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《环境科学》征订启事(4061) 《环境科学》征稿简则(4132) 信息(4233, 4293, 4304)

拟柱孢藻生长及碱性磷酸酶活性对不同磷浓度和磷形态响应的株系间差异

叶金梅¹, 赵莉¹, 罗旭¹, 彭亮^{1,2}, 雷腊梅^{1,2*}

(1. 暨南大学生命科学技术学院生态学系, 广州 510632; 2. 广东省水库蓝藻水华防治中心, 广州 510632)

摘要: 拟柱孢藻 (*Cylindrospermopsis raciborskii*) 是热带地区普遍存在的蓝藻种类, 近年来广泛扩张到温带地区水体, 耐受低磷环境和多生态型的存在被认为是该藻能成功入侵的重要原因. 为进一步了解不同藻株对磷波动的生理响应是否存在差异, 本研究以广东省镇海水库分离的 4 株拟柱孢藻 (N1、N8、N9 和 N10) 为材料, 观测它们的生长和碱性磷酸酶 (ALP) 活性在不同无机磷 (Pi) 浓度 (HP = 7.13 mg·L⁻¹、MP = 0.64 mg·L⁻¹、LP = 0.03 mg·L⁻¹) 和磷形态 [磷酸氢二钾 (K₂HPO₄)、焦磷酸钾 (K₄P₂O₇)、三聚磷酸钾 (K₅P₃O₁₀)、D-葡萄糖-6-磷酸 (D-G-6-P)、三磷酸腺苷 (ATP)、环磷酸腺苷 (cAMP)] 的变化. 结果表明, 4 株拟柱孢藻的生长对 Pi 浓度变化的响应基本一致, 即它们的生物量都随 Pi 浓度的升高而增加, 而 ALP 活性则反之; 无论在 LP、MP 或 HP 条件下, N8 藻株的 ALP 活性均显著低于其他 3 藻株, 表明该藻株更能适应环境中的磷波动. 在不同磷源培养下, 拟柱孢藻 N8 和 N9 在 3 种无机磷下的生物量显著高于 3 种有机磷组, 两者的比生长速率在 K₂HPO₄ 最高, 在 ATP 中最低, 这表明拟柱孢藻偏好无机磷, 但也能利用有机磷生长; 在有机磷源条件下, N8 藻株在 ATP 中的 ALP 活性显著高于其他 2 种有机磷, 而 N9 藻株的 ALP 活性在 3 种有机磷培养下无显著差异, 这表明 N8 藻株对无机磷缺乏的响应较 N9 藻株更为敏感. 本结果表明来源于同一水库的拟柱孢藻藻株间存在显著差异, 其中 N8 藻株对磷浓度变化的适应及响应能力均高于其它藻株. 株系差异性的存在有利于拟柱孢藻适应各种环境变化, 增强自身的竞争优势.

关键词: 拟柱孢藻; 株系差异; 无机磷; 有机磷; 生长; 碱性磷酸酶

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Intraspecific Variation in Growth and Alkaline Phosphatase Activity of *Cylindrospermopsis raciborskii* Strains in Response to Different Phosphorus Concentrations and Sources

YE Jin-mei¹, ZHAO Li¹, LUO Xu¹, PENG Liang^{1,2}, LEI La-mei^{1,2*}

(1. Department of Ecology, College of Life Science and Technology, Jinan University, Guangzhou 510632, China; 2. Guangdong Center for Control and Prevention of Reservoir Cyanobacterial Blooms, Guangzhou 510632, China)

Abstract: The cyanobacterial species *C. raciborskii* are ubiquitous in tropical regions, and its successful invasion into temperate zones has been partially attributed to its ability of survival in low P availability and the existence of multiple ecotypes. To explore the physiological response of different strains to phosphorus fluctuations, four strains of *C. raciborskii* isolated from the Zhenhai Reservoir were used to investigate their growth and alkaline phosphatase (ALP) activity at different inorganic phosphorus (Pi) concentrations (HP = 7.13 mg·L⁻¹, MP = 0.64 mg·L⁻¹, LP = 0.03 mg·L⁻¹) and different phosphorus forms [dipotassium hydrogen phosphate (K₂HPO₄), sodium pyrophosphate (K₄P₂O₇), sodium polyphosphate (K₅P₃O₁₀), D-glucose-6-phosphate (D-G-6-P), adenosine triphosphate (ATP), cyclic adenosine monophosphate (cAMP)]. Four *C. raciborskii* strains showed a similar growth response to phosphate changes: their biomass increased with an increase in Pi concentrations, while the ALP activity showed the opposite trend. The ALP activity of *C. raciborskii* N8 was significantly lower than that of other three strains, regardless of inorganic phosphorus concentrations, suggesting that this strain had a higher adaptability to phosphorus fluctuations. When cultured with different phosphorus forms, the biomass of *C. raciborskii* N8 and N9 in three dissolved inorganic phosphorus (DIP) compounds were significantly higher than those in three dissolved organic phosphorus (DOP) compounds, with the maximum and minimum specific growth rate in K₂HPO₄ and ATP treatments, respectively. *C. raciborskii* preferred DIP although they can also utilize DOP to sustain its growth. Under the DOP conditions, the ALP activity of *C. raciborskii* N8 in the ATP treatment was significantly higher than that in the other two organic phosphorus compounds, while we did not observe similar results in *C. raciborskii* N9, indicating that strain N8 was more sensitive to DIP deficiency. Our results showed an intraspecific variation within *C. raciborskii* strains from the same reservoir. Compared with the other strains, strain N8 represented better adaptability to phosphorus fluctuations and DIP deficiency. Variations within *C. raciborskii* strains may make this species more adaptable to environmental changes and enhance its competitive advantage.

Key words: *Cylindrospermopsis raciborskii*; intraspecific variation; inorganic phosphorus; organic phosphorus; growth; alkaline phosphatase

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作者简介: 叶金梅(1995~), 女, 硕士研究生, 主要研究方向为水域生态学, E-mail: m13414906226@163.com

* 通信作者, E-mail: tleilam@jnu.edu.cn

拟柱孢藻 (*Cylindrospermopsis raciborskii*) 属热带特征性蓝藻, 近 20 年来不断向温带地区扩张, 目前已广泛分布于世界各地的湖泊、水库和河流中^[1,2]. 该藻能产生拟柱孢藻毒素和石房蛤毒素等多种蓝藻毒素, 严重危害人类健康, 已成为一个对水环境安全极具挑战性的物种^[2,3]. 磷是所有藻类生长所必需的营养物质, 在合成核苷酸和磷脂以及通过磷酸化调控蛋白质功能中起重要作用, 是浮游植物生长的首要限制因子之一^[4~6], 也在拟柱孢藻的优势形成和地理扩张中起着决定作用^[2,3]. 有研究发现拟柱孢藻可在各种不同氮磷比的水体或实验条件下达到高生物量乃至形成水华^[7~11], 如 Chislock 等^[10] 进行的围隔实验中, 拟柱孢藻在氮磷比低至 7 或高至 122 时, 其生物量均占浮游植物总生物量的 100%. 在以色列的 Kinneret 湖和巴西的 Ingazeira 水库中, 拟柱孢藻在低氮磷 (< 6.4) 时达到较高生物量^[7,11], 但在澳大利亚的 Wivenhoe 湖, 该藻在氮磷比 22 时形成水华^[11]. 初步认为拟柱孢藻拥有快速吸收和储存无机磷的能力, 不但能在高磷环境中生长良好, 还能适应低磷环境, 从而在无机磷浓度极低的环境中占优势^[3,12,13].

在无机磷浓度较低的环境条件下, 通过碱性磷酸酶的作用有效地利用环境中的有机磷被认为是浮游植物获得竞争优势的重要原因之一^[14,15]. 目前已有少量研究对拟柱孢藻耐受低磷的机制进行了探讨, 发现该藻同样可在无机磷不足的情况下提高碱性磷酸酶活性, 特异性水解水体中的磷酸单酯, 释放无机磷供藻细胞生长^[13,16~18]. Wu 等^[16] 的研究发现在磷浓度低于 $0.05 \text{ mg} \cdot \text{L}^{-1}$ 的限制条件下, 拟柱孢藻藻株 CHAB155 能产生大量的碱性磷酸酶; 在仅有有机磷的条件下, 拟柱孢藻能利用不同的有机磷源进行生长, 且实验中有有机磷组的碱性磷酸酶活性均显著高于无机磷培养组^[13]. Prentice 等^[17] 的研究发现在无机磷不足的情况下, 碱性磷酸酶对有机磷的矿化对浮游植物 (拟柱孢藻占优势) 生长所需磷源的贡献可达到 89%, 因此能否产生碱性磷酸酶在一定程度上决定水华蓝藻的发生和分布.

目前人们在拟柱孢藻对低磷的响应策略上已积累了一定的认识, 但这些研究基本采用单藻株或模式株开展工作^[13,16]. 对不同拟柱孢藻藻株的比较基因组分析表明, 这些藻株都拥有完整的磷代谢相关基因^[19,20], 但基因的拷贝数大多不同, 这可能使得不同藻株对磷限制的响应存在差异^[18]. 其它研究也发现拟柱孢藻在资源利用特性上具有高度的可塑性和株系多样性. Piccini 等^[21] 对比分析了来自乌拉圭不同水体中的两株拟柱孢藻生理生化特征, 发现两藻株

的形态以及对光照和磷供应的生长响应差异显著, 因此作者认为拟柱孢藻存在不同的生态型. 近年来, 越来越多的研究表明同一区域甚至同一水体来源的拟柱孢藻藻株间存在高的性状差异, 不同藻株对温度、光强和营养等环境因子的喜好差异明显, 从而在生长速率、毒素含量和形态上表现出不同^[22~26]. 这种株系多样性被认为有利于拟柱孢藻适应多变的环境, 并成功入侵到新的群落和生境^[3]. 由于拟柱孢藻生态型和株系差异的广泛存在, 越来越多的研究者认为在室内实验中需采用多藻株^[18,24].

拟柱孢藻在广东省水库分布广泛^[27], 甚至已成为该省多座水库的优势种类^[28], 开平镇海水库中的浮游植物群落更是常年以拟柱孢藻为主, 总磷在其绝对优势形成中起决定作用^[29]. 笔者发现从镇海水库分离到的拟柱孢藻也具株系多样性^[30], 本研究继续以该水库分离的拟柱孢藻藻株为材料, 观测它们在不同磷浓度和磷形态下的生长和碱性磷酸酶活性, 了解 4 株拟柱孢藻在磷需求上是否存在差异, 探讨碱性磷酸酶在广东省拟柱孢藻适应低磷中的作用.

1 材料与方法

1.1 藻种的来源与培养

本实验所用藻种拟柱孢藻 N1、N8、N9 和 N10 分离自广东省江门市镇海水库 (库中 $22^{\circ}34'N$, $112^{\circ}33'E$; 取水口 $22^{\circ}55'N$, $112^{\circ}57'E$), 藻株均在 $(25.5 \pm 1)^{\circ}C$ 、光照强度为 $35 \mu\text{mol} \cdot (\text{m}^2 \cdot \text{s})^{-1}$ 、光暗周期比为 12 h: 12 h 的培养箱中进行保存培养, 培养基为 BG11.

1.2 不同磷浓度下的培养实验

本研究以 BG11 培养拟柱孢藻, BG11 中磷浓度为 $7.13 \text{ mg} \cdot \text{L}^{-1}$, 为磷丰富培养基, 因此直接将其设为高磷 (HP) 浓度组, 同时调整 K_2HPO_4 的浓度, 配置中磷 (MP) 和低磷 (LP) 浓度培养基, 其中的磷浓度分别为 $0.64 \text{ mg} \cdot \text{L}^{-1}$ 和 $0.03 \text{ mg} \cdot \text{L}^{-1}$, 每个处理组设置 3 个平行. 取一定体积生长良好的 4 株拟柱孢藻 $7000 \text{ r} \cdot \text{min}^{-1}$ 离心 15 min, 弃去上清液, 用无菌水清洗 3 次, 随后置于无磷的 BG11 培养基中饥饿培养 3 d. 将饥饿培养后的藻细胞分别转移到装有 400 mL 不同磷浓度的锥形瓶中, 置于恒温光照培养箱中培养, 培养条件同 1.1 节. 生长测定参考文献^[31], 即每隔 2~3 d 取样测定 $D_{680 \text{ nm}}$, 同时取 1 mL 藻细胞用于碱性磷酸酶活性的测定.

1.3 不同磷形态下的培养实验

以 BG11 培养基为基础, 维持培养基中磷浓度为 $7.13 \text{ mg} \cdot \text{L}^{-1}$, 分别以 3 种无机磷 [磷酸氢二钾

(K_2HPO_4)、焦磷酸钾($K_4P_2O_7$)、三聚磷酸钾($K_3P_3O_{10}$)和3种有机磷[D-葡萄糖-6-磷酸(D-G-6-P)、三磷酸腺苷(ATP)、环磷酸腺苷(cAMP)]为磷源配置培养基.这6种磷源常见易获得,是观测不同浮游植物磷利用策略的常用磷形态^[13,32,33].本实验藻株为拟柱孢藻 N8 和 N9,接种方法、培养条件和取样方式均同 1.2 节.

1.4 碱性磷酸酶活性的测定

碱性磷酸酶(ALP)活性测定方法为分光光度比色法^[34],本研究采用试剂盒(上海翊圣生物科技有限公司)对拟柱孢藻的碱性磷酸酶活性进行测定.测试时,在酶标板孔中依次加入显色底物和样品各 50 μ L,混匀后 37 $^{\circ}$ C 孵育 10 min,终止反应后用酶标仪在 405 nm 处测定对硝基苯酚的吸光值,根据试剂盒的说明制作标准曲线,计算单位时间内单位生物量产生的对硝基苯酚浓度,以此表示细胞碱性磷酸酶活性(μ mol \cdot min⁻¹,以 $D_{680\text{ nm}}$ 计).

1.5 比生长速率计算

比生长速率(μ)指在某一时间段内藻类生长的速率,计算方法为:

$$\mu = (\ln X_2 - \ln X_1) / (T_2 - T_1)$$

式中, T_1 和 T_2 为培养时间, X_1 和 X_2 分别为培养 T_1

和 T_2 时的 $D_{680\text{ nm}}$ 的值.

1.6 数据分析

显著性分析采用单因素方差分析(one-way analysis of variance, ANOVA)和多重比较分析(least-significant difference, LSD),显著水平为 $P < 0.05$.数据处理和图形绘制在 SPSS Statistics 16.0、Microsoft Excel 2013 和 Origin 8.0 中进行.

2 结果与分析

2.1 3种无机磷浓度对拟柱孢藻生长及碱性磷酸酶活性的影响

由图 1 可知,不同无机磷浓度下 4 株拟柱孢藻的生长趋势基本一致,它们的生物量随磷浓度的增加而增加.不同磷浓度下 4 藻株的生长在前 8 d 没有显著差异;在 HP 浓度组中,4 藻株直到实验结束时仍处于对数生长期,4 藻株在 MP 浓度组中的生长表现出株系差异,除 N8 藻株一直良好生长外,其他 3 藻株在实验末期进入稳定期,LP 浓度则显著限制拟柱孢藻的生长,4 藻株均没有明显的指数生长期.

由图 2 可知,4 株拟柱孢藻在 HP 和 MP 浓度组中的比生长速率显著高于 LP 浓度组中同藻株的比

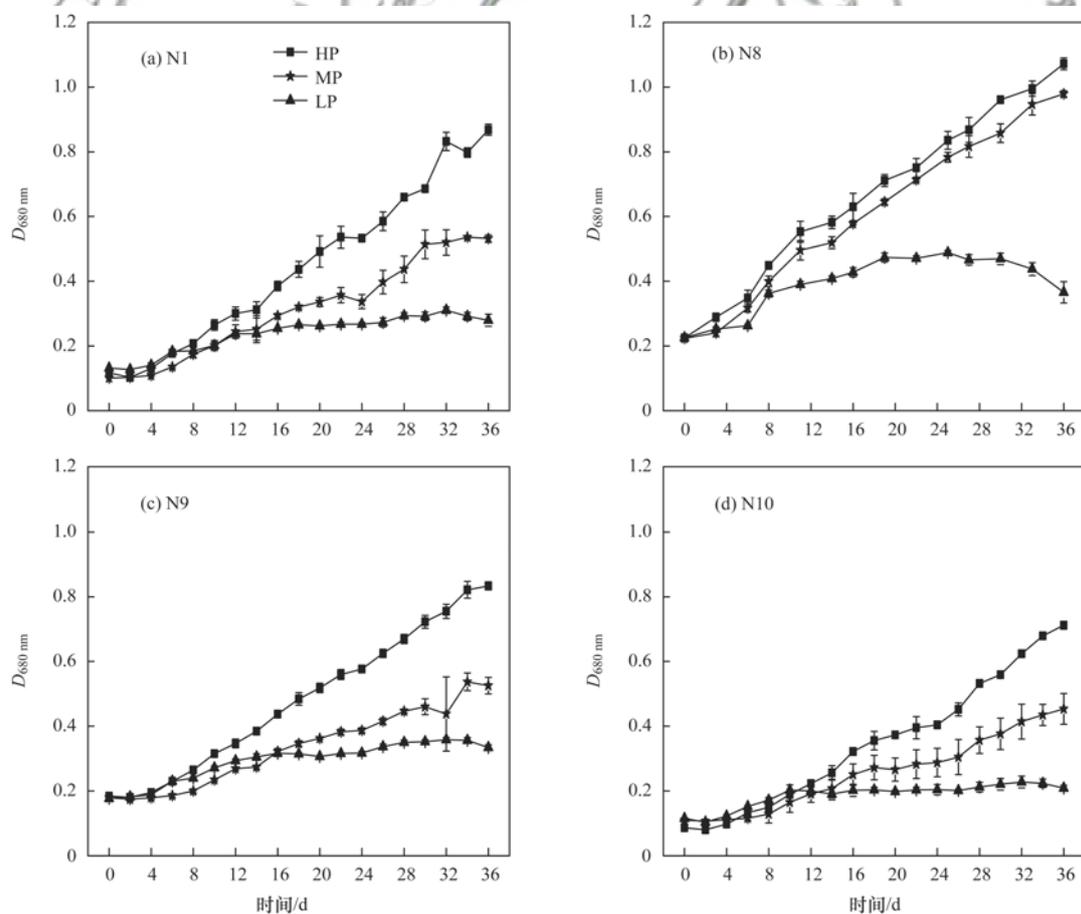
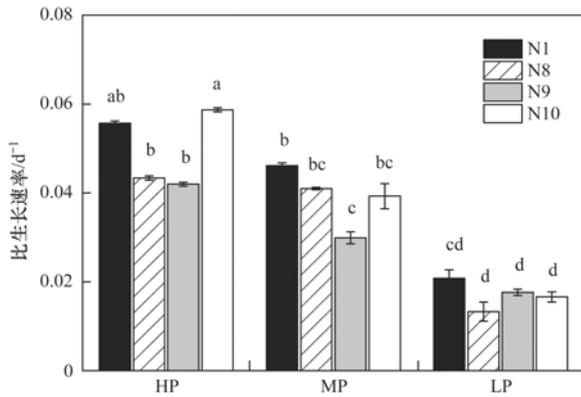


图 1 不同无机磷浓度下 4 株拟柱孢藻(N1、N8、N9 和 N10) 的生长曲线

生长速率 ($P < 0.05$). 其中 N10 藻株的 HP 浓度组比生长速率最高, 为 0.05871 d^{-1} , N8 藻株的 LP 浓度组比生长速率最低, 为 0.01329 d^{-1} . 在相同磷浓度处理下, 4 藻株在 HP 和 MP 浓度组中的比生长速率具有株系差异, 其中 N8、N9 藻株在 HP 浓度组的比生长速率显著低于 N10 藻株 ($P < 0.05$), N9 藻株在 MP 浓度组的比生长速率显著低于 N1 藻株的比生长速率 ($P < 0.05$).



不同字母表示具有显著性差异 ($P < 0.05$), 下同
图 2 不同无机磷浓度下 4 株拟柱孢藻 (N1、N8、N9 和 N10) 的比生长速率

Fig. 2 Specific growth rates of four strains of *Cylindrospermopsis raciborskii* (N1, N8, N9, and N10) under different inorganic phosphorus concentrations

不同无机磷浓度下 4 株拟柱孢藻的碱性磷酸酶活性见图 3. 4 藻株的响应趋势基本相同, 即碱性磷酸酶活性随着磷浓度的降低而升高, LP 浓度组下的碱性磷酸酶活性显著高于 MP 和 HP 浓度组 ($P < 0.05$), 而 4 藻株的碱性磷酸酶活性在 HP 和 MP 浓度组中无显著差异 ($P > 0.05$).

LSD 分析表明, N1 藻株的 LP 浓度组碱性磷酸酶活性最高, 除与 N10 藻株的 LP 浓度组无差异外, 与其他藻株不同浓度组碱性磷酸酶活性均有显著性差异 ($P < 0.05$). 在相同磷浓度处理下, 4 藻株的碱性磷酸酶活性具有株系差异, 其中 N8 藻株的碱性磷酸酶活性均显著低于其他 3 藻株 ($P < 0.05$), 这表明 N8 藻株更适应环境中磷浓度的波动.

2.2 不同形态的磷源对拟柱孢藻生长及碱性磷酸酶活性的影响

由图 4 可知, 在 3 种无机磷条件下, 拟柱孢藻 N8 和 N9 均能良好生长, 其中在以磷酸氢二钾为磷源的条件表现出最佳生长, 最大生物量 (以 $D_{680 \text{ nm}}$ 计) 分别为 1.15 ± 0.029 和 1.08 ± 0.019 , 比生长速率分别为 $(0.044 \pm 0.0008) \text{ d}^{-1}$ 和 $(0.041 \pm 0.0000) \text{ d}^{-1}$ (图 5). 拟柱孢藻 N8 和 N9 在 3 种有机磷中的生长显著低于无机磷, 在 D-葡萄糖-6-磷酸和

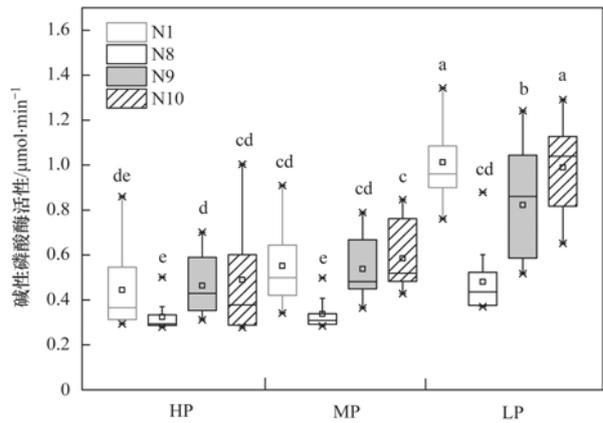


图 3 不同无机磷浓度下 4 株拟柱孢藻 (N1、N8、N9 和 N10) 的碱性磷酸酶活性

Fig. 3 Alkaline phosphatase activity of four strains of *Cylindrospermopsis raciborskii* (N1, N8, N9, and N10) under different inorganic phosphorus concentrations

环磷酸腺苷条件下, 2 藻株在实验开始前 6 d 可缓慢生长, 随后它们的生物量基本稳定直至实验结束, 而拟柱孢藻 N8 和 N9 在三磷酸腺苷下的生长基本停滞.

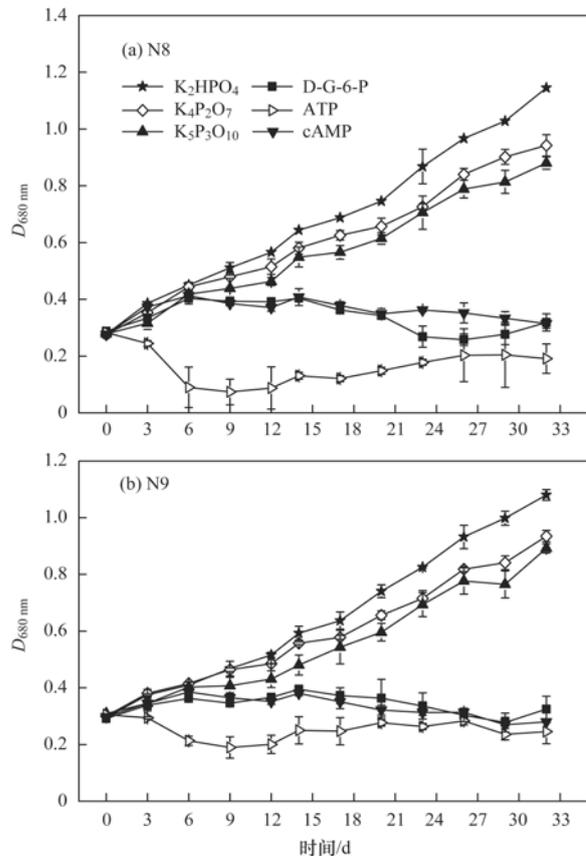


图 4 不同磷源下拟柱孢藻 (N8 和 N9) 的生长曲线
Fig. 4 Growth curves of *Cylindrospermopsis raciborskii* (N8 and N9) under different phosphorus sources

由图 5 可知, 在同种磷源条件下, N8 和 N9 藻株的比生长速率没有显著差异, 但 2 藻株在无机磷组的比生长速率均显著高于有机磷组 ($P < 0.05$). N8

藻株在三磷酸腺苷的比生长速率显著低于该藻株在 D-葡萄糖-6-磷酸以及环磷酸腺苷的比生长速率 ($P < 0.05$); N9 藻株在有机磷源的比生长速率则没有显著差异 ($P > 0.05$).

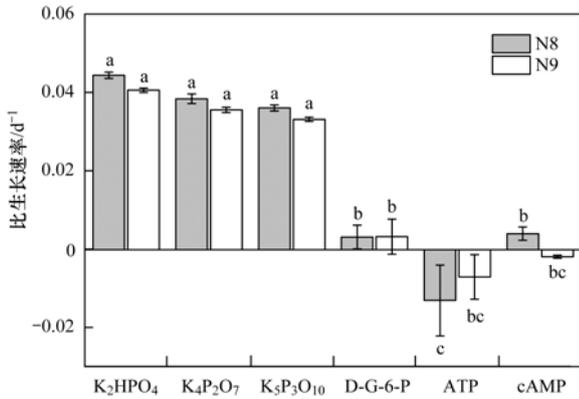


图5 不同磷源下拟柱孢藻(N8和N9)的比生长速率

Fig. 5 Specific growth rates of *Cylindrospermopsis raciborskii* (N8 and N9) under different phosphorus sources

由图6可知,3种有机磷培养下拟柱孢藻N8和N9的碱性磷酸酶活性高于3种无机磷实验组,但仅N8藻株的碱性磷酸酶活性在2类磷源下存在显著差异($P < 0.05$).在无机磷充足的培养下,拟柱孢藻N8和N9藻株的碱性磷酸酶活性一直维持在较低水平,2藻株的碱性磷酸酶活性均在磷酸氢二钾培养下最低,在三聚磷酸钾下最高,但两者差异不显著($P > 0.05$).在仅有有机磷源培养下,N8藻株在三磷酸腺苷中的碱性磷酸酶活性显著高于D-葡萄糖-6-磷酸和环磷酸腺苷中的碱性磷酸酶活性($P < 0.05$),而N9藻株的碱性磷酸酶活性在3种有机磷培养下无显著差异($P > 0.05$),这表明N8藻株对无机磷缺乏的响应较N9藻株更为敏感.

LSD分析表明,N8藻株在三磷酸腺苷中的碱性磷酸酶活性最高,显著高于其它5种磷源,以及N9藻株在所有6种磷源的碱性磷酸酶活性($P < 0.05$).

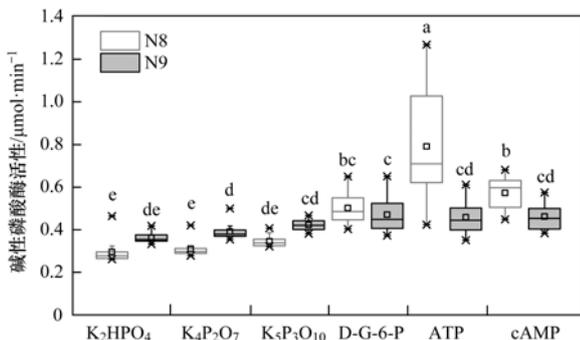


图6 不同磷源下拟柱孢藻(N8和N9)的碱性磷酸酶活性

Fig. 6 Alkaline phosphatase activity of *Cylindrospermopsis raciborskii* (N8 and N9) under different phosphorus sources

3 讨论

营养盐对浮游植物的生长至关重要,环境中的磷含量影响着浮游植物的生物量及其群落结构^[35].本研究发现,在MP和HP浓度下,4株拟柱孢藻的生物量和比生长速率显著高于LP浓度组,即高浓度的无机磷更适合拟柱孢藻的生长.这与前人的研究结果一致^[8,16,36],即低浓度无机磷显著地限制浮游植物的生长.

本实验所用的4株拟柱孢藻均来自于镇海水库,其中藻株N1、N9和N10的比生长速率在3种无机磷浓度中差异显著,藻株N8的生长也随磷浓度的降低而降低,但其比生长速率在MP和HP浓度下无显著差异,这表明4藻株对磷浓度的响应存在株系差异.有研究表明,拟柱孢藻具有较高的株系多样性^[21,22,37],笔者之前的研究已发现N8藻株对低温的适应能力要高于N1藻株^[30],本研究显示N8藻株在实验设置的MP浓度下的生长与HP无显著差异,表明该藻株对磷浓度波动的适应要高于其他3藻株,另外N8藻株碱性磷酸酶活性对无机磷缺乏的响应也高于N9藻株.前人的研究也观察到不同藻株对磷浓度变化的响应差异,如乌拉圭藻株MVCC19对低磷的适应性要高于另一藻株MVCC14^[21],澳洲藻株CS-505的碱性磷酸酶活性在磷充足和缺乏条件下均高于藻株CS-506^[18].同一水体株系多样性的存在可能是拟柱孢藻在镇海水库长期占据绝对优势的重要因素之一.

在无机磷不足的水体中,溶解性有机磷(DOP)被认为是蓝藻磷营养的重要来源^[14,38].已有研究表明拟柱孢藻能利用溶解性有机磷作为唯一磷源进行生长^[13,38].本研究也发现在仅有D-葡萄糖-6-磷酸和环磷酸腺苷的培养条件下,拟柱孢藻N8和N9在早期都能缓慢地生长,但它们的生物量显著低于3种无机磷培养下的生物量.这与Bai等^[13]的结果相反,他们发现拟柱孢藻FACHB 1096在D-葡萄糖-6-磷酸等有机磷培养下的生物量比磷酸氢二钾中高.这可能是拟柱孢藻的株系差异性所致,而本研究的结果更倾向于与Ren等^[39]和Vrba等^[40]的发现一致,即在同样的磷浓度下,无机磷比有机磷能更好地满足藻类的生长,这可能是因为合成水解有机磷的生化酶是一个高度耗能的过程^[41],碱性磷酸酶裂解有机磷所释放的无机磷难以满足藻类较快生长^[39,40,42,43].一般认为藻类普遍能以三磷酸腺苷作为生长所需的唯一磷源^[44],但本研究发现拟柱孢藻N8和N9在仅有三磷酸腺苷为磷源下几乎不能生长,这表明拟柱孢藻对培养基中三磷酸腺苷的利用

能力极低,目前认为浮游植物对水环境中三磷酸腺苷的利用需要 5-核苷酸酶^[6],对本实验室 N8 藻株全基因组数据(未发表的数据)分析表明 5-核苷酸酶以单拷贝基因存在,因此该酶在拟柱孢藻中的活性表达条件还有待阐明。

作为一种诱导酶,碱性磷酸酶的上调表达被认为可指示水体环境处于磷限制状态,浮游植物可通过碱性磷酸酶活性水解含磷酸单酯键的有机磷分子,从而获得生长所需无机磷^[18,42,45]。本研究发现 4 株拟柱孢藻的碱性磷酸酶活性和无机磷浓度呈显著的负相关,生长最差的 LP 浓度组中碱性磷酸酶活性最高,这种磷限制下碱性磷酸酶活性升高的现象不仅发现在拟柱孢藻中^[8,13,31],也已在其它很多藻类中观察到^[46~48]。在用 3 种无机磷作为磷源培养下,拟柱孢藻的生长和碱性磷酸酶活性不存在显著差异,这与钱善勤等^[32]的结果不一致,他们发现微囊藻更偏好磷酸氢二钾,在 2 种磷酸盐聚合体下的生长受到一定的限制,这意味着拟柱孢藻比微囊藻能更好地利用各种无机磷源。不同磷源培养实验中,N8 藻株的碱性磷酸酶活性在三磷酸腺苷实验组中最高,但拟柱孢藻在该种条件下生长最差,因此高的碱性磷酸酶表达只是指示了环境中磷不足,并不代表着对有机磷的高效利用^[49]。这意味着在磷限制水体中碱性磷酸酶的大量表达并不能赋予拟柱孢藻以竞争优势。因此,广东省拟柱孢藻在低无机磷水体形成优势的策略还需进一步研究。

4 结论

(1) 拟柱孢藻 N1、N8、N9 和 N10 均能适应较宽范围的无机磷浓度波动,可以较好地磷酸盐多聚体用于生长,但它们在有机磷下生长极差。

(2) 来源于同一水体的拟柱孢藻对磷浓度波动的适应和响应存在显著的株系差异,这有利于该藻在多变的环境条件下形成优势。

参考文献:

- [1] Sinha R, Pearson L A, Davis T W, et al. Increased incidence of *Cylindrospermopsis raciborskii* in temperate zones-Is climate change responsible? [J]. Water Research, 2012, **46**(5): 1408-1419.
- [2] Antunes J T, Leão P N, Vasconcelos V M. *Cylindrospermopsis raciborskii*: review of the distribution, phylogeography, and ecophysiology of a global invasive species [J]. Frontiers in Microbiology, 2015, **6**: 473.
- [3] Burford M A, Beardall J, Willis A, et al. Understanding the winning strategies used by the bloom-forming cyanobacterium *Cylindrospermopsis raciborskii* [J]. Harmful Algae, 2016, **54**: 44-53.
- [4] Su Z C, Olman V, Xu Y. Computational prediction of Pho regulons in cyanobacteria [J]. BMC Genomics, 2007, **8**(1): 156.
- [5] Merchant S S, Helmann J D. Elemental economy: microbial strategies for optimizing growth in the face of nutrient limitation [J]. Advances in Microbial Physiology, 2012, **60**: 91-210.
- [6] Dyhrman S T. Nutrients and their acquisition: phosphorus physiology in microalgae [A]. In: Borowitzka M, Beardall J, Raven J, (Eds.). The Physiology of Microalgae [M]. Cham: Springer, 2016. 155-183.
- [7] Bouvy M, Molica R, De Oliveira S, et al. Dynamics of a toxic cyanobacterial bloom (*Cylindrospermopsis raciborskii*) in a shallow reservoir in the semi-arid region of northeast Brazil [J]. Aquatic Microbial Ecology, 1999, **20**(3): 285-297.
- [8] Posselt A J, Burford M A, Shaw G. Pulses of phosphate promote dominance of the toxic cyanophyte *Cylindrospermopsis raciborskii* in a subtropical water reservoir [J]. Journal of Phycology, 2009, **45**(3): 540-546.
- [9] Dolman A M, Rucker J, Pick F R, et al. Cyanobacteria and cyanotoxins: the influence of nitrogen versus phosphorus [J]. PLoS One, 2012, **7**(6): e38757.
- [10] Chislock M F, Sharp K L, Wilson A E. *Cylindrospermopsis raciborskii* dominates under very low and high nitrogen-to-phosphorus ratios [J]. Water Research, 2014, **49**: 207-214.
- [11] Recknagel F, Zohary T, Rucker J, et al. Causal relationships of *Raphidiopsis* (formerly *Cylindrospermopsis*) dynamics with water temperature and N:P-ratios: a meta-analysis across lakes with different climates based on inferential modelling [J]. Harmful Algae, 2019, **84**: 222-232.
- [12] Isvánovics V, Shafik H M, Présing M, et al. Growth and phosphate uptake kinetics of the cyanobacterium, *Cylindrospermopsis raciborskii* (Cyanophyceae) in throughflow cultures [J]. Freshwater Biology, 2000, **43**(2): 257-275.
- [13] Bai F, Liu R, Yang Y J, et al. Dissolved organic phosphorus use by the invasive freshwater diazotroph cyanobacterium, *Cylindrospermopsis raciborskii* [J]. Harmful Algae, 2014, **39**: 112-120.
- [14] Moore L R, Ostrowski M, Scanlan D J, et al. Ecotypic variation in phosphorus-acquisition mechanisms within marine picocyanobacteria [J]. Aquatic Microbial Ecology, 2005, **39**(3): 257-269.
- [15] Dyhrman S T, Chappell P D, Haley S T, et al. Phosphonate utilization by the globally important marine diazotroph *Trichodesmium* [J]. Nature, 2006, **439**(7072): 68-71.
- [16] Wu Z X, Zeng B, Li R H, et al. Physiological regulation of *Cylindrospermopsis raciborskii* (Nostocales, Cyanobacteria) in response to inorganic phosphorus limitation [J]. Harmful Algae, 2012, **15**: 53-58.
- [17] Prentice M J, Hamilton D P, Willis A, et al. Quantifying the role of organic phosphorus mineralisation on phytoplankton communities in a warm-monocytic lake [J]. Inland Waters, 2019, **9**(1): 10-24.
- [18] Willis A, Chuang A W, Dyhrman S, et al. Differential expression of phosphorus acquisition genes in response to phosphorus stress in two *Raphidiopsis raciborskii* strains [J]. Harmful Algae, 2019, **82**: 19-25.
- [19] Sinha R, Pearson L A, Davis T W, et al. Comparative genomics of *Cylindrospermopsis raciborskii* strains with differential toxicities [J]. BMC Genomics, 2014, **15**(1): 83.
- [20] Willis A, Woodhouse J N, Ongley S E, et al. Genome variation in nine co-occurring toxic *Cylindrospermopsis raciborskii* strains [J]. Harmful Algae, 2018, **73**: 157-166.
- [21] Piccini C, Aubriot L, Fabre A, et al. Genetic and ecophysiological differences of South American *Cylindrospermopsis raciborskii* isolates support the hypothesis of multiple ecotypes [J]. Harmful Algae, 2011, **10**(6): 644-653.

- [22] Willis A, Chuang A W, Woodhouse J N, *et al.* Intraspecific variation in growth, morphology and toxin quotas for the cyanobacterium, *Cylindrospermopsis raciborskii* [J]. *Toxicon*, 2016, **119**: 307-310.
- [23] Yamamoto Y, Shiah F K. Growth, trichome size and akinete production of *Cylindrospermopsis raciborskii* (cyanobacteria) under different temperatures: Comparison of two strains isolated from the same pond[J]. *Phycological Research*, 2014, **62**(2): 147-152.
- [24] Bolius S, Wiedner C, Weithoff G. High local trait variability in a globally invasive cyanobacterium[J]. *Freshwater Biology*, 2017, **62**(11): 1879-1890.
- [25] Xiao M, Adams M P, Willis A, *et al.* Variation within and between cyanobacterial species and strains affects competition: Implications for phytoplankton modelling [J]. *Harmful Algae*, 2017, **69**: 38-47.
- [26] 路琰, 雷敏婷, 叶金梅, 等. 广东省千灯湖拟柱孢藻 (*Cylindrospermopsis raciborskii*) 的形态和产毒能力的株间差异及系统进化[J]. *湖泊科学*, 2020, **32**(1): 144-153.
- Lu Y, Lei M T, Ye J M, *et al.* Intraspecific variation of morphological traits and toxin-producing capacity and phylogenetic analysis for *Cylindrospermopsis raciborskii* from Qiandenghu Lake, Guangdong Province [J]. *Journal of Lake Sciences*, 2020, **32**(1): 144-153.
- [27] 雷敏婷, 彭亮, 韩博平, 等. 广东省水库拟柱孢藻 (*Cylindrospermopsis raciborskii*) 的分布特征及影响因子分析 [J]. *环境科学*, 2018, **39**(12): 5523-5531.
- Lei M T, Peng L, Han B P, *et al.* Distribution and factors affecting *Cylindrospermopsis raciborskii* in Guangdong reservoirs [J]. *Environmental Science*, 2018, **39**(12): 5523-5531.
- [28] Lei L M, Peng L, Huang X H, *et al.* Occurrence and dominance of *Cylindrospermopsis raciborskii* and dissolved cylindrospermopsin in urban reservoirs used for drinking water supply, South China [J]. *Environmental Monitoring and Assessment*, 2014, **186**(5): 3079-3090.
- [29] 赵莉, 雷腊梅, 彭亮, 等. 广东省镇海水库拟柱孢藻 (*Cylindrospermopsis raciborskii*) 的季节动态及驱动因子分析 [J]. *湖泊科学*, 2017, **29**(1): 193-199.
- Zhao L, Lei L M, Peng L, *et al.* Seasonal dynamic and driving factors of *Cylindrospermopsis raciborskii* in Zhenhai Reservoir, Guangdong Province [J]. *Journal of Lake Sciences*, 2017, **29**(1): 193-199.
- [30] 阮紫曦, 于婷, 雷腊梅, 等. 光照-温度交互作用及不同氮源对拟柱孢藻生长的影响 [J]. *热带亚热带植物学报*, 2018, **26**(2): 133-140.
- Ruan Z X, Yu T, Lei L M, *et al.* Effects of temperature-irradiance interactions and three nitrogen sources on growth of *Cylindrospermopsis raciborskii* [J]. *Journal of Tropical and Subtropical Botany*, 2018, **26**(2): 133-140.
- [31] Wu Z X, Shi J Q, Li R H. Comparative studies on photosynthesis and phosphate metabolism of *Cylindrospermopsis raciborskii* with *Microcystis aeruginosa* and *Aphanizomenon flos-aquae* [J]. *Harmful Algae*, 2009, **8**(6): 910-915.
- [32] 钱善勤, 孔繁翔, 史小丽, 等. 不同形态磷酸盐对铜绿微囊藻和蛋白核小球藻生长的影响 [J]. *湖泊科学*, 2008, **20**(6): 796-801.
- Qian S Q, Kong F X, Shi X L, *et al.* Effects of three types of phosphate on the growth of *Microcystis aeruginosa* and *Chlorella pyrenoidosa* [J]. *Journal of Lake Sciences*, 2008, **20**(6): 796-801.
- [33] 钱善勤, 孔繁翔, 张民, 等. 铜绿微囊藻和蛋白核小球藻对不同形态有机磷的利用及其生长 [J]. *湖泊科学*, 2010, **22**(3): 411-415.
- Qian S Q, Kong F X, Zhang M, *et al.* Utilization of dissolved organic phosphorus and the growth of *Microcystis aeruginosa* and *Chlorella pyrenoidosa* [J]. *Journal of Lake Sciences*, 2010, **22**(3): 411-415.
- [34] Berman T. Alkaline phosphatases and phosphorus availability in Lake Kinneret [J]. *Limnology and Oceanography*, 1970, **15**(5): 663-674.
- [35] Dyhrman S T, Ammerman J W, Van Mooy B A S. Microbes and the marine phosphorus cycle [J]. *Oceanography*, 2007, **20**(2): 110-116.
- [36] Nor N H M, Te S H, Mowe M A D, *et al.* Environmental factors influence cylindrospermopsin production of *Cylindrospermopsis raciborskii* (CR12) [J]. *Journal of Plankton Research*, 2019, **41**(2): 114-126.
- [37] Xiao M, Willis A, Burford M A. Differences in cyanobacterial strain responses to light and temperature reflect species plasticity [J]. *Harmful Algae*, 2017, **62**: 84-93.
- [38] Posselt A J. Are nutrients the key driver in prompting dominance of toxic cyanobacterial blooms in a sub-tropical reservoir? [D]. Queensland, Australia: Griffith University, 2010.
- [39] Ren L X, Wang P F, Wang C, *et al.* Algal growth and utilization of phosphorus studied by combined mono-culture and co-culture experiments [J]. *Environmental Pollution*, 2017, **220**: 274-285.
- [40] Vrba J, Macholdová M, Nedbalová L, *et al.* An experimental insight into extracellular phosphatases-differential induction of cell-specific activity in green algae cultured under various phosphorus conditions [J]. *Frontiers in Microbiology*, 2018, **9**: 271.
- [41] Bar-Yosef Y, Sukenik A, Hadas O, *et al.* Enslavement in the water body by toxic *Aphanizomenon ovalisporum*, inducing alkaline phosphatase in phytoplanktons [J]. *Current Biology*, 2010, **20**(17): 1557-1561.
- [42] Vahtera E, Laamanen M, Rintala J M. Use of different phosphorus sources by the bloom-forming cyanobacteria *Aphanizomenon flos-aquae* and *Nodularia spumigena* [J]. *Aquatic Microbial Ecology*, 2007, **46**(3): 225-237.
- [43] Ghyoot C, Gypens N, Flynn K J, *et al.* Modelling alkaline phosphatase activity in microalgae under orthophosphate limitation: the case of *Phaeocystis globosa* [J]. *Journal of Plankton Research*, 2015, **37**(5): 869-885.
- [44] Krumhardt K M, Callnan K, Roache-Johnson K, *et al.* Effects of phosphorus starvation versus limitation on the marine cyanobacterium *Prochlorococcus* MED4 I: uptake physiology [J]. *Environmental Microbiology*, 2013, **15**(7): 2114-2128.
- [45] Liu Z Y, Wu C D. Response of alkaline phosphatases in the cyanobacterium *Anabaena* sp. FACHB 709 to inorganic phosphate starvation [J]. *Current Microbiology*, 2012, **64**(6): 524-529.
- [46] Adams M M, Gómez-García M R, Grossman A R, *et al.* Phosphorus deprivation responses and phosphonate utilization in a thermophilic *Synechococcus* sp. from microbial mats [J]. *Journal of Bacteriology*, 2008, **190**(24): 8171-8184.
- [47] Orchard E D, Webb E A, Dyhrman S T. Molecular analysis of the phosphorus starvation response in *Trichodesmium* spp. [J]. *Environmental Microbiology*, 2009, **11**(9): 2400-2411.
- [48] Kelly L T, Ryan K G, Wood S A. Differential strain response in alkaline phosphatase activity to available phosphorus in *Microcoleus autumnalis* [J]. *Harmful Algae*, 2019, **89**: 101664.
- [49] Ma J J, Wang P F, Ren L X, *et al.* Using alkaline phosphatase activity as a supplemental index to optimize predicting algal blooms in phosphorus-deficient lakes: A case study of Lake Taihu, China [J]. *Ecological Indicators*, 2019, **103**: 698-712.

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