Phycoremediation Potential of Synechococcus Sp. through Heavy Metal Uptake Analysis

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ABSTRACT

Heavy metal pollution poses a severe threat to aquatic ecosystems, necessitating sustainable and effective remediation solutions. This study investigates the phycoremediation potential of *Synechococcus* sp. by examining its ability to absorb cadmium (Cd), copper (Cu), and chromium (Cr) from contaminated water. Results showed distinct, metal-specific uptake trends, particularly for Cu and Cr, with bioconcentration factor (BCF) values exceeding 1, indicating effective bioaccumulation. Initial uptake was high but decreased over time, suggesting physiological saturation or detoxification. These findings highlight *Synechococcus* sp. as a promising candidate for long-term, nature-based heavy metal remediation and water quality enhancement.

Keywords: Phycoremediation, Heavy metal uptake, Bioconcentration factor (BCF), Blue-green algae.

INTRODUCTION

The rapid pace of industrialization and urbanization has led to increased contamination of aquatic environments with heavy metals such as cadmium (Cd), copper (Cu), and chromium (Cr). These metals pose serious risks to aquatic ecosystems and human health due to their toxicity, persistence, and tendency to bioaccumulate. In addressing this challenge, phycoremediation—a subset of bioremediation that utilizes algae to remove or neutralize pollutants—has emerged as a sustainable and effective approach for mitigating heavy metal pollution in water bodies. Among the microalgae and cyanobacteria studied for this purpose, *Synechococcus* sp., a unicellular cyanobacterium, has shown considerable potential for heavy metal uptake and tolerance. This species exhibits distinctive physiological and biochemical adaptations that enable survival under metal-induced stress, including the activation of complex signalling pathways and regulation of gene expression [1]. These mechanisms enhance its ability to absorb and accumulate metal ions from aqueous environments efficiently.

Recent studies have demonstrated the applicability of microalgal phycoremediation systems in diverse contexts, such as the treatment of acid rock drainage and nutrient recovery from aquaculture wastewater [2, 3]. In addition to detoxifying water, *Synechococcus* sp. contributes to environmental sustainability through photosynthetic carbon dioxide fixation and oxygen production, thereby improving both air and water quality. Moreover, the resulting biomass has added value and can be converted into biofuels, fertilizers, or animal feed, supporting the principles of a circular bioeconomy [4].

The success of phycoremediation depends on several factors, including environmental conditions, reactor configuration, and species selection. This study focuses on evaluating the heavy metal uptake potential of *Synechococcus* sp. from synthetic aqueous solutions containing Cd, Cu, and Cr at varying concentrations. Using bioconcentration factor (BCF) analysis after acid digestion, this research aims to quantify the species' capacity for metal absorption, thereby contributing to the broader implementation of microalgae in environmental remediation and sustainable resource recovery.

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MATERIALS AND METHODS

A. Algae Stock Preparation

The selected algae species, *Synechococcus* sp., were cultured in 250 mL flasks for 14 days under controlled laboratory conditions to ensure optimal growth. The cultures were maintained at a light intensity of 1800 lux and a constant temperature of 24 ± 1°C. Manual agitation was performed three times daily to promote homogenous distribution. The pH of the culture medium was adjusted and maintained at 6.8 using either potassium hydroxide (KOH) or hydrochloric acid (HCl), as described in standard culturing protocols [5]. These optimized stock cultures were used for subsequent heavy metal biosorption experiments.

B. Preparation of Heavy Metal Stock Solutions

Cadmium chloride ($CdCl_2$), copper sulfate ($CuSO_4$), and chromium chloride ($CrCl_2$) were used as sources of cadmium (Cd), copper (Cu), and chromium (Cr), respectively. Stock solutions of 1000 mg/L for each metal were prepared by dissolving the appropriate amount of salt in 1000 mL of distilled water. From these stocks, working solutions at concentrations of 1 mg/L, 2 mg/L, and 3 mg/L were prepared and used in the exposure trials for the biosorption study.

C. Acid Digestion Procedure

To quantify the heavy metal content accumulated by the algae, samples were harvested after 1, 2, and 3 weeks of exposure. Microalgal cells were collected by centrifugation at 8000 rpm for 3 minutes. A total of 0.4 g of wet biomass from each sample was transferred into perfluoroalkoxy polymer (PFA) containers and then placed into polytetrafluoroethylene (TFM) digestion tubes. Acid digestion was performed using a Microwave Digestion Ethos EZ system, following the U.S. EPA 3015 protocol. Each sample was treated with 5 mL of 65% nitric acid (HNO_3) and sealed using a torque wrench. The vessels were subjected to controlled digestion conditions, then cooled for 30 minutes. The digested samples were transferred into 15 mL centrifuge tubes for analysis, with three replicates prepared per sample.

D. Heavy Metal Quantification via UV-Vis Spectrophotometry

The concentrations of Cd, Cu, and Cr in the digested samples were measured using a Mettler Toledo UV-Vis spectrophotometer. Calibration was performed using blank cuvettes containing the sample solvent. After blanking, each cuvette was rinsed with the respective sample solution and filled to approximately three-quarters of its volume. Absorbance readings were taken at metal-specific wavelengths, and background absorbance was subtracted from the final values. All measurements were performed in triplicate to ensure accuracy and reproducibility.

E. Bioconcentration Factor (BCF) Calculation

The efficiency of metal uptake by *Synechococcus* sp. was assessed using the bioconcentration factor (BCF), calculated as follows:

$$BCF = \text{Heavy metal concentration in algae (mg/kg)} / \text{Initial heavy metal concentration in water (mg/L)}$$

The BCF provides a quantitative measure of the microalgae’s capacity to sequester heavy metals from the aqueous phase. This ratio reflects the balance between uptake and elimination, serving as a key indicator of phycoremediation potential [2].

RESULT

The bioaccumulation performance of *Synechococcus* sp. was evaluated through the Bioconcentration Factor (BCF) over a three-week exposure to cadmium (Cd), copper (Cu), and chromium (Cr) at varying concentrations. A BCF value greater than 1 indicates effective uptake and sequestration of heavy metals by the microalgae. Figure 1 illustrates the concentrations of each metal in the algae after 1, 2, and 3 weeks of exposure across three

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different initial concentrations.

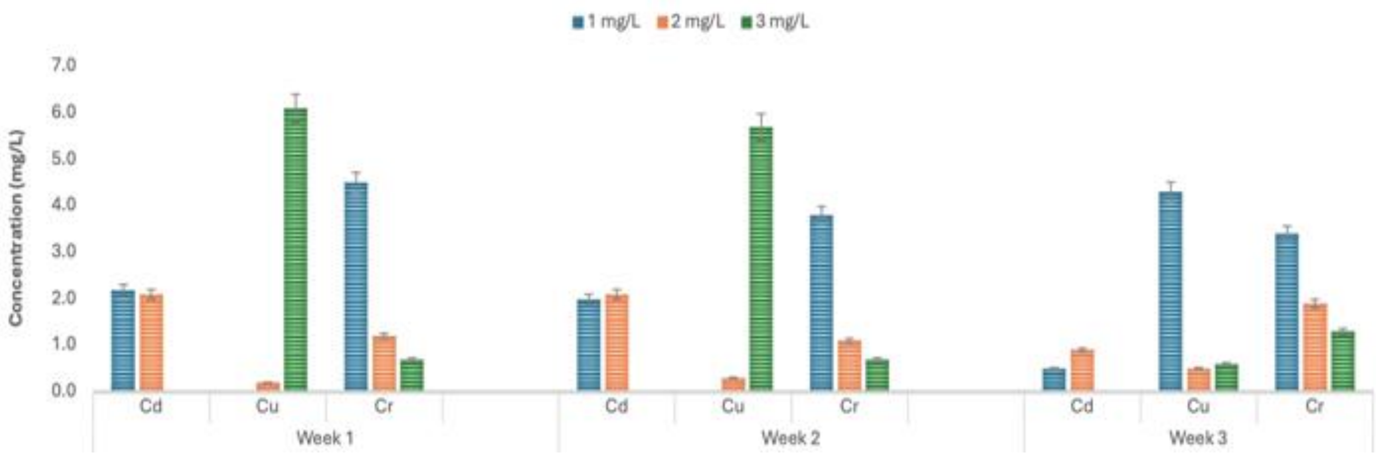

Fig. 1 Algae exposure in three different concentrations over three weeks.

A. Cadmium (Cd) Bioaccumulation

At an initial concentration of 1 mg/L, the BCF for Cd began at 2.2 in Week 1, decreased slightly to 2.0 in Week 2, and dropped to 0.5 in Week 3. A similar trend was observed at 2 mg/L, where the BCF remained stable at 2.1 for the first two weeks before declining to 0.9 in Week 3. These results indicate an initially efficient uptake of Cd by *Synechococcus* sp., followed by a notable reduction over time. This decline may be attributed to physiological saturation or the activation of detoxification mechanisms within the cells.

B. Copper (Cu) Bioaccumulation

The highest BCF values were recorded for copper, particularly at 3 mg/L, where the BCF reached 6.1 in Week 1, followed by a slight decrease to 5.7 in Week 2. This indicates a robust accumulation capacity even under higher metal stress. At a lower concentration of 1 mg/L, the BCF remained substantial at 4.3 by Week 3, demonstrating *Synechococcus'* consistent affinity for Cu. These findings identify copper as the most effectively accumulated heavy metal in this study.

At 1 mg/L, Cr bioaccumulation was moderate but stable, with BCF values decreasing from 4.5 in Week 1 to 3.8 in Week 2, and 3.4 in Week 3. However, at 2 mg/L, the BCF began at 1.2 in Week 1 but dropped below 1 in subsequent weeks, suggesting reduced sequestration efficiency at higher concentrations. This may be due to metal toxicity effects or a downregulation of uptake mechanisms.

Overall, *Synechococcus* sp. demonstrated a strong potential to bioaccumulate heavy metals, with the highest efficiency observed for Cu, followed by Cd and Cr. The consistent decline in BCF values over time across all metals suggests physiological limitations or adaptive cellular responses that affect long-term uptake. These trends support the application of *Synechococcus* in short-term bioremediation, particularly in environments contaminated with copper and cadmium.

DISCUSSION

The observed Bio-Concentration Factor (BCF) values exceeding 1 in most treatments confirm the effective metal uptake and sequestration capacity of *Synechococcus* sp., reinforcing its potential as a biological agent for phycoremediation. These results align with previous findings [7], which reported significant heavy metal removal by *Synechococcus* using Inductively Coupled Plasma (ICP) analysis, highlighting the species' applicability in wastewater treatment. Among the three tested metals, copper (Cu) exhibited the highest BCF values—peaking at 6.1 in Week 1 at a concentration of 3 mg/L—followed by a gradual decline. This suggests a strong, sustained affinity for Cu, even under elevated concentrations. In contrast, cadmium (Cd) and chromium (Cr) showed a marked decline in BCF over time, especially by Week 3. For Cd, this reduction may result from physiological saturation or the activation of detoxification pathways that inhibit further accumulation.

Similarly, the decreased Cr uptake at higher concentrations may reflect toxic effects or the suppression of uptake mechanisms. The bioaccumulation in *Synechococcus* is driven by both passive and active processes. Passive adsorption occurs on the cell wall surface, while active transport enables intracellular accumulation. These pathways are supported by metal-binding proteins and cellular components that facilitate tolerance and sequestration [8,9]. This dual mechanism enhances adaptability in varying environmental conditions. Abiotic factors such as pH, temperature, and nutrient availability also influence metal uptake efficiency. Optimizing these parameters could significantly enhance BCF values, making phycoremediation more effective. The physiological flexibility of *Synechococcus* under different environmental stresses supports its suitability for large-scale ecological restoration and industrial wastewater treatment, particularly in scenarios involving copper and cadmium contamination.

CONCLUSIONS

Synechococcus demonstrates strong potential as both a bioindicator and bioremediation agent for heavy metal contamination in aquatic environments. With Bio-Concentration Factor (BCF) values exceeding 1, the species effectively accumulated cadmium (Cd), copper (Cu), and chromium (Cr), particularly during the initial stages of exposure. Notably, copper exhibited the highest uptake, indicating a selective affinity and tolerance mechanism that positions *Synechococcus* as particularly effective for Cu removal. However, the observed decline in BCF values over time suggests that metal uptake may be limited by cellular saturation or the activation of adaptive detoxification responses. These trends underscore the dynamic interplay between environmental stressors and microbial physiology, highlighting the species' adaptive strategies under prolonged heavy metal exposure.

The efficient sequestration of metals by *Synechococcus*, especially at lower concentrations, supports its role in sustainable, nature-based solutions for pollution control. As a low-cost and eco-friendly organism, *Synechococcus* holds significant promise for integration into wastewater treatment systems aimed at reducing toxic metal loads while preserving ecological balance. These findings reinforce the broader applicability of microalgae in environmental management and offer valuable insights into their role in advancing Sustainable Development Goals (SDGs), particularly those related to clean water, pollution mitigation, and ecosystem health. Further investigations under real-world conditions are recommended to validate and scale these results for practical implementation.

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