

TABLE 1. Strains, plasmids, and primers used in this study

Strain, plasmid, or primer	Relevant genotype, description, or sequence	Source or reference
<i>E. coli</i> strains		
KC8	Km ^r RecA ⁺ <i>lac</i> Δ	Clontech
XL-1 Blue	Tc ^r nalidixic acid resistant	Agilent Technologies
<i>Cyanobacteria</i> sp. strains		
ATCC 51142	Isolated from intertidal area near Port Aransas, TX	Laboratory collection
PCC 7424	Isolated from rice field soil, Senegal, 1972	Laboratory collection
PCC 7425	Isolated from rice field soil, Senegal, 1972	Laboratory collection
PCC 7822	Isolated from rice field soil at Central Rice Research Institute, Cuttack, Orissa, India	Laboratory collection
PCC 8801	Isolated from rice field soil (during spring), Ping-Tong District, southern Taiwan, as <i>Synechococcus</i> sp. strain RF-1	Laboratory collection
PCC 8802	Isolated from rice field soil (during spring), Ping-Tong District, southern Taiwan, as <i>Synechococcus</i> sp. strain RF-2	Laboratory collection
Plasmids		
pUC19	Cloning vector	Laboratory collection
pRL1383a	RSF1010-derived broad-host-range vector, Sp ^r and Sm ^r , accession no. AF403426	10
pAM1037	Transposon Tn5 derivative (Km ^r)	19
pRL448	Plasmid carrying Km ^r cassette	8
pRL453	Plasmid carrying Sp/Sm Ω cassette	8
pHM54	NifK knockout construct for PCC 7822 with Sp ^r cassette going against <i>nifK</i>	This study
pHM55	NifK knockout construct for PCC 7822 with Sp ^r cassette going with <i>nifK</i>	This study
Primers		
7822 NifK1	GCTATGACCATGATTACGCCAAGACCACGTTGAATTATTCC	This study
7822 NifK2	GTTGTAAAACGACGGCCAGTGTACGATCGATATCTTCAAACAGAG	This study
7822 NifK3	CGGCTGTCTTACCATGTAACCAAGC	This study
Sp/Up	CCAAGGATCGGGCCTTGATG	This study
Sp/11Up	CGTAACGCGCTTGCTGCTTG	This study

likely contained a recombination system that could insert such a cassette randomly throughout the genome.

Cyanobacteria sp. strains PCC 7424, PCC 7425, PCC 7822, PCC 8801, and PCC 8802 were successfully transformed by electroporation with a Tn5 derivative (pAM1037) and pRL448 to kanamycin resistance and by pRL1383a and pRL453 to Sp^r. All of the strains, except PCC 7822, yielded many Sp^r colonies by nonhomologous recombination (Table 2). Since *Cyanobacteria* sp. strain PCC 7822 had the best ratio of legitimate transformation versus nonhomologous illegitimate recombination, it was chosen for mutagenesis by insertional inactivation.

PCR-amplified *nifK* was cloned into pUC19, and *Cyanobacteria* sp. strain PCC 7822 was transformed by electroporation using ssDNA made from pHM54 and pHM55 (Table 1 and Fig. 1). Twenty Sp^r colonies were picked from each group for segregation by stepwise transfer onto fresh Sp plates three times,

and 3 out of 20 colonies in each group demonstrated the mutant phenotype; i.e., they could not grow in the absence of combined nitrogen. We focused on three mutants from the pHM54 group. Colony PCR confirmed that two out of these three colonies had the Sp^r cassette inserted in *nifK* as shown in Fig. 1. DNA sequencing was performed on the PCR product from one colony, and the results (Fig. 2) indicated that the Sp^r cassette was inserted into the EcoRI site of *nifK* as designed and sketched in Fig. 1. Colony PCR on the $\Delta nifK$ mutant after 1 month of continuous growth in the presence of antibiotics indicated that chromosomal segregation was complete.

The phenotype of the $\Delta nifK$ mutant was demonstrated both on plates and in liquid culture (Fig. 3A and B). When the $\Delta nifK$ mutant and the wild type were spotted onto plates containing Sp, the wild type died, as seen after 5 weeks (Fig. 3B, left plate), whereas the $\Delta nifK$ mutant always grew well. When

TABLE 2. Transformation efficiency^a

<i>Cyanobacteria</i> sp. strain	No. of transformants/CFU, 10 ⁴		Km ^r ratio (pAM1037/pRL448)	No. of transformants/CFU, 10 ⁴		Sp ^r ratio (pRL1383a/pRL453)
	pAM1037 (Km ^r)	pRL448 (Km ^r)		pRL1383a (Sp ^r)	pRL453 (Sp ^r)	
ATCC 51142	2.0	2.0	1.0	2.0	2.0	1.0
PCC 7424	1.0	1.0	1.0	1.0	1.0	1.0
PCC 7425	2.0	2.0	1.0	2.0	2.0	1.0
PCC 7822	1.0	0.2	5.0	1.0	0.01	100.0
PCC 8801	1.0	1.0	1.0	1.0	1.0	1.0
PCC 8802	1.0	1.0	1.0	1.0	1.0	1.0

^a Six *Cyanobacteria* strains were transformed by transposon Tn5 derivative pAM1037 or broad-host-range plasmid pRL1383a in comparison with suicide vector pRL448 or pRL453, respectively. Only *Cyanobacteria* sp. strain PCC 7822 demonstrated a significantly lower background (transformation by suicide vectors) to evoke future mutagenesis by homologous recombination.

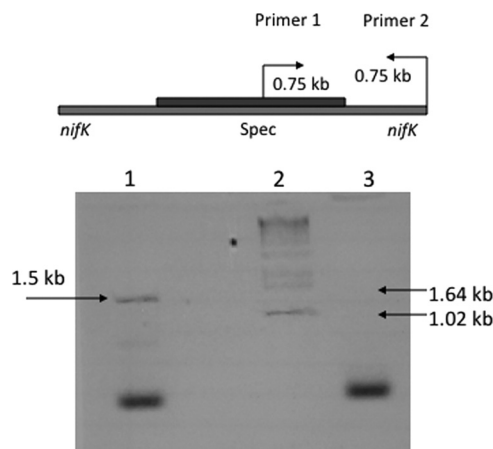


FIG. 1. PCR confirmation of the *Cyanothece* sp. strain PCC 7822 $\Delta nifK$ mutant. PCR with primer 1 in the Sp^r cassette ($Sp/11Up$) and primer 2 in the *nifK* gene (7822 NifK2) produced a band of about 1.5 kb from $\Delta nifK$ mutant DNA (lane 1) but not from wild-type DNA (lane 3). Lane 2 is the 1-kb DNA ladder, and the 1.64- and 1.02-kb bands are highlighted. The 1.5-kb band in the $\Delta nifK$ mutant then was sequenced to demonstrate that the Sp^r cassette (Spec) was located within the *nifK* gene as shown in the scheme at the top.

the two strains were spotted onto plates lacking combined nitrogen, the wild type always grew whereas the $\Delta nifK$ mutant slowly died (Fig. 3B, right plate). The phenotype was noticeable by 1 week, and by 5 weeks, the culture was completely bleached (Fig. 3A). This phenotype was demonstrated numerous times and has remained stable for >1 year. These results strongly suggested that the $\Delta nifK$ mutant was incapable of growth on media lacking combined nitrogen and presumably was defective in N_2 fixation. We then checked the mutant for both hydrogen production and nitrogenase activity. As shown in Table 3, the $\Delta nifK$ mutant produced little hydrogen when incubated either in air or under argon.

Similarly, the nitrogenase activity of the $\Delta nifK$ mutant differed from that of the wild type, but in an interesting fashion. As shown in Table 3, acetylene reduction by the $\Delta nifK$ mutant

GATTGATCCGGTGGATGACCTTTTGAATGACCTTTAATAGATTATATTAC
TAATTAATTGGGGACCCTAGAGGTCCCTTTTTTATTTTAAAAATTTTTT
CACAAAACGGTTTACAAGCATAAAGCTTGCTCAATCAATCACCGGATCCC
CGGGTACCGAGCTC**GAATTC**CAAGATGTACCAAGCGGTACAACCTTTAGAG
 GAAGGGCTGATTCATCAACGCAGAAGCTACCATCACCTACAAACCTA
 CCCCACCGTTAAAACCTCGGAATATATCGAGGAAAAATGGGGACAAAAA
 CCTTTACCTATCGTCTTGGGGTGTCAAAGGAACAGATGAGTTCTTAATG
 GGACTTTCTGAAGTACCGGTAATCTATCCCTGCTGAATTAGAACTCGA
 AAGAGGACCGCAGTTGACGCGATGACCGATAGCCATGCTTGGTTACATG
 GTAAGACAGCC

FIG. 2. The Sp^r cassette was inserted into *nifK* at the EcoRI site as designed. The PCR product from the $\Delta nifK$ mutant was sequenced from a primer within the Sp^r cassette, Sp/Up (Table 1). The sequence underlined is the Sp^r cassette, and the rest is *nifK*. The GAATTC sequence shown in bold is the EcoRI site. Another sequencing result using a primer with *nifK* (7822 NifK3, Table 1) confirmed the insertion of the Sp^r cassette into *nifK* as well (data not shown).

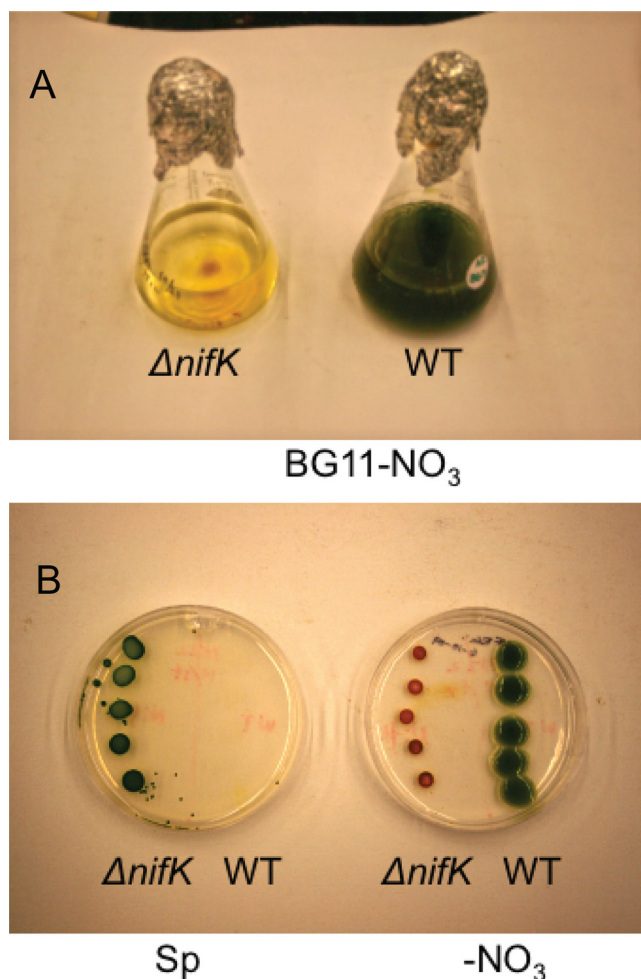


FIG. 3. Growth of the *Cyanothece* sp. strain PCC 7822 wild type (WT) and the $\Delta nifK$ mutant in liquid media (A) and on plates (B). (A) The wild type and the $\Delta nifK$ mutant were grown in BG11 medium without combined nitrogen for 5 weeks. The mutant was unable to fix nitrogen and began to appear bleached after 1 week. (B) The wild type and the $\Delta nifK$ mutant were spotted onto BG11 plates with Sp (left) to demonstrate that the mutant, but not the wild type, was antibiotic resistant. The plate on the right contained no combined nitrogen and demonstrated that the wild type, but not the $\Delta nifK$ mutant, could fix nitrogen.

was actually higher than that of the wild type when cells were incubated with either acetylene in air or acetylene in argon. The rate of acetylene reduction by the $\Delta nifK$ mutant under argon was $\sim 1,000$ -fold greater than that by the wild type with acetylene in air.

This nitrogenase phenotype is not unique, and we must consider the relationship of H_2 evolution and acetylene reduction to the nitrogenase enzyme (1, 2). Hydrogen is always produced when nitrogenase reduces N_2 to NH_3 , indicating that H_2 evolution is integral to the enzyme mechanism (23). Importantly, reduction of acetylene to ethylene is not accompanied by H_2 evolution and it is possible that nitrogenase reduces acetylene when only partially activated with no H_2 evolution. Acetylene reduction discharges nitrogenase before it ever reaches full activation. The current seven-stage mechanism for the fixation of N_2 to the production of $2NH_3$ also explains why

TABLE 3. Acetylene reduction activity and hydrogen production of *Cyanothece* sp. strain PCC 7822 and the $\Delta nifK$ mutant after incubation in air or argon

<i>Cyanothece</i> sp. strain PCC 7822	Incubation condition ^a	Avg relative acetylene reduction activity ^b \pm SD	Avg hydrogen production rate ^b \pm SD
Wild type	Air	1	5.1 \pm 1.8
$\Delta nifK$ mutant	Air	2.7 \pm 0.9	1.7 \pm 2.5
Wild type	Argon	31.5 \pm 10.6	58 \pm 16
$\Delta nifK$ mutant	Argon	1,139 \pm 363	2.4 \pm 3.4

^a Cultures were grown in medium containing N (2.5 mM NH₄NO₃) under low-light conditions for 10 days, washed with N-free medium twice, and grown in N-free medium for 3 days under low-light conditions. Then, 50 ml was added to 66-ml bottles. Some bottles were sparged with argon. Acetylene reduction assays were performed after the bottles were shaken under low-light conditions (30 μ mol photons m⁻² s⁻¹) for 22 h. After injection of 3 ml of acetylene, the bottles were also kept under light for 2 h.

^b Activities were computed as milligrams of chlorophyll *a* per hour, and the acetylene reduction activities were normalized to the wild-type value obtained in air. Hydrogen production rates are in micromoles of H₂ per milligram of chlorophyll *a* per hour.

acetylene is a competitive inhibitor of N₂ fixation, whereas N₂ is a noncompetitive inhibitor of acetylene reduction (2, 5, 15). Consistent with this feature, air (79% N₂) inhibited acetylene reduction in the wild type and the $\Delta nifK$ mutant, but to a greater extent in the $\Delta nifK$ mutant. This result suggested that the MoFe center is present in the mutant (1, 2). Finally, N₂ cannot fully stop H₂ evolution, as we have also demonstrated in *Cyanothece* sp. strain PCC 7822 (17), whereas acetylene can (1). Thus, the phenotype of the $\Delta nifK$ mutant indicated that the metal cofactors (e.g., MoFe) were assembled and were likely poorly integrated into the abnormal nitrogenase complex in the mutant.

Cyanothece sp. strain PCC 7822 represents an excellent organism for further studies. It demonstrates cycling behavior of photosynthesis and nitrogen fixation, and like *Cyanothece* sp. strain ATCC 51142, it produces large quantities of organic acids, lipids, and polyhydroxyalkanoates (pHAs) and copious levels of hydrogen (17). The genomic sequence has been completed, and we have the opportunity to use this strain for metabolic enhancement of one or more of these important compounds.

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