Environ Geochem Health (2007) 29:375–383
DOI 10.1007/s10653-007-9081-5

ORIGINAL PAPER

Antioxidant enzyme activities of *Microcystis aeruginosa* in response to nonylphenols and degradation of nonylphenols by *M. aeruginosa*

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Received: 1 August 2006 / Accepted: 10 January 2007 / Published online: 7 March 2007

Abstract The aim of this study was to examine the effects of chemical nonylphenols (NPs) on the antioxidant system of *Microcystis aeruginosa* strains. The degradation and sorption of NPs by *M. aeruginosa* were also evaluated. High concentrations of NPs (1 and 2 mg/l) were found to cause increases in superoxidase dismutase (SOD) and glutathione-*S*-transferase (GST) activities and in glutathione (GSH) levels. These results suggest that toxic stress manifested by elevated SOD and GST levels and GSH contents may be responsible for the toxicity of NPs to *M. aeruginosa* and that the algal cells could improve their antioxidant and detoxification ability through the enhancement of enzymatic and nonenzymatic prevention substances. The observed elevations in GSH levels and GST activities were relatively higher than those in SOD activities, indicating that GSH and GST contributed more in eliminating toxic effects than SOD. Low concentrations of NPs (0.05–0.2 mg/l) enhanced cell growth and decreased GST activity in algal cells of *M. aeruginosa*, suggesting that NPs may have acted as a protecting factor, such as an antioxidant. The larger portion of the NPs (>60%) disappeared after 12 days of incubation, indicating the strong ability of *M. aeruginosa* to degrade the moderate persistent NP compounds. The sorption ratio of *M. aeruginosa* after a 12-day exposure to low nominal concentrations of NPs (0.02–0.5 mg/l) was relatively high (>30%). The fact that *M. aeruginosa* effectively resisted the toxic effects of NPs and strongly degraded these pollutants indicate that *M. aeruginosa* cells have a strong ability to adapt to variations in environmental conditions and that low and moderate concentrations of organic compounds may favor its survival. Further studies are needed to provide detailed information on the fate of persistent organic pollutants and the survival of algae and to determine the possible role of organic pollutants in the occurrence of water blooms in eutrophic lakes.

Keywords Antioxidant system · Degradation · Glutathione · Glutathione *S*-transferase · *Microcystis* · Nonylphenols · Superoxide dismutase · Sorption

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Introduction

Nonylphenols (NPs) are degradation products of a class of nonionic surfactants known as alkylphenol polyethoxylates (APEs), which are widely used in industrial and domestic cleaning products, paints,

herbicides, pesticides, pulp and paper production processes, textile manufacturing and various household products. The occurrence of alkylphenols such as NPs in the environment has been demonstrated since the late 1970s (Sheldon & Hites, 1978), and NPs have been identified in air, wastewater, surface water and sediments and even in manufactured food (Bennie, 1999; Guenther et al., 2002; Van Ry et al., 2000). Various studies have found NP concentrations as high as 325 μg/l in surface water and 72 mg/kg in sediments (Ahel, Giger, & Koch, 1994; Bennie, 1999; Gross-Sorokin, Grist, Cooke, & Crane, 2003). To date, the maximum concentration of NPs has been the 6300 μg/l detected in an effluent from a shipyard oil/water separator (Hale et al., 2000). Concerns about the toxicity and endocrine potential of NPs have led to extensive studies being carried out during the last decade on their fate in the environment and their toxic effects on aquatic animals and plants (Hense et al., 2003; Jobling, Sheahan, Osborne, Matthiessen, & Sumpter, 1996). However, the biochemical mechanisms of the effects of NPs on various biological functions have been poorly elucidated. An understanding of the actual uptake, sorption and degradation of organic pollutants in different media is thus of critical importance for an understanding of the fate of these compounds in the environment.

Only a few studies have been published on the sorption of the moderately hydrophobic NP compounds by sediments (Holthaus et al., 2002; Lai, Johnson, Schrimshaw, & Lester, 2000), by dissolved organic matter (DOM) (Yamamoto, Liljestrand, & Shimizu, 2004) and by terrestrial soil (Düring, Krahe, & Gäth, 2002). The partition of NPs in the environment is assessed to be more than 60% in sediment, >10% in soil and approximately 25% in the water phase (Düring et al., 2002). As a hydrophobic chemical with a log K_{ow} of 4.48–5.76 (Yamamoto, Liljestrand, Shimizu, & Morita, 2003), the uptake of NPs adsorbed to sediments and organic material is likely to become increasingly important.

Algal blooms are becoming an increasingly more frequent occurrence in freshwater bodies worldwide (Codd et al., 1999). This phenomenon is necessarily related with industrial pollution, which contains a vast amount of organic pollutants, however little is known about how interactions between algae and organic pollutants influence the fate of these pollutants in aquatic ecosystems. Cyanobacteria are the dominant phytoplankton group in eutrophic freshwater bodies worldwide, causing harmful impacts on recreation, ecosystem integrity and human and animal health (Sivonen, 1996). A recent study by our group (Wang, Xie, & Guo, 2007) demonstrated that high concentrations of NPs inhibited the growth of *Microcystis aeruginosa*, while low concentrations of NPs enhanced the growth and toxin production of *M. aeruginosa*. The algal cells seemingly possess a well-developed ability to adapt quickly to an adverse stress because increases in both cell size and growth rate of the algal strains resumed if the experiment continued for a longer period of time. Similar to animals, plants have a strong enzymatic defense system to handle xenobiotics. It has been shown that oxygen radicals play important roles in numerous biological processes, such as enzymatic reactions, detoxifying reactions and cytopathological reactions (Vichnevetskaia & Roy, 1999).

The aim of this study was to investigate the biochemical mechanisms of the toxic effects of NPs on *M. aeruginosa*. To this end, we measured changes in antioxidant enzymatic activities of *M. aeruginosa* in response to NPs stress. In the laboratory, four *M. aeruginosa* strains were cultured in different concentrations of NPs, and their toxic effects on the antioxidant system of *Microcystis* were evaluated by measuring the levels of the antioxidant enzymes superoxidase dismutase (SOD), glutathione-*S*-transferase (GST) and glutathione (GSH) in the cells of the four *M. aeruginosa* strains after a 12-day incubation. At the mean time, the NPs concentrations in both the algal cells and the cultural media of two of the *M. aeruginosa* strains were determined to investigate the sorption and degradation ability of *Microcystis* to NPs.

Materials and methods

Experimental organisms, growth conditions and chemicals

Four axenic *Microcystis aeruginosa* strains – the toxic PCC7820 and 562 strains and the nontoxic

PCC7820N and 315 strains – provided by Prof. Lirong Song, the Culture Collection of Algae in the Institute of Hydrobiology (Wuhan, China), were used for this study. Both PCC7820 and 562 produce mainly microcystin-LR as the major toxin. The nontoxic PCC7820N strain, which is not able to produce toxins, developed spontaneously during the subculturing of a toxic strain, succeeding the toxic one under laboratory conditions.

The strains were grown in CT medium (Jang, Ha, Lucas, Joo, & Takamura, 2004) as batch cultures in an incubation chamber with an initial inoculum of 6×10^6 cells/ml. The laboratory conditions were maintained at 25 ± 1°C and a 14/10-h (light/dark) photo regime with light supplied by cool-white fluorescent lights at an intensity of 48 μE m^{-2} s^{-1}. The strains were inoculated in 250-ml Erlenmeyer flasks containing 150 ml growth medium. The flasks were incubated with continuous shaking (100 rev/min). Technical NPs (4-NP >98%; Sigma-Aldrich, Seelze, Germany) were kindly donated by Dr. Schramm (GSF-National Research Center of Environment and Health, Germany). 4-n-NP (99.9%) was purchased from Aldrich Chemical Co. The NPs were dissolved in dimethyl sulfoxide (DMSO) as a carrier solvent, which was diluted to give the desired concentrations of NPs in the growth medium. The effects of the carrier were tested by running controls with and without DMSO. In the DMSO control and in all of the NP treatments, the DMSO concentration was kept constant at 0.02% (v/v). Eight different concentrations of NPs (0, 0.02, 0.05, 0.1, 0.2, 0.5, 1, 2 mg/l) were chosen for the algal exposure experiment.

At the end of the experiment, 50 ml of the growth medium was used to analyze for the levels of the antioxidant enzymes, and another 50 ml was collected for the determination of NPs. The cells were harvested by centrifugation at 12,000 *g* at 4°C prior to the analyses of the antioxidant enzymes and NPs. The supernatants were decanted and retained for NP analysis.

Antioxidant enzyme analyses

The harvested cells were ground to a slurry with a mortar and pestle which was kept cool on liquid nitrogen, and then 4 ml phosphate buffer (pH 7.8) containing 1% (w/v) of insoluble polyvinylpyrrolidone (PVPP) was used to extract enzymes. SOD activity was measured by the photochemical NBT method (Bayer & Fridovich, 1987) in which 1 U of SOD was defined as that amount which caused a 50% decrease of the SOD-inhibitable NBT reduction. The reduced GSH was measured spectrophotometrically at 420 nm with the substrate 5,5′-ditrobenzoic acid (DTNB), as described by Ellman (1959) and Ren, Lu, and Bai (2003). GSH content was linear in the range of 0.1–10 nmol of GSH consumed per minute per milliliter. GST activity was assayed spectrophotometrically at 340 nm with the standard substrate (1-chloro-2,4-dinitrobenzene, CDNB) and co-substrate (reduced glutathione, GSH), as described by Habig, Pabst, and Jakoby (1974) and Adachi et al. (1980). The activity of GST was expressed in units per milligram wet weight of algae, which corresponded to the conversion rate of 1 μmol substrate per minute at 37°C.

High-performance liquid chromatography (HPLC) analysis for NPs

Sample treatment procedures for NPs detection were modified from previously described methods (Comber, Williams, & Stewart, 1993; Jonkers, Laane, & de Voogt, 2003; Solé et al., 2000). The algal cells were first extracted three times with methanol. The extracts were then centrifuged and the supernatants pooled and subsequently applied to a C_{18} cartridge (Dalian Institute of Chemical and Physical, China). NPs dissolved in the culture media were also extracted by C_{18} cartridge. The cartridge containing the NPs was washed with 10 ml methanol, which was reduced to dryness under reduced pressure. The residue was dissolved in 100 μl acetonitrile for HPLC analysis on a Shimazu (Kyoto, Japan) LC-9A liquid chromatograph system equipped for fluorescence detection. The injection volume was 10 μl on 4.6×150-mm C_{18} reversed-phase columns (ODS; 5C18-AR, Nacalai, Japan). The pump was operated at a flow 1.0 ml/min with a solvent gradient from acetonitrile:water (70:30, v/v) to 100% acetonitrile in 9 min followed by 100% acetonitrile for 6 min. Under these conditions, the numerous compounds of the NPs, mainly

branched alkyl chain isomers, were eluted in a single peak with good separation from 4-n-NP, which was used as the internal standard (Jontofsohn et al., 2002; Pfister, Jüttner, Severin, Schramm, & Kettrup, 2003). Fluorescence detection was at wavelengths of 230 nm for excitation and 310 nm for emission. The concentrations of the NPs were calculated from the peak area using a nine-point calibration curve. Individual quantifications of NPs were corrected for recovery of the 4-n-NP internal standard, the average of which was 80 ± 6% (mean ± SD, $n = 6$).

Statistics

Statistical significance was established at $P \leq 0.05$. The Student Neuman–Keuls test was used to compare the means of observations at the $P = 0.05$ level. All statistical analyses were carried out using STATISTICA ver. 6.0 (Statsoft, Tulsa OK.).

Results

SOD activities of the toxic PCC7820 strain at low and medium concentrations of NPs (0.05 and 1 mg/l, respectively) showed a slight decrease in comparison with the control, with a 30% decrease in activity at the lowest concentration. In contrast, the other three strains showed only a 9–15% decrease in SOD activity relative to the controls. SOD activity of the toxic PCC7820 strain cultured at a high concentration of NPs (2 mg/l) increased only slightly, being 5% higher than that of control, while those of the other three strains showed a relatively higher increase when exposed to 1 or 2 mg/l NPs, with the SOD acitivity of toxic strain 562 increasing by 42 and 51% relative to the control, that of nontoxic strain PCC7820N increasing by 5 and 23% and that of nontoxic strain 315 increasing by 28 and 32%, respectively (Fig. 1).

The GSH levels of the four strains cultured at low concentrations of NPs (0.05–0.5 mg/l) decreased slightly (3–14%) compared to the controls, but exposure to 1 and 2 mg/l NPs produced quite different results: the two nontoxic strains showed slightly higher GSH contents, with a 3

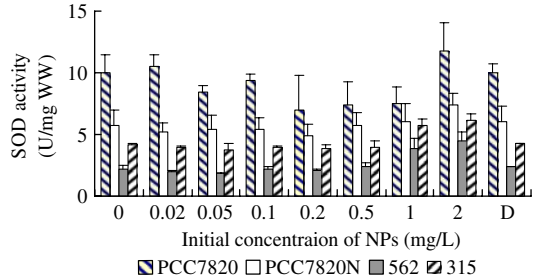

Fig. 1 Response of superoxidase dismutase (SOD) of *Microcystis aeruginosa* strains after a 12-day exposure to different concentrations of Nonylphenols (NPs). *Vertical bars* show the standard deviation ($n = 6$). *D* Solvent control, *WW* fresh wet weight of algal cells

and 54% relative increase by PCC7820N and a 46 and 56% relative increase by strain 315, respectively. The GSH levels of toxic strain PCC7820 increased very distinctly, with an 85% increase over the control when exposed to 2 mg/l NPs. The GSH levels of toxic strain 562 also increased quite distinctly, being 78 and 92% higher than that of control when exposed to 1 and 2 mg/l NPs, respectively (Fig. 2).

The GST activities of all the four strains showed a definite decrease when exposed to low concentrations of NPs (0.05–0.5 mg/l): at the lowest concentration, strains PCC7820, PCC7820N, 562 and 315 showed a decrease of 82, 92, 47 and 44% relative to the control. When these strains were exposed to high concentrations of NPs, the activity of GST was enhanced to different extents: the GST activity of toxic strain PCC7820 increased by 36%

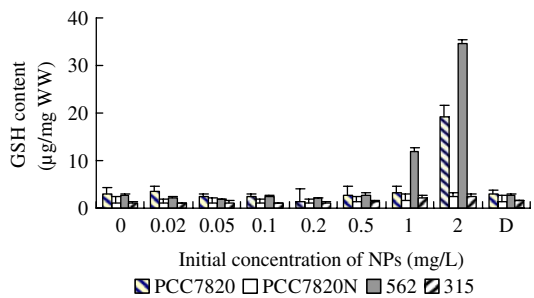

Fig. 2 Glutathione (GSH) levels in the *M. aeruginosa* strains after a 12-day exposure to different concentrations of NPs. *Vertical bars* show the standard deviation ($n = 6$). *D* Solvent control, *WW* fresh wet weight of algal cells

relative to the control at 2 mg/l NPs and that of toxic strain 562 increased by 48 and 83% relative to the control at 1 and 2 mg/l NPs, respectively. In contrast, nontoxic strain PCC7820N showed no obvious variation in terms of GST activity when exposed to high concentrations of NPs, and GST activities in nontoxic strain 315 were only slightly stimulated, being 14 and 36% higher than the control when exposed to 1 and 2 mg/l NPs, respectively (Fig. 3). The addition of the solvent DMSO to the culture medium at the designated concentration had no obvious effect on the activities of these three antioxidant enzymes.

The NPs absorbed on or in algal cells (NPs content) and the concentrations of NPs in the culture media of the two toxic *M. aeruginosa* strains PCC7820 and 562 after 12 days of incubation at different concentrations of NPs were determined by HPLC (Figs. 4 and 5). Both of the concentrations of NPs in the culture media and those absorbed on or in the algal cells increased with increasing initial NPs concentrations.

The ratios of sorption and degradation of NPs by the two toxic *M. aeruginosa* strains after a 12-day incubation in different concentrations of NPs are presented in Table 1. There was no obvious difference in the sorption and degradation of NPs by these two strains. Higher degradation rates were found following exposure to 0.1–1 mg/l NPs for strain PCC7820 and 0.1–0.5 mg/l for strain 562. The sorption ratios of NPs in algal cells to NPs in the culture media were 34.9–60.8%

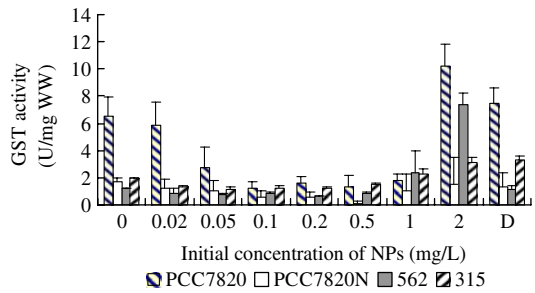

Fig. 3 Glutathione-*S*-transferase (GST) levels in the *M. aeruginosa* strains after a 12-day exposure to different concentrations of NPs. *Vertical bars* show the standard deviation ($n = 6$). *D* Solvent control, *WW* fresh wet weight of algal cells

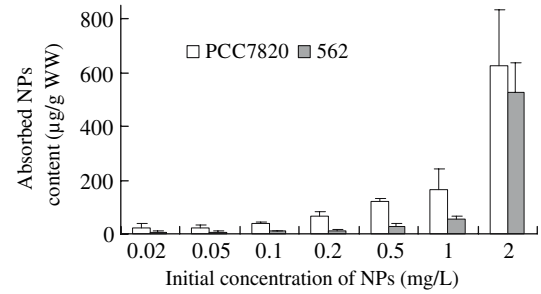

Fig. 4 Content of NPs in cells of *M. aeruginosa* strains PCC7820 and 562 after a 12-day incubation in different concentrations of NPs. *Vertical bars* show the standard deviation ($n = 3$)

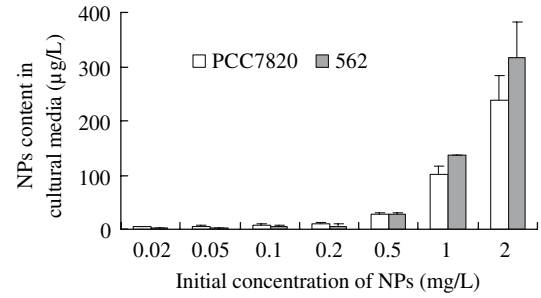

Fig. 5 Levels of NPs in the culture media of *M. aeruginosa* strains PCC7820 and 562 after a 12-day incubation in different concentrations of NPs. *Vertical bars* show the standard deviation ($n = 3$)

for the two strains at low initial concentrations of NPs (0.02–0.5 mg/l), however, these sorption ratios decreased significantly for the 1 and 2 mg/l treatments.

Discussion

The toxic effect of NPs on the growth of both toxic and nontoxic *M. aeruginosa* strains has been reported in Wang et al. (2007). The results of this earlier study demonstrated that nontoxic strains were more resistant to NPs than toxic ones at concentrations above 1 mg/l. The present study has shown that the activities of SOD, GSH and GST in the four *M. aeruginosa* strains were affected differently at concentrations of NPs above 1 mg/l, with the increases in GSH and GST activities in toxic strains PCC7820 and 562 being much more significant than those in

Table 1 Sorption and degradation of nonylphenols (NPs) by the toxic *Microcystis aeruginosa* strains PCC7820 and 562 after a 12-day incubation in different concentrations of NPs[a]

Initial concentration of NPs (mg/l)	Percentage degradation of NPs after a 12-day incubation[b]		Percentage sorption of NPs by algal cells after a 12-day incubation[c]	
	PCC7820	562	PCC7820	562
0.02	61.7	65.4	34.9	60.8
0.05	81.7	83.0	37.4	58.0
0.1	86.7	89.2	43.3	53.2
0.2	88.1	93.6	59.0	54.1
0.5	89.7	91.6	44.3	31.1
1	87.3	84.0	21.1	14.4
2	86.4	82.1	12.3	11.4

[a] The experiment was repeated three times ($n = 3$)

[b] Percentage degradation of NPs = 100 × (total initial NPs – NPs remain in solution and cells)/total initial NPs

[c] Percentage sorption of NPs = 100 × (NPs in cells/NPs remain in solution and cells)

nontoxic strains PCC7820N and 315. The present results substantiate those of our earlier investigation (Wang et al. 2007) in providing further proof that the nontoxic *M. aeruginosa* strains used in our study are more resistant to the stress of exposure to 1 and 2 mg/l NPs than the toxic strains.

Oxygen radicals are generated during plant metabolism; this is particularly the case in plants exposed to environmental stresses. These oxygen radicals need to be scavenged for the maintenance of normal growth. A large body of evidence has been accumulated on various plant systems showing that environmental stresses alter the amounts and the activities of enzymes involved in scavenging oxygen radicals (Gueta-Dahan, Yaniv, Zilinskas, & Ben-Hayyim, 1997). The levels of SOD, GSH and GST in the four *M. aeruginosa* strains used in our study varied to different extents following exposure of the strains to different concentrations of NPs, suggesting that the algal cells were under oxidative stress as a result of exposure to NPs and that these antioxidant enzymes may play important roles in eliminating the excessive reactive oxygen species (ROS). The extent to which SOD activity increased in response to high concentrations of NPs stress was less than the increased activity shown by GSH and GST, demonstrating that GSH and GST contributed more significantly to the elimination of the toxic effect of NPs than SOD.

GSH is considered to be one of the most important and abundant cytosolic components of the antioxidant system. One of its more important functions is to exclude ROS before these reactive molecules can initiate their chain reaction-damaging effects on macromolecules (Pinho et al., 2003). It also plays an important role in the detoxification and clearance of toxins (Pflugmacher et al., 1998). In the present study, the GSH levels of algae exposed to high concentrations of NPs (1 and 2 mg/l) rose more markedly than those of the control, demonstrating that the algae had a sensitive response mechanism to these concentrations of the chemical. Through the enhancement of GSH content, the cells were able to improve their detoxification ability to eliminate ROS or conjugate NPs.

GST is also an important enzyme in terms of the detoxification of xenobiotics. GST catalyzes the conjugation of reduced GSH to nucleophilic xenobiotics or cellular components damaged by ROS attack, which represents detoxification reactions. It is also able to chemically modify a multitude of electrophilic substances. The increase in GST activity in our study represents a response mechanism to the exposure of NPs and, as such, it is a protective mechanism which protects the cells from the destructive effects of ROS and xenobiotics. Therefore, the main detoxification process for toxic NPs was through GSH conjugation and GST, which is a phase II detoxification enzyme system.

As a challenge to the toxic and potentially lethal effects of active oxygen species, aerobic organisms have evolved protective scavenging or antioxidant defense systems, both enzymatic and nonenzymatic (Halliwell & Gutteridge, 1985). Among the former are peptides, phenolic compounds, nitrogen compounds, carotenoids and sulfur-containing materials (Larson, 1995). Natural antioxidants are found in numerous plant materials and commonly include an aromatic ring as part of the molecular structure as well as one or

more hydroxyl groups to provide a labile hydrogen and a basis for free radical formation (Vichnevetskaia & Roy, 1999). Among the secondary metabolites, phenolic compounds have been widely studied. Most of these compounds make a significant contribution to the antioxidant activity of plants and are thus of major importance in the mechanisms of protection of plants against stress (Ferrat, Pergent-Martini, & Roméo, 2003). The chemical structure of NPs suggests that they possess antioxidant properties. Alkylphenols (APs), which include NPs, are reported to have been used as antioxidant or material for the synthesis of antioxidants (Ahel et al., 1994; Naylor, 1995; Sonnenschein & Soto, 1998). In conjugation reactions between APs and glutathione, the GSH moiety was found to be attached to the benzylic carbon on the alkyl chain of the alkylphenol (Bolton, Valero, & Thompson, 1992). Therefore, it is likely that NPs may function as an antioxidant in a reaction with *M. aeruginosa*, thereby enabling the donation of a H^+ to oxygen radicals, which subsequently interrupts the free radical chain reaction. The growth inhibition test using *M. aeruginosa* strains exposed to NPs showed that algae cell growth in both the toxic and nontoxic strains was enhanced by 0.02–0.2 mg/l NPs (Wang et al., 2007). In the present study, GST activities in the four strains of *Microcystis* were lower than that of the controls at low concentrations of NPs (0.05–0.5 mg/l). This may be explained by the fact that NPs act as an antioxidant to stimulate algal cell growth and, correspondingly, decrease GST activity in the algal cell. Detailed studies are needed to test this hypothesis in the future.

Since NPs exhibit a lower solubilities in water and higher lipophilicities, they have a greater tendency to bioaccumulate and to partition to organic-rich sediments. The biodegradation of free NPs is only about 0.06% per day in the absence of sediments (Ekelund, Granmo, Magnusson, & Berggren, 1993). Topp and Starratt (2000) suggest that the recalcitrance of NPs to biodegradation in sewage treatment plants and outflows is due to environmental constraints (e.g., oxygen limitation) rather than an inherent environmental recalcitrance of the compounds. These researchers discovered that technical NPs were readily biodegradable in soils. Hense et al. (2003) reported that the concentrations of NPs declined rapidly and reached the detection limit within 2 weeks in man-made aquatic microcosms. A removal of NPs by more than 90% in soil under normal field conditions within 1–3 months was observed by Marcomini, Capel, Lichtensteiger, Brunner, and Giger (1989). To date, there have been no reports on the sorption and degradation behavior of NPs by *M. aeruginosa* strains. Our study has shown that after 12 days of incubation with different concentrations of NPs, the degradation ratios of NPs by the two toxic *M. aeruginosa* strains PCC7820 and 562 were higher than 60%. Although the sorption loss of containers (Johnson, White, Besien, & Jürgens, 1998), light (Mann & Boddy, 2000; Pfister et al., 2003) and volatility may influence the determination of NP degradation, our primary experimental results have provided data indicating that *M. aeruginosa* has a relatively high ability to biodegrade NPs. Johnson et al. (1998) studied suspended sediments under the microscope and found that the sediments that adsorbed far less octylphenol (OP) consisted largely of algae. Their finding may also imply that algae have a strong ability to degrade OP. In our study, the sorption ratio of NPs in the *M. aeruginosa* strains to NPs dissolved in the cultures ranged from 35 to 61% after a 12-day exposure to nominal concentrations of 0.02–0.5 mg/l NPs. Johnson et al. (1998) determined that sediments consisting mainly of organic aggregates had the potential to absorb 30–40% of OP in solution, which is similar to our results. The sorption ratio of NPs by the *M. aeruginosa* strains cultured at high nominal concentrations of NPs (1 and 2 mg/l) decreased greatly (range: 11.4–21.1%), which may be due to the toxic effect of the NPs. These results suggest that NPs were able to be taken up from the surrounding medium by the cyanobacteria *M. aeruginosa*.

To summarize, the present study represents the first investigation into the effects of NPs on the possible detoxification mechanism of *Microcystis*. At the mean time, the degradation and absorption of NPs by *Microcystis* were also investigated. Our results show that NPs enhance growth and toxin production in *M. aeruginosa* at low concentrations (0.02–0.5 mg/l) that might possibly be

found in natural freshwaters (Wang et al., 2007). We found that *M. aeruginosa* has a relatively high ability to degrade and adsorb NPs at low concentrations of NPs in solution. Low concentrations of NPs may act as a protective factor, such as an antioxidant, to favor the survival of *M. aeruginosa* in the field. *M. aeruginosa* can effectively resist the toxic effects of high concentrations of NPs by elevating its SOD and GST levels and GSH contents, indicating that *M. aeruginosa* has a strong ability to adapt to variations in environmental conditions. As *Microcystis* plays a significant role in algal bloom in eutrophic lakes and NPs are increasingly seen to be persistent organics and endocrine disrupters, these results may be ecologically relevant for aquatic systems. Therefore, further studies are required to investigate the effect of NPs on the bloom of *Microcystis.*

Acknowledgements This study was financially supported by grants from National Natural Science Foundation of China (Grant No. 30225011) and a key project of CAS (Grant No. KSCX2-SW-129).

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