








Enhanced removal of copper (Cu^{2+}) by microalgae-bacteria consortium: Mechanistic insights, physiological responses, and artificial neural network (ANN)-based prediction


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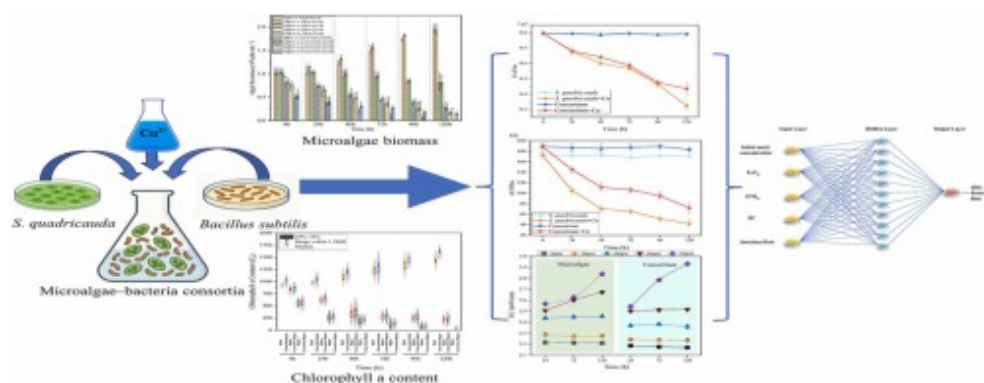
HIGHLIGHTS

- *Scenedesmus quadricauda* exhibited Cu^{2+} -induced physiological inhibition in a concentration- and time-dependent manner.
- Microalgae–bacteria consortium significantly enhanced Cu^{2+} removal and mitigated oxidative stress in algal cells.
- Co-cultivation preserved chlorophyll content and photosynthetic performance under heavy metal stress.
- Artificial neural network (ANN) models accurately predicted Cu^{2+} removal efficiency ($R^2 = 0.99$).

Abstract

Copper (Cu) is a typical heavy metal pollutant that poses serious threats to aquatic ecosystems by damaging algal physiology and inducing oxidative stress. To mitigate its negative effects, this study explored more effective bioremediation strategies using the green alga *Scenedesmus quadricauda* and its consortium with *Bacillus subtilis*, and to utilize the empirical data for predictive assessment of treatment outcomes. Physiological and biochemical analyses revealed that Cu exposure (20-80 ppm) significantly inhibited algal biomass, chlorophyll *a* content and photosystem II (PSII) efficiency (Fv/Fm, Y(II), α , rETRmax) and induced oxidative damage as indicated by increased malondialdehyde (MDA) levels. The activities of antioxidant enzymes (SOD and POD) increased first and then decreased after long-term exposure to high Cu. In contrast, co-cultivation with bacteria alleviated these effects, maintained high chlorophyll levels, PSII stability and enzyme defense, and achieved greater biomass retention at 40 to 80 ppm Cu. In the 80ppm treatment, copper removal was also improved in the consortium group (84.8%) compared with the microalgae group (74.6%). The artificial neural network (ANN) model showed strong predictive performance ($R^2=0.99$), accurately simulating copper removal across processing stages. These findings provide an innovative integrated framework combining physiological metrics and machine learning to understand and optimize microbe-based metal detoxification for sustainable aquatic ecosystem management.

Graphical abstract



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