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ORIGINAL ARTICLE

Physiological and metabolic responses of *Scenedesmus quadricauda* (Chlorophyceae) to nickel toxicity and warming

Wai-Kuan Yong[1,2] · Kae-Shin Sim[3] · Sze-Wan Poong[1] · Dong Wei[4] · Siew-Moi Phang[1,3] · Phaik-Eem Lim[1]

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Abstract

An ecologically important tropical freshwater microalga, *Scenedesmus quadricauda*, was exposed to Ni toxicity under two temperature regimes, 25 and 35 °C to investigate the interactive effects of warming and different Ni concentrations (0.1, 1.0 and 10.0 ppm). The stress responses were assessed from the growth, photosynthesis, reactive oxygen species (ROS) generation and metabolomics aspects to understand the effects at both the physiological and biochemical levels. The results showed that the cell densities of the cultures were higher at 35 °C compared to 25 °C, but decreased with increasing Ni concentrations at 35 °C. In terms of photosynthetic efficiency, the maximum quantum yield of photosystem II (F_v/F_m) of *S. quadricauda* remained consistent across different conditions. Nickel concentration at 10.0 ppm affected the maximum rate of relative electron transport ($rETR_m$) and saturation irradiance for electron transport (E_k) in photosynthesis. At 25 °C, the increase of non-photochemical quenching (NPQ) values in cells exposed to 10.0 ppm Ni might indicate the onset of thermal dissipation process as a self-protection mechanism against Ni toxicity. The combination of warming and Ni toxicity induced a strong oxidative stress response in the cells. The ROS level increased significantly by 40% after exposure to 10.0 ppm of Ni at 35 °C. The amount of Ni accumulated in the biomass was higher at 25 °C compared to 35 °C. Based on the metabolic profile, temperature contributed the most significant differentiation among the samples compared to Ni treatment and the interaction between the two factors. Amino acids, sugars and organic acids were significantly regulated by the combined factors to restore homeostasis. The most affected pathways include sulphur, amino acids, and nitrogen metabolisms. Overall, the results suggest that the inhibitory effect of Ni was lower at 35 °C compared to 25 °C probably due to lower metal uptake and primary metabolism restructuring. The ability of *S. quadricauda* to accumulate substantial amount of Ni and thrive at 35 °C suggests the potential use of this strain for phycoremediation and outdoor wastewater treatment.

Keywords Nickel toxicity · Global warming · *Scenedesmus* · Microalgae · Photosynthesis · Metabolomics

Introduction

The global demand for nickel (Ni) has risen over the years due to its wide application in the metallurgical, chemical, agricultural and manufacturing industries. More than two-thirds of the world's Ni lateritic deposits are located in the tropics especially in the South East Asia region (Binet et al. 2018). The increasing anthropogenic release of Ni into the environment has been identified as a key pollutant in tropical waters and may be toxic to various organisms in the aquatic ecosystems (Cempel and Nikel 2006).

Microalgae, the primary producer with ecological significance in tropical freshwater, are highly or moderately sensitive to Ni. Nickel is an 'ultra-micronutrient' essential to photosynthetic organisms, particularly as a cofactor for nickel-dependent enzymes such as urease, hydrogenase, and

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✉ Phaik-Eem Lim
phaikeem@um.edu.my

[1] Institute of Ocean and Earth Sciences, University of Malaya, Kuala Lumpur, Malaysia

[2] Institute for Advanced Studies, University of Malaya, Kuala Lumpur, Malaysia

[3] Institute of Biological Sciences, Faculty of Science, University of Malaya, Kuala Lumpur, Malaysia

[4] School of Food Sciences and Engineering, South China University of Technology, Guangzhou, China

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