Introduction

Due to the industrial disposal of electronic components, environmental pollution of Cd\(^{2+}\) is a serious global problem [1]. Cd\(^{2+}\) can be accumulated in organisms and then biomagnified through food chains [2]. Investigations have revealed notable daily intakes and health risks of Cd\(^{2+}\) exposure through drinking water and vegetable consumption in humans [3], which may correlate with cancer mortality rates [4]. Since Cd\(^{2+}\) is similar to Ca\(^{2+}\), Cd\(^{2+}\) may interfere with different kinds of Ca\(^{2+}\)-dependent metabolic or developmental processes [5, 6] and induce widespread misfolding and aggregation of nascent proteins [7], thus highly intoxicating all kinds of lives [1].

Toxicity of Cd\(^{2+}\) to animals and plants has been well studied. In animals, Cd\(^{2+}\) was greatly accumulated in kidneys and livers/hepatopancreas, which then caused pathological disturbances, triggered lipid peroxidation and oxidative stress [1, 8], and suppressed immunity functions [9]. Besides, Cd\(^{2+}\) displayed genotoxicity to animals, including the calanoid copepod *Acartia tonsa*, the decapod shrimp *Palaemon varians* and the pleuronectiform fish *Solea senegalensis* [10]. In response to Cd\(^{2+}\) exposure, animals may increase the expression level of transferrin, which can interact with...
and detoxicate Cd²⁺ to livers [11]. In plants, exposure to Cd²⁺ inhibited cell division [12], seed germination and seedling growth [13], declined photosynthesis activity, chlorophyll content and the Calvin cycle [6, 14, 15], damaged chloroplast [16, 17] and induced genetic toxicity [18].

Algae are primary producers in aquatic ecosystems. Damage to algae cells and bioaccumulation of heavy metals in algae will negatively influence higher trophic levels and finally endanger human beings [19]. Although algae had bioremediation potential in Cd²⁺-polluted areas [20], Cd²⁺ revealed obvious toxicity to algae in most cases. As previously reported, 7 mg/L Cd²⁺ significantly reduced contents of photosynthetic pigments and induced oxidative stress in Chlorella vulgaris [21]. Transcriptome and metabolome studies revealed that exposure to 12.90 mg/L Cd²⁺ induced oxidative stress in the freshwater alga Chlamydomonas reinhardtii [22]. Similar physiological results were revealed in Desmodesmus armatus when treated with 10.45 mg/L Cd²⁺ [23]. At higher concentrations of Cd²⁺, more severe effects were observed. For example, treatment with 67.45 mg/L Cd²⁺ induced stronger cellular toxic impacts on Chlamydomonas reinhardtii, such as inhibition of cellular division and photosynthesis, increase of cell size and cellular granularity [24]. These studies have investigated the effects of Cd²⁺ at levels above 5 mg/L. However, in most Cd²⁺-polluted waterbodies, environmental concentrations of Cd²⁺ were generally below 0.50 mg/L [25]. These investigations of high concentrations of Cd²⁺ could not comprehensively reveal environmental risks of Cd²⁺ pollution in nature.

In the present study, the effects of low concentrations of Cd²⁺ (0.05 to 0.20 mg/L) on chlorophyll fluorescent parameters in Scenedesmus quadricauda, Chlorella pyrenoidosa, Scenedesmus obliquus, Nitzschia palea, Selenastrum minutum and Scenedesmus acutus were investigated, which might reveal the early toxicity of Cd²⁺ to green algae. Besides, changes of growth indices were also monitored to compare their sensitivity to low concentration of Cd²⁺ with chlorophyll fluorescent parameters. These results would be useful to evaluate risks of trace Cd²⁺ to aquatic environments.

Materials and Methods

S. quadricauda, C. pyrenoidosa, S. obliquus, N. palea, S. minutum and S. acutus were isolated from the Xin’an River in Huangshan City, P. R. China. The composition of water quality in the sampling area varied among seasons. The NH₄⁻N concentrations were 0.30±0.03, 0.16±0.02, 0.14±0.08 and 0.60±0.10 mg/L, the total phosphorus (TP) content was 0.064±0.003, 0.033±0.001, 0.029±0.009 and 0.068±0.002 mg/L, and the dissolved oxygen (DO) content was 5.83, 8.12, 8.81 and 8.70 mg/L during spring, summer, autumn and winter, respectively. To the best of our knowledge, no obvious pollution took place in this area. The ordinary heavy metal pollutants (such as Cu, Cr, Cd, Pb and Zn) were not detectable in this area.

Stock alga culture solution was maintained in 500 ml flasks in a light incubator with light cycle of 12:12 h and light intensity of approximately 6,000 lux. The culture temperature was 25±1°C, and BG-11 was used as the culture medium [27]. To suspend alga cells, flasks were shaken manually three times per day.

Four concentrations of Cd²⁺, including 0.05, 0.10, 0.15 and 0.20 mg/L, were prepared by dissolving CdCl₂ (analytic grade) in BG-11 medium. BG-11 medium without the addition of Cd²⁺ was used as the control. Algae at the exponential growth stage were used for Cd²⁺ treatments. Alga density was determined using a hemocytometer. The initial alga density was adjusted to 1×10⁵ cells/mL and then cultured as described above. Alga density was monitored every 24 hours for overall 10 days (8 days for C. pyrenoidosa) in order to calculate population growth rate. Each assay was repeated three times independently.

On the fifth day, 100 ml of alga solution was collected from each treatment. After being placed in the dark for 15 min, chlorophyll fluorescence parameters – including maximal photochemical efficiency of PS II (Fv/Fm), actual photochemical efficiency of PS II (Yield), maximal relative electron transport rate (rETR_max), electron transport efficiency (α) and half-saturation light intensity (Iₛ) – were determined using a phytoplankton fluorescence instrument (phyto-PAM, Walz-Germany).

Statistical analyses were performed using SPSS 19.0. After homogeneity of variance tests, effects of Cd²⁺ on each parameter were analyzed using one-way analysis of variance (ANOVA) followed by least significant difference (LSD). 

Results

Effects of Cd²⁺ on Algae Growth

Along with increasing culture time, cell density of all alga species (except C. pyrenoidosa) increased in all treatments and the control. Cell density of C. pyrenoidosa declined in most treatments and the control at day 8, suggesting that alga populations might be aged (Fig. S1).

There was no significant difference in growth curve of C. pyrenoidosa, N. palea and S. acutus among Cd²⁺ treatments and the control. Growth curve of S. quadricauda, S. minutum and S. obliquus seemed a little higher in the control in comparison to Cd²⁺ treatments (Fig. S1).

One-way analysis of variance revealed that Cd²⁺ did not significantly affect population growth rate of S. quadricauda, C. pyrenoidosa, S. obliquus, N. palea, S. minutum and S. acutus (Fig. S2).
Early Toxic Effects of Cd²⁺...  

**Effects of Cd²⁺ on Chlorophyll Fluorescent Parameters**

Compared with the control, treatments with 0.05-0.20 mg/L Cd²⁺ significantly increased $F_v/F_m$ of *N. palea* and *S. minutum*, but decreased $F_v/F_m$ of *S. obliquus* and *S. acutus*. No significant difference in $F_v/F_m$ of *C. pyrenoidosa* was detected among Cd²⁺ treatments and the control. Treatments with 0.15-0.20 mg/L Cd²⁺ significantly reduced $F_v/F_m$ of *S. quadricauda* (Fig. 1). For all alga species, the changes of yield among Cd²⁺ treatments and the control were exactly identical to those of $F_v/F_m$ (Fig. 2, Table S1).

In comparison to the control, treatments with 0.05-0.2 mg/L Cd²⁺ significantly reduced rETR$_{max}$ of *S. obliquus* and *C. pyrenoidosa*, but elevated those in *N. palea* and *S. minutum*. Treatments with 0.10-0.20 mg/L Cd²⁺ significantly reduced rETR$_{max}$ of *S. acutus*. Similar results were revealed in *S. quadricauda* exposed to 0.15-0.20 mg/L Cd²⁺ (Fig. 3, Table S1).

All Cd²⁺ treatments significantly decreased $\alpha$ in *S. obliquus* and *S. acutus*, but did not affect $\alpha$ in *N. palea* and *C. pyrenoidosa*. Treatments with 0.15-0.20 mg/L Cd²⁺ significantly reduced $\alpha$ of *S. quadricauda* and treatments with 0.10-0.20 mg/L Cd²⁺ significantly increased $\alpha$ of *S. minutum* (Fig. 4, Table S1).

In response to Cd²⁺ treatments, $I_k$ significantly decreased in *S. obliquus*, increased in *S. minutum*, but did not change in *N. palea*. When exposed to 0.10-0.20 mg/L Cd²⁺, $I_k$ was significantly reduced in *S. acutus*, *C. pyrenoidosa* and *S. quadricauda* (Fig. 5, Table S1).

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Fig. S1. Growth curves of *S. quadricauda*, *C. pyrenoidosa*, *S. obliquus*, *N. palea*, *S. minutum* and *S. acutus* in treatments with 0.05, 0.10, 0.15 and 0.20 mg/L Cd²⁺. Data represent mean±SD (n = 3).
Fig. 1. Effects of Cd\(^{2+}\) (mg/L) on maximal photochemical efficiency of PS II (F\(_{v}/F\_m\)) of green algae (mean±SD, n = 3). Sq: S. quadricauda. Cp: C. pyrenoidosa. So: S. obliquus. Np: N. palea. Sm: S. minutum. Sa: S. acutus. Different letters above bars represent significant differences among treatments with Cd\(^{2+}\) and the control within the same species.

Fig. 2. Effects of Cd\(^{2+}\) (mg/L) on actual photochemical efficiency of PS II (yield) of green algae (mean±SD, n = 3). Sq: S. quadricauda. Cp: C. pyrenoidosa. So: S. obliquus. Np: N. palea. Sm: S. minutum. Sa: S. acutus. Different letters above bars represent significant differences among treatments with Cd\(^{2+}\) and the control within the same species.

Fig. 3. Effects of Cd\(^{2+}\) (mg/L) on maximal relative electron transport rate (rETR\(_{max}\)) of green algae (mean±SD, n = 3). Sq: S. quadricauda. Cp: C. pyrenoidosa. So: S. obliquus. Np: N. palea. Sm: S. minutum. Sa: S. acutus. Different letters above bars represent significant differences among treatments with Cd\(^{2+}\) and the control within the same species.

Fig. 4. Effects of Cd\(^{2+}\) (mg/L) on electron transport efficiency (\(\alpha\)) of green algae (mean±SD, n = 3). Sq: S. quadricauda. Cp: C. pyrenoidosa. So: S. obliquus. Np: N. palea. Sm: S. minutum. Sa: S. acutus. Different letters above bars represent significant differences among treatments with Cd\(^{2+}\) and the control within the same species.

Fig. 5. Effects of Cd\(^{2+}\) (mg/L) on half-saturation light intensity (Ik) of green algae (mean±SD, n = 3). Sq: S. quadricauda. Cp: C. pyrenoidosa. So: S. obliquus. Np: N. palea. Sm: S. minutum. Sa: S. acutus. Different letters above bars represent significant differences among treatments with Cd\(^{2+}\) and the control within the same species.
Table S1. Effects of Cd²⁺ on chlorophyll fluorescent parameters in *S. obliquus*, *N. palea*, *S. acutus*, *C. pyrenoidosa*, *S. quadricauda* and *S. minutum* (mean ± standard deviation). Different letters represent significant difference among treatments with Cd²⁺ and the control within the same species.

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Discussion

Toxicity of pollutants to green algae varied among species [28] and strains [29]. In the present study, based on locally collected alga strains, the as-obtained toxic assessment results should be more accurate to evaluate environmental risk of Cd²⁺ to the local environments [29]. Branco et al. [30] revealed that IC₅₀ of Cd²⁺ to N. palea was 0.0276 mg/L. Zhou, and Xiang [31] suggested that 0.01 mg/L significantly reduced growth of S. minutum. However, treatment with up to 0.20 mg/L Cd²⁺ did not affect the population growth rate of N. palea and S. minutum in the present study, suggesting that these two species from the Xin'an river might be more tolerant to Cd²⁺ than those used in Branco et al. [30] and Zhou and Xiang [31].

As previously reported, treatments with 6.74 mg/L, 0.72 mg/l, 1 mg/L and 0.51 mg/L Cd²⁺ suppressed growth of S. quadricauda [32], C. pyrenoidosa [33], S. obliquus [34] and S. acutus [35], respectively. In the present study, treatments with 0.20 mg/L Cd²⁺ did not affect the population growth rate of this species, which might be due to the low level of Cd²⁺. However, chlorophyll fluorescent parameters were more or less affected by treatments with 0.05-0.20 mg/L Cd²⁺, suggesting that chlorophyll fluorescent parameters were more sensitive to Cd²⁺ pollution compared with growth parameters. These results were consistent with the previous viewpoint that photosystem II is one of the most sensitive indices to environmental stress [26]. Thus, we proposed that chlorophyll fluorescent parameters might be used as biomarkers to monitor early toxicity of Cd²⁺ in green algae.

Cd²⁺ has been reported to inhibit chlorophyll fluorescent parameters of Solanum melongena [36], Robinia pseudoacacia [37] and Arabidopsis thaliana [38]. In response to Cd²⁺ treatments, F/Fₘ, yield, α and Iₙ all significantly decreased in S. obliquus, S. acutus and S. quadricauda, suggesting that the whole photosynthetic system was damaged by Cd²⁺ in these species. However, all these indices were not significantly reduced by Cd²⁺ in N. palea and S. minutum, indicating that those two species might be more tolerant to Cd²⁺ pollution than S. obliquus, S. acutus and S. quadricauda.

Moreover, in N. palea and S. minutum, treatment with 0.05 mg/L Cd²⁺ even increased Fₚ/Fₘ, yield and rETRmax, compared with the control (Table S1). Two possibilities might explain these results. First, as reported in Juncus acutus, treatment with Cd²⁺ inhibited the electron transport rate and led to the accumulation of extra energy in chlorophylls. The accumulated energy was then dissipated in the forms of heat and/or fluorescence, displaying enhanced fluorescent intensity, which might affect the determination of chlorophyll fluorescent parameters [39]. Second, treatments with low concentrations of Cd²⁺ have been reported to increase chlorophyll content in Lolium multiflorum [40] and Lactuca sativa [41]. Accumulation of chlorophyll should also increase the chlorophyll fluorescent parameters. However, more investigations are still required to validate these hypotheses in N. palea and S. minutum.

In response to Cd²⁺ treatments, Iₚ and rETRmax decreased significantly in C. pyrenoidosa, but α, F/Fₘ and yield were not affected. rETRmax represents the maximal relative electron transport rate [42]. A decrease of rETRmax suggested that electron transport to the PS II reaction center was blocked. The subsequent accumulation of electrons should be harmful to alga cells and trigger photoinhibition, reducing Iₚ simultaneously. Both F/Fₘ and yield represent photosynthetic ability. F/Fₘ and yield did not change under Cd²⁺ stress in C. pyrenoidosa, suggesting that photoinhibition might not occur. Electron transport efficacy α remained stable to Cd²⁺ exposure, which might make up for the reduction of rETRmax.

The Chinese Environmental Quality Standard for Surface Water (GB3838-2002) stipulates that the maximum limit concentration of Cd is 0.001 mg/L, 0.005 mg/L and 0.01 mg/L in Class I, Class II-IV and Class V surface water, respectively [43]. The criterion of maximum concentration (CMC) and continuous concentration (CCC) of Cd in the freshwater ecosystem was 0.4 μg/L and 0.2 μg/L in the United States of America, respectively [44]. The criterion of Cd in fresh ecosystems in Canada [45], Malaysia (Class II) [46] and Europe [47] were 0.008 μg/L, 10 μg/L and <0.07 μg/L, respectively. In the present study, treatment with 0.05 mg/L Cd significantly inhibited one or more chlorophyll fluorescent parameters in S. obliquus, S. acutus and C. pyrenoidosa. Considering that the safe concentration of pollutants should be 10 times lower than the no-observed-effect concentration (NOEC) [45], the criterion of Cd in surface water should be lower than 0.005 mg/L. Thus, the concentration of Cd in the Chinese Environmental Quality Standard for Surface Water should be re-evaluated.

Conclusions

Treatments with up to 0.20 mg/L Cd²⁺ did not significantly affect population growth of S. quadricauda, C. pyrenoidosa, S. obliquus, N. palea, S. minutum and S. acutus. However, exposure to 0.05-0.20 mg/L Cd²⁺ significantly reduced chlorophyll fluorescent parameters of S. obliquus, S. acutus and S. quadricauda, but not of N. palea and S. minutum. N. palea, S. minutum and C. pyrenoidosa were more tolerant to Cd²⁺ than S. obliquus, S. acutus and S. quadricauda.

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Entrepreneurship and Innovation of Anhui Province (201810375112, 201810375117, 201710375004, 201710375022).

Conflict of Interest

There is no conflict of interest in this research.

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