave prospects of the further research directions of mercury-tolerance mechanisms for cyanobacteria, the promising future of mercury detoxification and pollution remediation utilizing cyanobacteria.

Keywords: cyanobacteria; mercury; tolerance mechanism; accumulation

汞是生态系统中唯一能完善循环的重金属。其在自然界中主要以单质汞(Hg^0)、二价无机汞化合物($Hg^{2+}X$)和有机汞化合物(如甲基汞MeHg)的形式存在[1]。单质汞在常温常压下易挥发进入大气环流，再通过干湿沉降到达地面，因此可以被传输到距排放源非常远的区域，例如沙漠[2−3]、冰川[4]等。沉降到地表的部分汞进入河流、湖泊和湿地等环境。同时，作为生物非必需的重金属元素，汞的所有化合物形态对生物都具有一定的毒性。过量的汞暴露会损伤动物的神经和生殖系统[5−7]，微生物的光合活性[8]、酶活性[9]以及生长繁殖能力[10]等，而有机形态的汞如甲基汞、二甲基汞和苯基汞等在生物体内具有更高的分配系数[11]，对生物的毒害作用更强[12]。

蓝细菌对自然界中汞的形态转化及分布有重要影响[13−16]。多项研究发现，蓝细菌对汞具有很强的富集能力，例如 *Aphanothece flocculosa* 和 *Spirulina platensis* 在对 Hg^{2+}的富集效应能达到 456 mg/g 和 428 mg/g[17]。蓝细菌的富集特性能改变环境中的汞浓度，影响不同形态汞之间转变的化学平衡。其次，蓝细菌是自然界重要的初级生产者，是异养菌[18]、浮游动物[19−21]、昆虫[22]、鱼类[23]等生物的食物来源，对浮游动

物和鱼类的分布和组成具有强烈影响[24–25]。经过蓝细菌富集的汞更容易进入食物链进行吸收、富集和传递，浓度可达到最初的几万倍，改变汞的分布，放大汞的毒害作用(图 1)。例如 Zhang 等发现在人类活动较少的青藏高原南部湖泊中汞平均含量仅为 3.82×10^{-3} mg/L[26]，但是通过食物网累积放大，当地鱼类体内总汞平均含量可高达 217.33×10^{-3} mg/g，而且其中 45% 的样本肌肉内甲基汞含量超过了美国鱼类和野生动物服务标准(100×10^{-3} mg/g)[27]。蓝细菌也可以直接作为人类食物和保健品[28]，例如，螺旋藻曾被发现富集有微量汞[29]。此外，蓝细菌具有汞还原能力，能够将汞离子还原为汞单质，并使其从水体环境中以蒸气形式散失[30]。最后，蓝细菌还可能对微生物介导的汞甲基化过程有影响。在野外环境和实验室模拟实验中发现，蓝细菌的丰度或者生物量与 MeHg 浓度存在相关性[13–14]，目前认为蓝细菌本身不具有汞甲基化能力，但是围绕蓝细菌形成的微生态系统可能是自然界中汞还原和微生物汞甲基化发生的热点场所。因此蓝细菌对汞的生物地球化学循环具有重要影响。

研究发现，蓝细菌除了能富集汞，也能在高浓度无机汞和有机汞的环境界面中生存[31–32]，表现出很强的汞耐受性，如 *Microcystis aeruginosa* 可在 MeHg 浓度高达 0.568 mg/L 的条件下生存[33]。由于不同种类的蓝细菌应对环境中汞暴露的耐受机制不同，其对汞暴露的耐受性具有一定差异。近年来，关于蓝细菌对汞的耐受机制研究较多，但尚无系统综述。本文系统

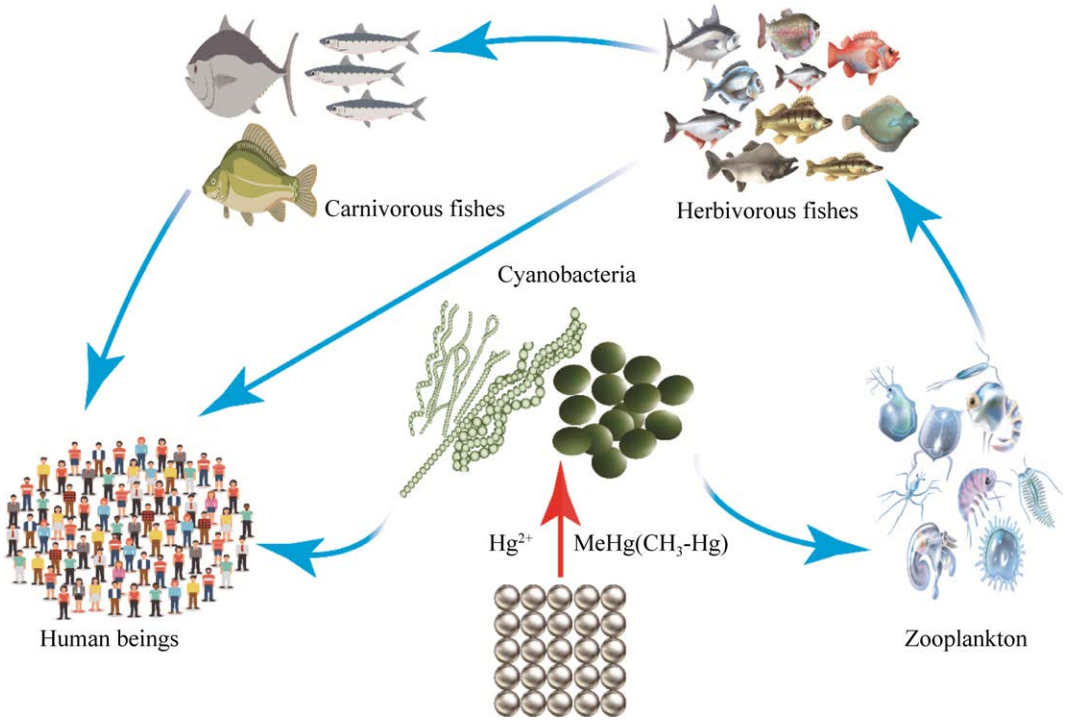

图 1　蓝细菌在汞的食物网循环中的作用

Figure 1　The role of cyanobacteria in mercury's food web cycle. The red arrow indicates that mercury and methylmercury are enriched by cyanobacteria. The blue arrows indicate the accumulation and transmission of mercury and methylmercury in the food web.

总结了近年来国内外关于蓝细菌对汞耐受机制的研究结果，以期为开展汞循环、蓝细菌对汞的耐受机制和利用蓝细菌修复汞污染的研究提供指导。

1 汞耐受相关蓝细菌的多样性

早在 1979 年，研究人员就观察了蓝细菌对有机汞的代谢过程[34]。自 20 世纪 90 年代，研究人员逐渐关注聚球藻和念珠藻的汞耐受性[35–38]，截至目前，至少已经发现 5 个目、10 个科、16 个属、27 种的蓝细菌具有汞耐受能力。其中念珠藻科(*Nostocaceae*)、微鞘藻科(*Microcoleaceae*)、颤藻科(*Oscillatoriaceae*)和平裂藻科(*Merismopediaceae*)表现出较其他种蓝细菌更强的汞耐受能力。多个研究团队在含有不同浓度和不同类型汞的培养环境下进行了蓝细菌的培养实验(表 1)，其中 *Microcystis aeruginosa*、*Aphanothece flocculosa*、*Spirulina platensis* 可以在 Hg^{2+}浓度高达 50 mg/L 的环境中生存，*Nostoc calcicola* 可以在浓度高达 0.31 mg/L 的 MeHg 环境中生存。Huang 等[33]和 Franco 等[39]测试了蓝细菌受到生长抑制的 MeHg 有效浓度，而其他大部分研究并未检测蓝细菌的汞耐受极限。汞对蓝细菌造成的损伤有细胞形态缺陷、光合色素失活、胞内色素沉着、DNA 缺失和细胞骨架改变等[40–41]，部分损伤在蓝细菌汞耐受机制发挥作用后可以恢复。例如，Chu 等发现聚球藻(*Synechococcus* sp. IU 625)在 0.1–1.0 mg/L 浓度的 $HgCl_2$ 环境下发生 DNA 缺失、细胞弯曲和细胞骨架改变等损伤后，能够将 Hg^{2+}转换为 Hg^0，使它们以蒸气的形式散失，并且使自身从色素沉着和形态缺陷中恢复[30]。除了对蓝细菌汞耐受特性的研究，汞对蓝细菌光合作用、蓝细菌对微生物介导的汞甲基化过程的影响也是当前研究热点。

2 蓝细菌的汞耐受机制

结合现有的研究，蓝细菌的耐受机制可归纳为以下 5 个方面，如图 2 所示。蓝细菌通过胞外的胶质鞘集结在一起，降低暴露在汞胁迫环境的细胞面积，减少进入胞内的汞；胞外聚合物中的化合物能够与汞结合，将部分汞隔离在蓝细菌胞外；进入蓝细菌胞内的汞与其中的聚磷酸盐颗粒、金属硫蛋白结合，降低胞内组织受到的毒害；蓝细菌可以利用自身抗氧化能力来修复汞胁迫造成的损伤；蓝细菌胞外共生的汞耐受细菌也可能增强蓝细菌在汞暴露环境中的耐受性。

2.1 在细胞壁外合成胶质鞘隔离汞

蓝细菌细胞壁的外侧包被着由果胶酸和粘多糖构成的胶质鞘(sheath)。这种鞘能够形成并保留一个包围着细胞的微环境，在细胞边缘水体中富集营养，并且在营养匮乏时作为其他细菌的食物来保护蓝细菌自身[61]。在高浓度 Pb (10^{-6} mol/L)和 Cu (10^{-5} mol/L)环境下的念珠藻(*Nostoc muscorum*)可以通过胶质鞘互相凝结形成桥状结构[62]，其中一个连续的鞘通常包裹和胶结数百个蓝细菌细胞。有研究表明，蓝细菌吸收 MeHg 的体积浓度因子(VCF)随细胞表面积与体积比的增加而显著增加[55,57]。例如，Lee 等在 6.25×10^{-5}–9.06×10^{-5} mg/L 的 MeHg 环境下观察了聚球藻(*Synechococcus bacillaris* CCMP1333)和其他 4 种真核藻类的生物累积现象，发现不同藻种吸收 MeHg 的 VCF 随细胞表面积与体积比的增加而显著增加[55]。Pickhardt 等也对集胞藻(*Synechocystis* sp.)和其他 3 种真核藻类进行了生物富集汞的对比实验，研究发现在 4.6×10^{-3}–2.95×10^{-2} mg/L 的 $HgCl_2$ 环境中，VCF 与细胞表面积/体积之间没有显著的相关性(R^2=0.021，P>0.73)，而在 1.99×10^{-2}–1.10×10^{-1} mg/L

表 1　蓝细菌的汞耐受能力

Table 1　Mercury tolerance of cyanobacteria

Phylum	Family	Genus	Types of mercury	Mercury concentration*	References
Chroococcales	*Aphanothecaceae*	*Aphanizomenon flosaquae*	$HgCl_2$	0.1 mg/L, total 20 μg	[42]
		Aphanothece flocculosa	$HgCl_2$	10 mg/L, 50 mg/L	[17]
		Aphanothece halophytica	$HgCl_2$	4 mg/L	[43]
Nostocales	*Nostocaceae*	*Anabaena cylindrical*	$HgCl_2$	0.1 mg/L	[44]
		Anabaena sp. 595	$HgCl_2$	0.03 mg/L	[40]
		Nostoc calcicola	CH_3HgCl	0.31 mg/L	[45]
		Nostoc calcicola	$HgCl_2$	0.5 mg/L	[46]
		Nostoc muscorum	$HgCl_2$	4 mg/L	[47]
		Nostoc paludosum BA033	CH_3HgCl	0.015 mg/L, 0.023 mg/L, 0.034 mg/L, 0.051 mg/L	[39]
		Nostoc paludosum BA033	$HgCl_2$	0.015 mg/L, 0.02 mg/L, 0.025 mg/L, 0.03 mg/L, 0.035 mg/L	[39]
	Scytonemataceae	*Scynetonema hofmanni* 248	$HgCl_2$	0.03 mg/L	[40]
Oscillatoriales	*Microcoleaceae*	*Arthrospira platensis*	$Hg(NO_3)_2$	0.2 mg/L	[48]
		Microcystis aeruginosa	CH_3HgCl	0.001 mg/L, 0.01 mg/L, 0.05 mg/L, 0.25 mg/L; 1×10^{-4} mg/L, 5×10^{-4} mg/L, 1×10^{-3} mg/L, 5×10^{-3} mg/L	[33,49]
		Microcystis aeruginosa	$Hg(NO_3)_2$	1 mg/L, 5 mg/L, 10 mg/L, 50 mg/L	[50]
		Microcystis aeruginosa	$HgCl_2$	0.1 mg/L, total 20 μg	[42]
		Microcystis incerta	CH_3HgOH	0.07 mg/L	[34]
	Oscillatoriaceae	*Oscillatoria tenuisa*	CH_3HgCl	0.001 mg/L, 0.01 mg/L, 0.05 mg/L, 0.25 mg/L	[33]
		Oscillatoria woronichinii	$Hg(CH_3COO)_2$	10 mg/L	[51]
		Phormidium fragile	$HgCl_2$	0.01 mg/L, 0.05 mg/L, 0.1 mg/L, 0.5 mg/L, 1.0 mg/L, 1.5 mg/L	[52]
		Phormidium limnetica	$HgCl_2$	0.14 mg/L	[53]
		Plectonema boryanum 246	$HgCl_2$	0.2 mg/L	[40]
Spirulinales	*Spirulinaceae*	*Spirulina platensis*	$HgCl_2$	10 mg/L, 50 mg/L; 0.3 mg/L, 0.6 mg/L, 3.6 mg/L	[17,41]
		Spirulina sp.	THg	216 μg/kg	[54]
Synechococcales	*Merismopediaceae*	*Synechococcus bacillaris*	MeHg	6×10^{-6}–8×10^{-6} mg/L	[55]
		Synechococcus PCC 7942	$HgCl_2$	4 mg/L	[47]
		Synechococcus sp.	$Hg(NO_3)_2$	Hg(II)/DOC=7.45 ng/mg, 5.41 ng/mg, 14.38 ng/mg, 1.78 ng/mg	[56]
		Synechococcus sp. IU 625	$HgCl_2$	1.0 mg/L	[30]
		Synechocystis sp.	CH_3HgCl	1.3×10^{-4}–1.5×10^{-4} mg/L	[57]
		Synechocystis sp.	$HgCl_2$	1.5×10^{-4}–3.2×10^{-4} mg/L	[57]
	Pseudanabaenaceae	*Limnothrix planctonica*	HgCl2	0.1 mg/L, 0.12 mg/L, 0.2 mg/L	[53,58]
	Schizotrichaceae	*Schizothrix calcicola*	MeHg	5×10^{-8}–8×10^{-6} mg/L; 4×10^{-5} mg/L	[59–60]
	Synechococcaceae	*Anacystis nidulans*	$HgCl_2$	0.3 mg/L, 0.6 mg/L, 3.6 mg/L	[41]

* All units are converted to mg/L.

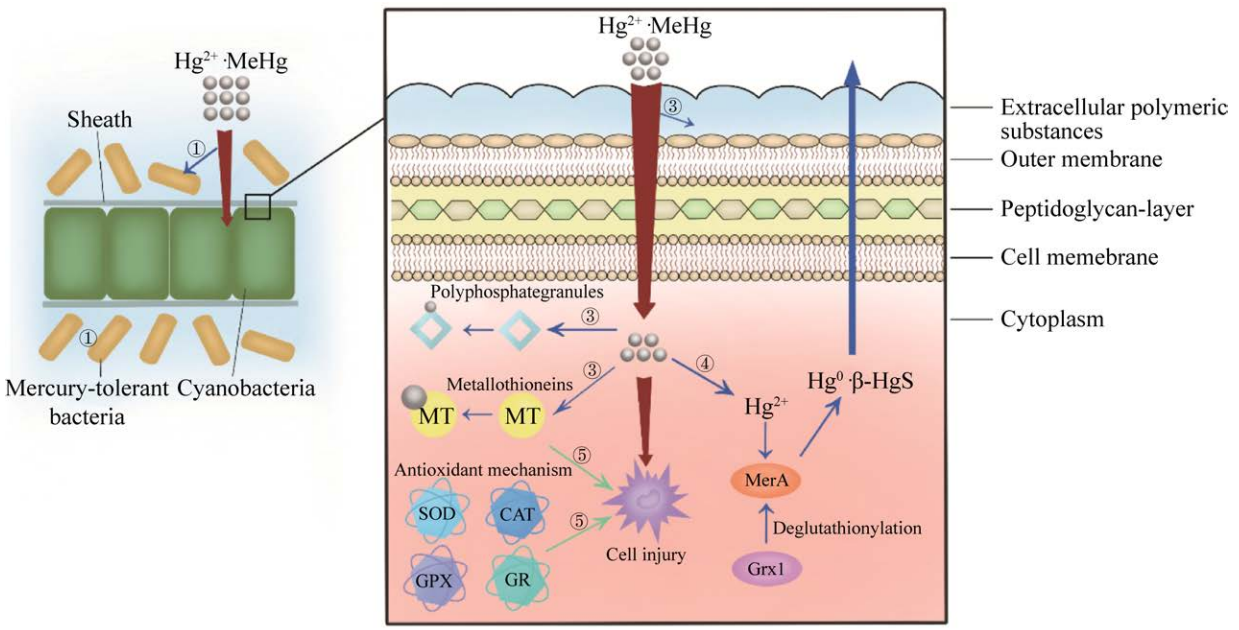

图 2　蓝细菌的汞耐受机制示意图

Figure 2　Schematic diagram of the mercury tolerance mechanism of cyanobacteria. ① Extracellular mercury-tolerant bacteria increase the mercury tolerance of cyanobacteria. ② Sheath reduces the mercury exposure area of cyanobacteria. ③ Polyphosphate granules, metallothioneins and compounds in extracellular polymeric substances combine mercury. ④ The mercury reduction pathway reduces the toxicity of mercury. ⑤ Metallothioneins and antioxidant mechanism repair cell injury.

的 MeHg 环境中，VCF 与细胞表面积/体积比呈正相关(R^2=0.922，P<0.001)[57]。通过对 Lee 等[55]、Miles 等[59]、Pickhardt 等[57]的 3 项研究的对比发现，虽然三者的培养条件有些许差异(Lee 等：18 °C、MeHg 浓度为 6.25×10^{-5}–9.06×10^{-5} mg/L、实验蓝细菌为 *Synechococcus bacillaris*；Miles 等：20–22 °C、MeHg 浓度为 5×10^{-8}–8×10^{-6} mg/L、实验对象为 *Schizothrix calcicole*；Pickhardt 等：17 °C、MeHg 浓度为 1.99×10^{-2}–1.10×10^{-1} mg/L、所用蓝细菌为 *Synechocystis* sp.)，但是 MeHg 的体积浓度因子明显随蓝细菌的体积减小而增大(Vol：1.1–1.6 μm^3，VCF=6.4×10^6；Vol：212 μm^3，VCF=4×10^5；Vol：4.5 μm^3，VCF=14.5×10^5–14.6×10^5)。这三项研究表明，具有更大相对暴露面积的蓝细菌更容易在胞内富集环境中的 MeHg。因此，胶鞘减少蓝细菌暴露在汞胁迫环境中的细胞表面积，能够避免过量的 MeHg 进入蓝细菌。

2.2　通过自身化合物钝化汞的毒性

蓝细菌在胞内和胞外的分泌物含有某些能够与汞结合的化合物。胞外聚合物与汞结合后可以有效减少汞进入细胞，减少胞内组织受到毒害，胞内的聚磷酸盐、金属硫蛋白等化合物能够及时与进入细胞的汞结合并钝化汞的毒性，避免汞造成更严重的损伤。

蓝细菌的胞外具有丰富的胞外聚合物(extracellular polymeric substances，EPS)，这种聚合物对胞外重金属有螯合作用[63]。Maldonado 等在扫描电镜下观察到颤藻(*Oscillatoria* sp. PCC 7515)、色球藻(*Chroococcus* sp. PCC 9106)

和螺旋藻(*Spirulina* sp. PCC 6313)表面的胞外聚合物上螯合了环境中的 Pb[64]。Tonietto 等观察到蓝细菌 *C. raciborskii* 的分泌物中含有游离脂肪酸(FFA)，可以络合海水中的重金属(Cu，Cd，Zn)[65]。Ozturk 等分离的集胞藻属、色球藻属和微囊藻属的 10 株蓝细菌在重金属 Cr(VI)环境下会改变自身 EPS 组成成分，由葡萄糖(99%)和少量半乳糖醛酸(1%)转变为木糖(75%)、少量葡萄糖(9%)、鼠李糖(14%)和半乳糖醛酸(2%)，并且胞外聚合物浓度与重金属抗性存在正相关[66]。蓝细菌代谢产生的 EPS 对汞暴露环境中的汞也具有较好的螯合或络合能力。在 $Hg(NO_3)_2$ 环境中，微囊藻(*Microcystis aeruginosa*)的 EPS 是抵御外部 Hg^{2+}的保护屏障，对数期更高的 EPS 量意味着更高的 Hg^{2+}有效浓度(EC_{50})[50]。在 0–5×10^{-3} mg/L 浓度的单甲基汞(monomethylmercury，MMeHg)培养中，微囊藻(*Microcystis aeruginosa*)的 EPS 质量也会随 MMeHg 浓度的提高而增加[49]。Song 等[67]研究了一株色球藻的胞外聚合物与 Hg^{2+}的结合能力。EPS-Hg^{2+}体系的条件稳定常数(log K_a)和结合常数(log K_b)分别为 3.84–4.24 和 6.99–7.69，并且在三维荧光光谱(EEM)观察到 3 个蛋白质样荧光峰在 0.12 mg/L 的 Hg^{2+}环境下被淬灭，表明 Hg^{2+}与 EPS 中的蛋白质形成络合物。EPS 中谷胱甘肽质子化的巯基也可以与 MeHg 发生强烈的结合[68]。

汞进入蓝细菌细胞内，能够与胞内有效结合汞的化合物反应，减少对细胞产生的毒害作用。作为高电荷的阴离子，聚磷酸盐对金属阳离子有很强的结合力，蓝细菌胞内的主要金属阳离子都富集在细胞壁中的聚磷酸盐颗粒[69]。Wallace 等构建的重金属与亚细胞结构结合的模型，生物体内富含金属的颗粒(metal-rich granules，MRG)和金属硫蛋白(metallothioneins，MT)共同构成生物解毒金属组分(biologically detoxified metal，BDM)来减轻重金属毒性[70]，这说明蓝细菌胞内的聚磷酸盐是抵抗 Hg^{2+}毒性的 MRG 组分。在钝顶节旋藻(*Arthrospira platensis*)暴露于 2×10^{-7} mg/L 的 $Hg(NO_3)_2$ 环境中几秒钟内，生物膜会增加多聚磷酸盐进行抵抗[48]，导致金属离子的利用率降低，弱化金属离子在细胞内的活动，进而抵抗 Hg^{2+}的毒性。在 X 光下可以直接观察到鲍氏织线藻(*Plectonema boryanum*)在 99.82 mg/L 的 $HgCl_2$ 环境下，胞内的聚磷酸盐与 Hg^{2+}结合并在胞内被隔离的现象[71]。

金属硫蛋白(MT)是一类维持生物体内金属含量平衡和缓解重金属毒性的低分子量蛋白质或多肽，广泛分布于动植物及微生物中。有研究表明，金属硫蛋白在动物体内可以缓解甲基汞和汞中毒的症状、修复细胞损伤[72–75]，在鱼类、酵母菌、原生动物等生物中也发现类似现象，是生物体内广泛存在的汞解毒机制。蓝细菌的胞质和囊体间隙分布着谷胱甘肽[76]，其巯基可以与 MeHg 发生强烈的结合[68]，半胱氨酰硫醇盐也能够与 Hg^{2+}发生强烈的结合[77]。研究发现，蓝细菌中金属硫蛋白可以抵抗 Cu^+、Ag^+、Zn^{2+}和 Cd^{2+}的毒性[78]，但对蓝细菌中金属硫蛋白的研究较少，缺乏蓝细菌中金属硫蛋白与汞相互作用的直接报道。鉴于蓝细菌具有与其他重金属，例如 Cu^+、Zn^{2+}、Cd^{2+}、He^{2+}和 Pb^{2+}等作用的金属硫蛋白[78–79]，和其他生物体内金属硫蛋白抵御汞毒性的机制类似，蓝细菌很可能也能通过金属硫蛋白缓解汞的毒性。

植物螯合肽(phytochelatins，PC)也称为Ⅲ型金属硫蛋白，在植物和真核藻类中具有抵御重金属毒害的功能[80]。在蓝细菌中也有植物螯合肽和类植物螯合肽蛋白的存在[81–82]，在念珠藻(*Nostoc punctiforme*)、红海束毛藻 IMS101

(*Trichodesmium erythraeum* IMS101)、海洋原绿球藻 MIT (*Prochlorococcus marinus* MIT)、念珠藻 PCC 7120 (*Nostoc* sp. PCC 7120)的基因组序列分析中发现了类编码 PC 合酶蛋白的基因[83]。在对照实验中，用丁硫氨酸亚砜胺(buthionine sulphoximine)抑制鱼腥藻(*Anabaena doliolum*)植物螯合肽的合成后，同样浓度 Cd^{2+}下蓝细菌内的 SOD 量增加到原来的约 1.75 倍，蓝细菌遭受到更强的氧化毒害[84]。这些研究表明，类植物螯合肽存在于蓝细菌中，并且具有抵御重金属毒害的作用。从植物螯合肽的基础水平、Cd^{2+}胁迫时的响应程度、随 Cd^{2+}浓度和暴露时间增加的变化来看，线状蓝细菌(*Geitlerinema* sp. PCC 7407)中的植物螯合肽合成酶与真核藻类(*Marchantia polymorpha*)的非常相似[85]，因此蓝细菌内的植物螯合肽的功能与机制也可能与真核藻类的类似。结合真核藻类内植物螯合肽抵御汞的多项研究[86–88]，蓝细菌的植物螯合肽可能具备同样的功能。

2.3 利用自身抗氧化机制修复汞对细胞的损伤

与其他重金属类似，汞会诱导蓝细菌产生过氧化物自由基对细胞产生毒害，并且这种毒害作用会受到高光强的促进[89–90]。相关研究在蓝细菌以外的生物体内已有报道，例如汞能刺激腰鞭毛虫 *Gonyaulax polyedra* 的抗氧化机制，细胞的总 SOD 活性在暴露的第一天增加至对照组的 134%[91]。人类[92]、真核藻类[93–94]、动物[95]和植物[96]等生物在汞暴露条件下产生氧化应激反应的实验也有报道[97]。对于蓝细菌，灰色念珠藻(*Nostoc muscorum*)和聚球藻(*Synechococcus* 7942)胞内自由基在 4 mg/L 的 $HgCl_2$ 环境中分别增加了 152%、132%[47]。自由基的产生进而刺激蓝细菌的抗氧化机制。灰色念珠藻(*Nostoc muscorum* Meg1)在 0.499 mg/L 的 Cd^{2+}环境中，抗氧化酶包括超氧化物歧化酶(SOD)、过氧化氢酶(CAT)、谷胱甘肽过氧化物酶(GSH-Px)、谷胱甘肽还原酶(GR)和非酶抗氧化剂(谷胱甘肽、总硫醇、植物螯合素和脯氨酸)的含量均增加，*Dolichospermum flosaquae* 暴露于 5 mg/L 的 Cr 环境中时，抗氧化酶 SOD 和 CAT 的活性显著增加[98]，表明蓝细菌具有应对重金属胁迫下活性氧(ROS)的机制[99]。在蓝细菌中汞暴露引起氧化应激反应的研究很少，其中 Singh 等进行了强光和汞暴露共同介导的氧化应激反应研究[89]。结合蓝细菌胞内应对其他重金属的氧化应激反应和汞在其他生物体内引起氧化应激的多项研究，我们推测蓝细菌的氧化应激反应能够修复汞造成的毒害。

除了各类抗氧化酶，蓝细菌还具有其他的氧化应激防御措施。Kumar 等发现蓝细菌(*Dolichospermum flosaquae*)在 5 mg/L 的 Cr 胁迫下会改变自身饱和脂肪酸和不饱和脂肪酸的比例，形成更高的饱和脂肪酸比例[98]。非酶类抗氧化物质——脯氨酸，在蓝细菌抵抗重金属毒性时也发挥修复作用，它可以由蓝细菌自身合成[100]，并且具有应对环境胁迫的功能[101]。Goodgame 等通过光谱观察到脯氨酸能够与 Hg^{2+}形成络合物[102]，可能在蓝细菌处于汞暴露环境时减轻汞的毒害。其他生物，例如植物芫荽[96]和细菌[103]的汞耐受能力可以在外源脯氨酸添加下得到增强，并且脯氨酸可以与谷胱甘肽协同增强植物抵御重金属胁迫的能力[104]。尽管有研究表明 Cu^{2+}能够引起蓝细菌脯氨酸产量增加[105]，目前蓝细菌内脯氨酸对汞胁迫响应的研究仍然很少。除此之外，金属硫蛋白也具有抗氧化功能，在修复细胞内重金属损伤时发挥作用[106]。

2.4 利用自身酶转化汞的形态降低毒性

除了自身物理结构和化合物构建的汞防御机制外，蓝细菌具有改变汞形态来减轻汞毒性的代谢途径。Mason 等认为蓝细菌是海洋环境中汞还原的主要贡献者[15]。汞在不同价态具有不同强弱的毒性，蓝细菌能够将 Hg^{2+}转化为毒性低和生物可利用度较低的单质汞和硫化汞。Marteyn 等在集胞藻(*Synechocystis* PCC6803)中发现的汞还原蛋白(MerA)，在 NADPH 驱动下对环境中的 Hg^{2+}具有还原能力，特别是它的 C78 残基，在抵抗环境中的汞离子时发挥重要作用[107]。2019 年，Singh 等发现与其他细菌门包含 5 个不同 *mer* 基因组成的 *mer* 操纵子不同，集胞藻(*Synechocystis* sp. PCC6803)基因组中只具有一个保守的转录调节因子(*MerR*)和一个汞还原酶基因(*merA*)，并且它们在基因组上的位置彼此分开[108]。通过同源物的相似性比较，Singh 等推测蓝细菌的 *mer* 基因可能是从其他汞还原物种水平转移得到的[108]。同时，蓝细菌胞内的谷氧还蛋白(Grx1)可以对还原 Hg^{2+}后谷胱甘肽化的 MerA 进行去谷胱甘肽化，激活 MerA 的活性[107]，重新参与蓝细菌对汞的还原。蓝细菌的汞还原能力已在实验室中被进一步证实。由 80.5% $HgCl_2$、15.8% HgClOH 和 3.0% $HgCl^{3-}$组成的 0.14 mg/L Hg^{2+}，1 h 后被席藻(*Phormidium limnetica*)转换为 56% β-HgS、36% Hg^0 和 8%酸还原 Hg[53,109]。Chu 等将蓝细菌(*Synechococcus* sp. IU 625)在 1 mg/L 的 $HgCl_2$ 环境中培养 3 d 后，环境中 76%的 Hg^{2+}被转换为单质汞，并以气态形式散失[30]。

2.5 与抗汞细菌共生抵御汞

蓝细菌胞外粘液中富集着大量共生细菌，Brunberg 发现湖泊中上层微囊藻共生菌的丰度达到细菌总丰度的 19%–40%[110]。其中某些细菌具有很强的重金属抗性，Abdulaziz 等发现其中的枝芽孢菌(*Virgibacillus* sp. MMRF-571)和蜡样芽孢杆菌(*Bacillus cereus* MMRF-575)对 Hg (100 mg/L)表现出特别的抵抗能力[111]。这些重金属抗性优异的细菌可能在帮助蓝细菌抵抗重金属毒性方面发挥着作用。Shi 等发现集胞藻(*Synechocystis* sp. PCC6803)的抗 Cd^{2+}最小抑制浓度(MIC)为 25 μmol/L，而氨基杆菌(*Aminobacter* sp. Y9)能够与 PCC6803 互作，使受到 Cd^{2+}毒性抑制的 PCC6803 逐渐恢复生长[112]。然而，共生细菌帮助蓝细菌抵抗汞毒性的机制并没有被报道。

3 结论与展望

相比其他重金属，蓝细菌对汞的耐受性研究较为欠缺，特别是毒性和扩散速率更强的甲基汞。从目前的研究我们总结和探讨了 5 个方面的耐受机制，并提出以下几个有待研究的方向：(1) 蓝细菌对不同形态汞的耐受性极限。蓝细菌的汞耐受性得到了观察和实验验证，但是目前各种蓝细菌对无机汞和有机汞耐受的极限缺少研究。(2) 蓝细菌胞外聚合物对汞的抵抗机制。胞外聚合物抵抗汞的能力已有研究，并且观察到汞耐受过程中胞外聚合物成分组成和质量浓度会发生改变，然而胞外聚合物中化合物和与汞的交互机制的报道很少。(3) 蓝细菌金属硫蛋白和抗氧化机制对汞的特异性研究。蓝细菌的这两种机制对其他重金属的响应和其他生物中这两种机制对汞的研究都已有报道。唯独缺乏这两种机制在蓝细菌内针对汞的特异性研究。(4) 蓝细菌对有机汞的耐受机制。与无机汞相比，蓝细菌对毒性更强、分布速率更高的有机汞的耐受性研究很少。有机汞耐受性让蓝细菌能够富集更多的有机汞，有机汞进入食物链中累积和传递后，最终毒害人类等大型生物体。(5) 蓝细菌通过共生细菌抵抗汞毒性的机制研

究。Abdulaziz 等[111]提出蓝细菌共生的汞耐受细菌具有保护初级生产者免受重金属毒害的潜力，Shi 等[112]报道了异养细菌提高蓝细菌镉耐受能力的现象，但是仍然缺乏共生细菌提高蓝细菌汞耐受性的研究和深入的机制探究。(6)蓝细菌汞还原基因的调控和来源。目前 2013 年和 2019 年的两项研究报道了模式蓝细菌集胞藻 PCC6803 的 *merA* 基因的调控和亲缘关系，其他蓝细菌内汞还原基因的发现和汞还原基因亲缘性、调控机制尚待研究。

蓝细菌对汞的耐受和富集能力在汞污染治理和汞中毒的治疗或缓解方面具有广阔的应用前景。蓝细菌应用于汞污染治理尚处于起步阶段。Cain 等[17]发现 *Aphanothece flocculosa* 能够去除 $HgCl_2$ 溶液中 90%的 Hg^{2+}。吸附 Hg^{2+}的细胞，经 NH_4Cl 和盐酸分别处理后解吸，还可进行汞回收，效率可达 100%。Sun 等也发现 *Microcystis aeruginosa* 能够去除 $HgCl_2$ 溶液中 70.14%的 Hg^{2+}[113]。蓝细菌还可以用于处理固体废弃物中的汞污染[114]。应用研究中也发现一些问题，例如蓝细菌死亡后细胞的 Hg^{2+}富集作用降低了 50%[17]，蓝细菌经过汞解吸处理后吸附能力减低等。目前的研究都是直接选用了现有的蓝细菌菌株进行汞污染处理，为了提升处理效果，还需要筛选或者驯化具有更强的汞耐受能力、更高的汞吸附能力和生长周期更快的蓝细菌菌株。蓝细菌还可以用于治疗汞中毒。多种蓝细菌菌株都对小鼠汞中毒具有很好的缓解作用[115–120]，例如，*Spirulina fusiformis*[115,117,120]、*Spirulina arthrospira*[116]、*Spirulina platensis*[118]、*Pseudanabaena tenuis*[119]能显著降低汞对小鼠肾脏和睾丸细胞(注射 5 mg/kg 剂量 $HgCl_2$)造成的氧化应激反应和细胞损伤。在治疗汞中毒时，除直接投喂蓝细菌细胞，还可将蓝细菌中的汞结合化合物进行表达制成解毒剂使用。蓝细菌的多种抗汞机制都有汞中毒治疗的潜力，既能降低汞的毒性也可修复汞造成的损伤。

参考文献

[1] 康世昌, 黄杰, 张强弓. 雪冰中汞的研究进展. 地球科学进展, 2010, 25(8): 783–793.
Kang SC, Huang J, Zhang QG. Progress in the study of mercury in snow and ice. *Advances in Earth Science*, 2010, 25(8): 783–793. (in Chinese)

[2] Bu-Olayan AH, Thomas BV. Assessment of the ultra-trace mercury levels in selected desert plants. *International Journal of Environmental Science and Technology*, 2014, 11(5): 1413–1420.

[3] Huang J, Kang SC, Yin RS, Ram K, Liu XC, Lu H, Guo JM, Chen SY, Tripathee L. Desert dust as a significant carrier of atmospheric mercury. *Environmental Pollution*, 2020, 267: 115442.

[4] Zhang BL, Chen T, Guo JM, Wu MH, Yang RQ, Chen XM, Wu XK, Zhang W, Kang SC, Liu GX, Dyson P. Microbial mercury methylation profile in *Terminus* of a high-elevation glacier on the northern boundary of the Tibetan Plateau. *Science of the Total Environment*, 2020, 708: 135226.

[5] 林晶, 闫海鱼, 荆敏, 杨光红. 河流汞污染对青鳉鱼早期发育的毒性影响. 生态学杂志, 2020, 39(5): 1706–1714.
Lin J, Yan HY, Jing M, Yang GH. Toxic effects of river mercury contamination on early development of *Oryzias latipes*. *Chinese Journal of Ecology*, 2020, 39(5): 1706–1714. (in Chinese)

[6] 安建博, 张瑞娟. 低剂量汞毒性与人体健康. 国外医学: 医学地理分册, 2007, 28(1): 39–42.
An JB, Zhang RJ. Low dose mercury toxicity and human health. *Foreign Medical Sciences*: *Section of Medgeography*, 2007, 28(1): 39–42. (in Chinese)

[7] 万双秀, 王俊东. 汞对人体神经的毒性及其危害. 微量元素与健康研究, 2005, 22(2): 67–69.
Wan SX, Wang JD. Mercury toxicity to human nerves and its hazards. *Studies of Trace Elements and Health*, 2005, 22(2): 67–69. (in Chinese)

[8] Suresh Kumar K, Dahms HU, Lee JS, Kim HC, Lee WC, Shin KH. Algal photosynthetic responses to toxic metals and herbicides assessed by chlorophyll a fluorescence. *Ecotoxicology and Environmental Safety*, 2014, 104: 51–71.

[9] Gao YX, Peng XM, Zhang JC, Zhao JT, Li YY, Li YF,

Li B, Hu Y, Chai ZF. Cellular response of *E. coli* upon Hg^{2+} exposure — a case study of advanced nuclear analytical approach to metalloproteomics. *Metallomics*, 2013, 5(7): 913.

[10] Tyler G, Påhlsson AMB, Bengtsson G, Bååth E, Tranvik L. Heavy-metal ecology of terrestrial plants, microorganisms and invertebrates. *Water*, *Air*, *and Soil Pollution*, 1989, 47(3/4): 189–215.

[11] Kehrig HA, Seixas TG, Baêta AP, Malm O, Moreira I. Inorganic and methylmercury: do they transfer along a tropical coastal food web? *Marine Pollution Bulletin*, 2010, 60(12): 2350–2356.

[12] Scheuhammer AM, Meyer MW, Sandheinrich MB, Murray MW. Effects of environmental methylmercury on the health of wild birds, mammals, and fish. *Ambio*, 2007, 36(1): 12–18.

[13] Lázaro WL, Díez S, Bravo AG, Da Silva CJ, Ignácio ÁRA, Guimaraes JRD. Cyanobacteria as regulators of methylmercury production in periphyton. *Science of the Total Environment*, 2019, 668: 723–729.

[14] Lázaro WL, Guimarães JRD, Ignácio ARA, Da Silva CJ, Díez S. Cyanobacteria enhance methylmercury production: a hypothesis tested in the periphyton of two lakes in the Pantanal floodplain, Brazil. *Science of the Total Environment*, 2013, 456/457: 231–238.

[15] Mason RP, Morel FMM, Hemond HF. The role of microorganisms in elemental mercury formation in natural waters. *Water*, *Air*, *and Soil Pollution*, 1995, 80(1/2/3/4): 775–787.

[16] Heimbürger LE, Cossa D, De Marty JC, Migon C, Averty B, Dufour A, Ras J. Methyl mercury distributions in relation to the presence of nano- and picophytoplankton in an oceanic water column (Ligurian Sea, North-western Mediterranean). *Geochimica et Cosmochimica Acta*, 2010, 74(19): 5549–5559.

[17] Cain A, Vannela R, Woo LK. Cyanobacteria as a biosorbent for mercuric ion. *Bioresource Technology*, 2008, 99(14): 6578–6586.

[18] Yamamuro M. Importance of epiphytic cyanobacteria as food sources for heterotrophs in a tropical seagrass bed. *Coral Reefs*, 1999, 18(3): 263–271.

[19] Berezina NA, Tiunov AV, Tsurikov SM, Kurbatova SA, Korneva LG, Makarova OS, Bykova SN. Cyanobacteria as a food source for invertebrates: results of a model experiment. *Russian Journal of Ecology*, 2021, 52(3): 247–252.

[20] Panosso R, Carlsson P, Kozlowsky-Suzuki B, Azevedo SMFO, Granéli E. Effect of grazing by a neotropical copepod, *Notodiaptomus*, on a natural cyanobacterial assemblage and on toxic and non-toxic cyanobacterial strains. *Journal of Plankton Research*, 2003, 25(9): 1169–1175.

[21] Burns CW, Xu ZK. Calanoid copepods feeding on algae and filamentous cyanobacteria: rates of ingestion, defaecation and effects on trichome length. *Journal of Plankton Research*, 1990, 12(1): 201–213.

[22] Krivosheina MG. On insect feeding on cyanobacteria. *Paleontological Journal*, 2008, 42(6): 596–599.

[23] Kamjunke N, Schmidt K, Pflugmacher S, Mehner T. Consumption of cyanobacteria by roach (*Rutilus rutilus*): useful or harmful to the fish? *Freshwater Biology*, 2002, 47(2): 243–250.

[24] Briland RD, Stone JP, Manubolu M, Lee J, Ludsin SA. Cyanobacterial blooms modify food web structure and interactions in western Lake Erie. *Harmful Algae*, 2020, 92: 101586.

[25] Fujibayashi M, Okano K, Takada Y, Mizutani H, Uchida N, Nishimura O, Miyata N. Transfer of cyanobacterial carbon to a higher trophic-level fish community in a eutrophic lake food web: fatty acid and stable isotope analyses. *Oecologia*, 2018, 188(3): 901–912.

[26] Li CD, Zhang QG, Kang SC, Liu YQ, Huang J, Liu XB, Guo JM, Wang K, Cong ZY. Distribution and enrichment of mercury in Tibetan lake waters and their relations with the natural environment. *Environmental Science and Pollution Research*, 2015, 22(16): 12490–12500.

[27] Zhang QG, Pan K, Kang SC, Zhu AJ, Wang WX. Mercury in wild fish from high-altitude aquatic ecosystems in the Tibetan Plateau. *Environmental Science & Technology*, 2014, 48(9): 5220–5228.

[28] Ciferri O. *Spirulina*, the edible microorganism. *Microbiological Reviews*, 1983, 47(4): 551–578.

[29] Slotton DG, Goldman CR, Franke A. Commercially grown spirulina found to contain low-levels of mercury and lead . *Nutrition Reports International*, 1989, 40(6): 1165–1172.

[30] Chu TC, Murray SR, Todd J, Perez W, Yarborough JR, Okafor C, Lee LH. Adaption of *Synechococcus* sp. IU 625 to growth in the presence of mercuric chloride. *Acta Histochemica*, 2012, 114(1): 6–11.

[31] Vishnivetskaya TA, Mosher JJ, Palumbo AV, Yang ZK, Podar M, Brown SD, Brooks SC, Gu BH, Southworth GR, Drake MM, Brandt CC, Elias DA. Mercury and

other heavy metals influence bacterial community structure in contaminated Tennessee streams. *Applied and Environmental Microbiology*, 2011, 77(1): 302–311.

[32] Yoshimura KM, Todorova S, Biddle JF. Mercury geochemistry and microbial diversity in meromictic Glacier Lake, Jamesville, NY. *Environmental Microbiology Reports*, 2020, 12(2): 195–202.

[33] Huang WJ, Lu YM, Yu WL. Toxicity and bioaccumulation of monomethylmercury in freshwater cyanobacteria: *Oscillatoria tenuisa* and *Microcystis aeruginosa*. *Environmental Forensics*, 2012, 13(3): 255–261.

[34] Havlík B, Starý J, Pršilová J, Kratzer K, Hanušová J. Mercury circulation in aquatic environment. part 2: metabolism of methyl and phenyl mercury in phytoplankton. *Acta Hydrochimica et Hydrobiologica*, 1979, 7(4): 401–408.

[35] Bisen PS, Shukla HD, Gupta A, Bagchi SN. Preliminary characterization of a novel *Synechococcus* isolate showing mercury, cadmium and lead tolerance. *Environmental Technology Letters*, 1987, 8(9): 427–432.

[36] Gothalwal R, Bisen PS. Isolation and physiological characterization of *Synechococcus cedrorum* 1191 strain tolerant to heavy metals and pesticides. *Biomedical and environmental sciences*: *BES*, 1993, 6(2): 187–194.

[37] Mehta R, Shukla HD, Bisen PS. Physiological and genetical characterization of a novel *Synechococcus* sp. isolate, showing resistance against cyanide, heavy metals and drugs. *Environmental Technology*, 1992, 13(3): 253–258.

[38] Prasad AB, Samanta R, Vishwakarma ML, Vaishampayan A. Biological effects of a mercury fungicide on a N_2-fixing blue-green alga *Nostoc muscorum*: isolation and preliminary characterization of a Hg-resistant mutant. *New Phytologist*, 1986, 102(1): 45–49.

[39] Franco MW, Mendes LA, Windmöller CC, Moura KAF, Oliveira LAG, Barbosa FAR. Mercury methylation capacity and removal of Hg species from aqueous medium by cyanobacteria. *Water*, *Air*, *& Soil Pollution*, 2018, 229(4): 1–12.

[40] Wu H, Zhao Y, Guo H, Zhang T, Guo W. Vacuole formation induced by heavy metal and trace element in cyanobactera (blue-green algae) . *Microbiology*, 2003, 30(3): 60–64.

[41] Murthy SDS, Bukhov NG, Mohanty P. Mercury-induced alterations of chlorophyll a fluorescence kinetics in cyanobacteria: multiple effects of mercury on electron transport. *Journal of Photochemistry and Photobiology B*: *Biology*, 1990, 6(4): 373–380.

[42] Sun RG, Mo YF, Feng XB, Zhang LM, Jin L, Li QH. Effects of typical algae species (*Aphanizomenon flosaquae* and *Microcystis aeruginosa*) on photoreduction of Hg^{2+} in water body. *Journal of Environmental Sciences*, 2019, 85: 9–16.

[43] Laloknam S, Sirisopana S, Phornphisutthimas S, Takabe T, Incharoensakdi A. Removal of mercury, arsenic, and cadmium in synthetic wastewater by cyanobacterium *Aphanothece halophytica*. *NU Science Journal*, 2009, 6: 96–104.

[44] Deng L, Wu F, Deng NS, Zuo YG. Photoreduction of mercury(II) in the presence of algae, *Anabaena* cylindrical. *Journal of Photochemistry and Photobiology B*: *Biology*, 2008, 91(2/3): 117–124.

[45] Pant A, Srivastava SC, Singh SP. Factors regulating methyl mercury uptake in a cyanobacterium. *Ecotoxicology and Environmental Safety*, 1995, 32(1): 87–92.

[46] Pandey PK, Singh SP. Hg^{2+} uptake in a cyanobacterium. *Current Microbiology*, 1993, 26(3): 155–159.

[47] Rahman MA, Soumya KK, Tripathi A, Sundaram S, Singh S, Gupta A. Evaluation and sensitivity of cyanobacteria, *Nostoc muscorum* and *Synechococcus* PCC 7942 for heavy metals stress — a step toward biosensor. *Toxicological & Environmental Chemistry*, 2011, 93(10): 1982–1990.

[48] Tekaya N, Gammoudi I, Braiek M, Tarbague H, Moroté F, Raimbault V, Sakly N, Rebière D, Ben Ouada H, Lagarde F, Ben Ouada H, Cohen-Bouhacina T, Dejous C, Jaffrezic Renault N. Acoustic, electrochemical and microscopic characterization of interaction of *Arthrospira platensis* biofilm and heavy metal ions. *Journal of Environmental Chemical Engineering*, 2013, 1(3): 609–619.

[49] Chen HW, Wu YY, Li YX, Huang WJ. Methylmercury accumulation and toxicity to cyanobacteria: implications of extracellural polymeric substances and growth properties. *Water Environment Research*, 2014, 86(7): 626–634.

[50] Chen HW, Huang WJ, Wu TH, Hon CL. Effects of extracellular polymeric substances on the bioaccumulation of mercury and its toxicity toward the cyanobacterium *Microcystis aeruginosa*. *Journal of Environmental Science and Health*, *Part A*, 2014, 49(12): 1370–1379.

[51] Fisher NS, Bone M, Teyssie JL. Accumulation and toxicity ol Cd, Zn, Ag, and Hg in four marine phytopiankters. *Marine Ecology Progress Series*, 1984, 18: 201–213.

[52] Khalil Z. Toxicological response of a cyanobacterium, *Phormidium fragile*, to mercury. *Water*, *Air*, *and Soil Pollution*, 1997, 98(1/2): 179–185.

[53] Lefebvre DD, Kelly D, Budd K. Biotransformation of Hg(II) by cyanobacteria. *Applied and Environmental Microbiology*, 2007, 73(1): 243–249.

[54] Chojnacka K, Chojnacki A, Górecka H. Trace element removal by *Spirulina* sp. from copper smelter and refinery effluents. *Hydrometallurgy*, 2004, 73(1/2): 147–153.

[55] Lee CS, Fisher NS. Methylmercury uptake by diverse marine phytoplankton. *Limnology and Oceanography*, 2016, 61(5): 1626–1639.

[56] Soto Cárdenas C, Queimaliños C, Ribeiro Guevara S, Gerea M, Diéguez MC. The microbial mercury link in oligotrophic lakes: bioaccumulation by picocyanobacteria in natural gradients of dissolved organic matter. *Chemosphere*, 2019, 230: 360–368.

[57] Pickhardt PC, Fisher NS. Accumulation of inorganic and methylmercury by freshwater phytoplankton in two contrasting water bodies. *Environmental Science & Technology*, 2007, 41(1): 125–131.

[58] Kelly D, Budd K, Lefebvre DD. Mercury analysis of acid- and alkaline-reduced biological samples: identification of meta-cinnabar as the major biotransformed compound in algae. *Applied and Environmental Microbiology*, 2006, 72(1): 361–367.

[59] Miles CJ, Moye HA, Phlips EJ, Sargent B. Partitioning of monomethylmercury between freshwater algae and water. *Environmental Science & Technology*, 2001, 35(21): 4277–4282.

[60] Dranguet P, Freiburghaus A, Slaveykova V, Le Faucheur S. Long-term effects of mercury on biofilms grown in contaminated microcosms: a pilot study. *Environments*, 2019, 6(3): 28.

[61] Lange W. Speculations on a possible essential function of the gelatinous sheath of blue-green algae. *Canadian Journal of Microbiology*, 1976, 22(8): 1181–1185.

[62] Schecher WD, Driscoll CT. Interactions of copper and lead with *Nostoc muscorum*. *Water*, *Air*, *and Soil Pollution*, 1985, 24(1): 85–101.

[63] Pandey VD. Cyanobacteria-mediated heavy metal remediation. Agro-Environmental Sustainability. Cham: Springer International Publishing, 2017: 105–121.

[64] Maldonado J, Solé A, Puyen ZM, Esteve I. Selection of bioindicators to detect lead pollution in Ebro delta microbial mats, using high-resolution microscopic techniques. *Aquatic Toxicology*, 2011, 104(1/2): 135–144.

[65] Tonietto AE, Lombardi AT, Henriques Vieira AA, Parrish CC, Choueri RB. *Cylindrospermopsis raciborskii* (Cyanobacteria) exudates: chemical characterization and complexation capacity for Cu, Zn, Cd and Pb. *Water Research*, 2014, 49: 381–390.

[66] Ozturk S, Aslim B. Relationship between chromium(VI) resistance and extracellular polymeric substances (EPS) concentration by some cyanobacterial isolates. *Environmental Science and Pollution Research*, 2008, 15(6): 478–480.

[67] Song WJ, Pan XL, Mu SY, Zhang DY, Yang X, Lee DJ. Biosorption of Hg(II) onto goethite with extracellular polymeric substances. *Bioresource Technology*, 2014, 160: 119–122.

[68] Rabenstein DL, Fairhurst MT. Nuclear magnetic resonance studies of the solution chemistry of metal complexes. XI. Binding of methylmercury by sulfhydryl-containing amino acids and by glutathione. *Journal of the American Chemical Society*, 1975, 97(8): 2086–2092.

[69] Pettersson A, Hällbom L, Bergman B. Aluminum effects on uptake and metabolism of phosphorus by the cyanobacterium *Anabaena cylindrica*. *Plant Physiology*, 1988, 86(1): 112–116.

[70] Wallace WG, Lee BG, Luoma SN. Subcellular compartmentalization of Cd and Zn in two bivalves. I. Significance of metal-sensitive fractions (MSF) and biologically detoxified metal (BDM). *Marine Ecology Progress Series*, 2003, 249: 183–197.

[71] Jensen TE, Baxter M, Rachlin JW, Jani V. Uptake of heavy metals by *Plectonema* boryanum (*Cyanophyceae*) into cellular components, especially polyphosphate bodies: an X-ray energy dispersive study. *Environmental Pollution Series A*, *Ecological and Biological*, 1982, 27(2): 119–127.

[72] Lima LADO, Bittencourt LO, Puty B, Fernandes RM, Nascimento PC, Silva MCF, Alves-Junior SM, Pinheiro JDJV, Lima RR. Methylmercury intoxication promotes metallothionein response and cell damage in salivary glands of rats. *Biological Trace Element Research*, 2018, 185(1): 135–142.

[73] 王欣卉, 王颖, 徐炳政, 佐兆杭, 张东杰, 宫雪, 刘淑婷. 酵母源金属硫蛋白(MT-2)对慢性汞中毒小鼠

肝脏损伤的修复作用. 中国食品学报, 2018, 18(8): 55–61.
Wang XH, Wang Y, Xu BZ, Zuo ZH, Zhang DJ, Gong X, Liu ST. The repairing effects of metallothionein (MT-2) from yeast on chronic mercury poisoning mice' liver. *Journal of Chinese Institute Of Food Science and Technology*, 2018, 18(8): 55–61. (in Chinese)

[74] Yasutake A, Sawada M, Shimada A, Satoh M, Tohyama C. Mercury accumulation and its distribution to metallothionein in mouse brain after sub-chronic pulse exposure to mercury vapor. *Archives of Toxicology*, 2004, 78(9): 489–495.

[75] Fang Y, Yang HS, Liu BZ. Tissue-specific response of metallothionein and superoxide dismutase in the clam *Mactra* veneriformis under sublethal mercury exposure. *Ecotoxicology*, 2012, 21(6): 1593–1602.

[76] Zechmann B, Tomašić A, Horvat L, Fulgosi H. Subcellular distribution of glutathione and cysteine in cyanobacteria. *Protoplasma*, 2010, 246(1/2/3/4): 65–72.

[77] Stillman MJ, Thomas D, Trevithick C, Guo X, Siu M. Circular dichroism, kinetic and mass spectrometric studies of copper(I) and mercury(II) binding to metallothionein. *Journal of Inorganic Biochemistry*, 2000, 79(1/2/3/4): 11–19.

[78] Liu T, Nakashima S, Hirose K, Shibasaka M, Katsuhara M, Ezaki B, Giedroc DP, Kasamo K. A novel cyanobacterial SmtB/ArsR family repressor regulates the expression of a CP_x-ATPase and a metallothionein in response to both Cu(I)/Ag(I) and Zn(II)/Cd(II). *Journal of Biological Chemistry*, 2004, 279(17): 17810–17818.

[79] Acharya C, Blindauer CA. Unexpected interactions of the cyanobacterial metallothionein SmtA with uranium. *Inorganic Chemistry*, 2016, 55(4): 1505–1515.

[80] Perales-Vela HV, Peña-Castro JM, Cañizares-Villanueva RO. Heavy metal detoxification in eukaryotic microalgae. *Chemosphere*, 2006, 64(1): 1–10.

[81] Mallick N, Rai LC. Characterization of Cd-induced low molecular weight protein in a N-fixing cyanobacterium *Anabaena Doliolum* with special reference to co-/multiple tolerance. *Biometals*, 1998, 11(1): 55–61.

[82] Harada E, Von Roepenack-Lahaye E, Clemens S. A cyanobacterial protein with similarity to phytochelatin synthases catalyzes the conversion of glutathione to γ-glutamylcysteine and lacks phytochelatin synthase activity. *Phytochemistry*, 2004, 65(24): 3179–3185.

[83] Tsuji N, Nishikori S, Iwabe O, Shiraki K, Miyasaka H, Takagi M, Hirata K, Miyamoto K. Characterization of phytochelatin synthase-like protein encoded by alr0975 from a prokaryote, *Nostoc* sp. PCC 7120. *Biochemical and Biophysical Research Communications*, 2004, 315(3): 751–755.

[84] Bhargava P, Kumar Srivastava A, Urmil S, Chand Rai L. Phytochelatin plays a role in UV-B tolerance in N2-fixing cyanobacterium *Anabaena Doliolum*. *Journal of Plant Physiology*, 2005, 162(11): 1220–1225.

[85] Bellini E, Varotto C, Borsò M, Rugnini L, Bruno L, Sanità Di Toppi L. Eukaryotic and prokaryotic phytochelatin synthases differ less in functional terms than previously thought: a comparative analysis of *Marchantia polymorpha* and *Geitlerinema* sp. PCC 7407. *Plants*, 2020, 9(7): 914.

[86] Gómez-Jacinto V, García-Barrera T, Gómez-Ariza JL, Garbayo-Nores I, Vílchez-Lobato C. Elucidation of the defence mechanism in microalgae *Chlorella sorokiniana* under mercury exposure. Identification of Hg-phytochelatins. *Chemico-Biological Interactions*, 2015, 238: 82–90.

[87] Agrawal S B, Chaudhary B R. Mercury-induced changes in glutathione content of a green-alga, *Cosmarium conspersum*. *Microbios*, 1993, 76(309): 223–229.

[88] Morelli E, Ferrara R, Bellini B, Dini F, Di Giuseppe G, Fantozzi L. Changes in the non-protein thiol pool and production of dissolved gaseous mercury in the marine diatom *Thalassiosira weissflogii* under mercury exposure. *Science of the Total Environment*, 2009, 408(2): 286–293.

[89] Singh R, Srivastava PK, Singh VP, Dubey G, Prasad SM. Light intensity determines the extent of mercury toxicity in the cyanobacterium *Nostoc muscorum*. *Acta Physiologiae Plantarum*, 2012, 34(3): 1119–1131.

[90] Singh R, Dubey G, Singh VP, Srivastava PK, Kumar S, Prasad SM. High light intensity augments mercury toxicity in cyanobacterium *Nostoc muscorum*. *Biological Trace Element Research*, 2012, 149(2): 262–272.

[91] Okamoto OK, Colepicolo P. Response of superoxide dismutase to pollutant metal stress in the marine dinoflagellate *Gonyaulax polyedra*. *Comparative Biochemistry and Physiology Part C*: *Pharmacology*, *Toxicology and Endocrinology*, 1998, 119(1): 67–73.

[92] Balali-Mood M, Naseri K, Tahergorabi Z, Khazdair MR, Sadeghi M. Toxic mechanisms of five heavy

metals: mercury, lead, chromium, cadmium, and arsenic. *Frontiers in Pharmacology*, 2021, 12: 643972.

[93] Ajitha V, Sreevidya CP, Sarasan M, Park JC, Mohandas A, Singh ISB, Puthumana J, Lee JS. Effects of zinc and mercury on ROS-mediated oxidative stress-induced physiological impairments and antioxidant responses in the microalga *Chlorella vulgaris*. *Environmental Science and Pollution Research*, 2021, 28(25): 32475–32492.

[94] Samadani M, El-Khoury J, Dewez D. Tolerance capacity of *Chlamydomonas* VHL^R mutants for the toxicity of mercury. *Water*, *Air*, *& Soil Pollution*, 2020, 231(4): 1–12.

[95] Vieira HC, Bordalo MD, Rodrigues ACM, Pires SFS, Rocha RJM, Soares AMVM, Rendón-von Osten J, Abreu SN, Morgado F. Water temperature modulates mercury accumulation and oxidative stress status of common goby (*Pomatoschistus microps*). *Environmental Research*, 2021, 193: 110585.

[96] Kapoor D, Kavani K, Rattan A, Landi M, Sharma A. Ameliorative role of pre-sowing proline treatment in *Coriandrum sativum* L. seedlings under mercury toxicity. *Phyton*, 2021, 90(2): 489–501.

[97] Pinto E, Sigaud-Kutner TCS, Leitão MAS, Okamoto OK, Morse D, Colepicolo P. Heavy metal-induced oxidative stress in algae1. *Journal of Phycology*, 2003, 39(6): 1008–1018.

[98] Kumar MS, Praveenkumar R, Ilavarasi A, Rajeshwari K, Thajuddin N. Biochemical changes of fresh water cyanobacteria *Dolichospermum flos*-aquae NTMS07 to chromium-induced stress with special reference to antioxidant enzymes and cellular fatty acids. *Bulletin of Environmental Contamination and Toxicology*, 2013, 90(6): 730–735.

[99] Ahad RIA, Syiem MB. Analyzing dose dependency of antioxidant defense system in the cyanobacterium *Nostoc muscorum* Meg 1 chronically exposed to Cd^{2+}. *Comparative Biochemistry and Physiology Part C*: *Toxicology & Pharmacology*, 2021, 242: 108950.

[100] Luesch H, Hoffmann D, Hevel JM, Becker JE, Golakoti T, Moore RE. Biosynthesis of 4-methylproline in cyanobacteria: cloning of *nosE* and *nosF* genes and biochemical characterization of the encoded dehydrogenase and reductase activities. *The Journal of Organic Chemistry*, 2003, 68(1): 83–91.

[101] Singh AP, Asthana RK, Kayastha AM, Singh SP. A comparison of proline, thiol levels and GAPDH activity in cyanobacteria of different origins facing temperature-stress. *World Journal of Microbiology and Biotechnology*, 2005, 21(1): 1–9.

[102] Goodgame D M L, Hill S P W. Heterometallic lanthanide mercury complexes of sarcosine and L-proline. *Journal of the Indian Chemical Society*, 1993, 70(11/12): 865–869.

[103] Al-Mailem DM, Eliyas M, Radwan SS. Ferric sulfate and proline enhance heavy-metal tolerance of halophilic/halotolerant soil microorganisms and their bioremediation potential for spilled-oil under multiple stresses. *Frontiers in Microbiology*, 2018, 9: 394.

[104] Anjum NA, Aref IM, Duarte AC, Pereira E, Ahmad I, Iqbal M. Glutathione and proline can coordinately make plants withstand the joint attack of metal(loid) and salinity stresses. *Frontiers in Plant Science*, 2014, 5: 662.

[105] Wu JT, Chang SC, Chen KS. Enhancement of intracellular proline level in cells of *Anacystis* nidulans (cyanobacteria) exposed to deleterious concentrations of copper1. *Journal of Phycology*, 1995, 31(3): 376–379.

[106] 王颖, 王欣卉, 徐炳政, 王月, 张桂芳, 张东杰. 金属硫蛋白体内抗氧化功能研究进展. 食品工业科技, 2016, 37(10): 377–380, 385.
Wang Y, Wang XH, Xu BZ, Wang Y, Zhang GF, Zhang DJ. Research progress of metallothionein function *in vivo* antioxidant. *Science and Technology of Food Industry*, 2016, 37(10): 377–380, 385. (in Chinese)

[107] Marteyn B, Sakr S, Farci S, Bedhomme M, Chardonnet S, Decottignies P, Lemaire SD, Cassier-Chauvat C, Chauvat F. The *Synechocystis* PCC6803 MerA-like enzyme operates in the reduction of both mercury and uranium under the control of the glutaredoxin 1 enzyme. *Journal of Bacteriology*, 2013, 195(18): 4138–4145.

[108] Singh DK, Lingaswamy B, Koduru TN, Nagu PP, Jogadhenu PSS. A putative merR family transcription factor Slr0701 regulates mercury inducible expression of MerA in the cyanobacterium *Synechocystis* sp. PCC6803. *Microbiology Open*, 2019, 8(9): e00838.

[109] Kuss J, Wasmund N, Nausch G, Labrenz M. Mercury emission by the Baltic sea: a consequence of cyanobacterial activity, photochemistry, and low-light mercury transformation. *Environmental Science & Technology*, 2015, 49(19): 11449–11457.

[110] Brunberg AK. Contribution of bacteria in the mucilage of *Microcystis* spp. (Cyanobacteria) to benthic and pelagic bacterial production in a hypereutrophic lake. *FEMS Microbiology Ecology*, 1999, 29(1): 13–22.

[111] Abdulaziz A, Sageer S, Chekidhenkuzhiyil J, Vijayan V, Pavanan P, Athiyanathil S, Nair S. Unicellular cyanobacteria *Synechocystis* accommodate heterotrophic bacteria with varied enzymatic and metal resistance properties. *Journal of Basic Microbiology*, 2016, 56(8): 845–856.

[112] 石遵计, 曹政, 胡科鑫, 彭鑫碧, 朱一帆, 谢波. 镉离子污染条件下微生物群落中细菌与藻类的相互作用. 微生物学报, 2019, 59(6): 1156–1163.
Shi ZJ, Cao Z, Hu KX, Peng XB, Zhu YF, Xie B. Interactions between bacteria and phytoplankton in microbial communities under cadmium contamination conditions. *Acta Microbiologica Sinica*, 2019, 59(6): 1156–1163. (in Chinese)

[113] Sun RG, Fan L, Yang Y. Adsorption and desorption behaviors of Hg^{2+} by *Microcystis aeruginosa*. *Polish Journal of Environmental Studies*, 2021, 30(2): 1385–1392.

[114] Mishra BB, Nanda DR. Reclamation with cyanobacteria: toxic effect of mercury contaminated waste soil on biochemical variables. *Cytobios*, 1997, 92(370/371): 203–208.

[115] Saxena PS, Kumar M. Modulatory potential of *Spirulina* fusiformis on testicular phosphatases in Swiss albino mice against mercury intoxication. *Indian Journal of Experimental Biology*, 2004, 42(10): 998–1002.

[116] Rodríguez-Sánchez R, Ortiz-Butrón R, Blas-Valdivia V, Hernández-García A, Cano-Europa E. Phycobiliproteins or C-phycocyanin of *Arthrospira* (*Spirulina*) maxima protect against $HgCl_2$-caused oxidative stress and renal damage. *Food Chemistry*, 2012, 135(4): 2359–2365.

[117] Sharma MK, Sharma A, Kumar A, Kumar M. Evaluation of protective efficacy of *Spirulina fusiformis* against mercury induced nephrotoxicity in Swiss albino mice. *Food and Chemical Toxicology*, 2007, 45(6): 879–887.

[118] El-Desoky GE, Bashandy SA, Alhazza IM, Al-Othman ZA, Aboul-Soud MAM, Yusuf K. Improvement of mercuric chloride-induced testis injuries and sperm quality deteriorations by *Spirulina platensis* in rats. *PLoS One*, 2013, 8(3): e59177.

[119] Cano-Europa E, Ortiz-Butrón R, Gallardo-Casas CA, Blas-Valdivia V, Pineda-Reynoso M, Olvera-Ramírez R, Franco-Colin M. Phycobiliproteins from *Pseudanabaena tenuis* rich in c-phycoerythrin protect against $HgCl_2$-caused oxidative stress and cellular damage in the kidney. *Journal of Applied Phycology*, 2010, 22(4): 495–501.

[120] Kumar M, Sharma MK, Kumar A. *Spirulina fusiformis*: a food supplement against mercury induced hepatic toxicity. *Journal of Health Science*, 2005, 51(4): 424–430.

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