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Assessing the Impact of Heavy Metals on *Arthrospira platensis*: Growth Dynamics, Pigment Composition and Detoxifying Enzyme Activities

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Abstract

This study evaluates the impact of copper (Cu) stress on cell biomass, pigment profiles, and the oxidative response of *Arthrospira platensis* following a 96-hour exposure. Exponentially growing *A. platensis* cultures were subjected to Cu concentrations of 0, 0.6, 1.2, 1.8, and 2.4 µg/mL in Zarrouk medium. Increasing Cu concentrations resulted in a progressive, dose-dependent reduction in biomass, photosynthetic pigments, carbohydrate, and protein contents. Notably, superoxide radical (SOR) and malondialdehyde (MDA) levels showed no significant increase at the lowest Cu concentration (0.6 µg/mL), but exhibited marked elevation at higher concentrations, underscoring the onset of oxidative stress. In response, heightened activity of antioxidant enzymes, including superoxide dismutase (SOD) and peroxidase (POD), as well as increased proline accumulation, was observed, indicating activation of the organism's antioxidative defense mechanisms. These results provide valuable facts for elucidating the physiological adaptations of *A. platensis* under copper exposure, and highlight its suitability for environmental pollutant monitoring and toxicity risk assessment

Keywords: Arthrospira platensis, oxidative stress, Growth, Pigment content, antioxidant activity, Biochemical constituents

Introduction

Heavy metals released from urban and industrial sources contaminate natural waters, posing serious risks to both aquatic and terrestrial ecosystems, as well as human health, even at low levels (Olladimeji et al, 2024). Heavy metals, such as mercury, chromium, cadmium, lead, copper, and nickel, have interfered with photosynthesis and enzyme activity in algae, leading to stunted growth and cell death (Mehri A., 2020). Some Heavy metals are harmful to living things only when they exceed a definite threshold (Dahbi et al., 2022). Copper is considered an essential micronutrient for living organisms, facilitating growth by serving as a catalytic component in enzymes such as plastocyanin and cytochrome oxidase, which are necessary for electron transport (Tiffany et al., 2021; Budi et al., 2020). However, at high concentrations, it becomes toxic, causing oxidative stress, growth reduction, and deteriorated levels of key metabolites, which may lead to cell death (Romano et al., 2022; Mohy El-Din, 2017).

Cyanobacteria are widespread prokaryotic microorganisms that perform photosynthetic processes, recognized for their remarkable resilience to diverse environmental stresses (Faruque et al., 2024; Allaf and Peerhosaini, 2022). Moreover, despite the exposure of several harmful effects that cause oxidative damage at the cellular and biochemical levels, cyanobacteria employ a sophisticated antioxidant defense system to restore redox

balance and sustain cellular survival under stressful conditions (Hazeem, L. 2022). Among cyanobacteria, *Arthrospira platensis* (*A. platensis*) is one of the most widely studied species, primarily because of its remarkable nutritional and biochemical profile. It is especially recognized for its rich, high-quality protein content, making it suitable for both human and animal consumption. (Sotiroudist et al, 2012). In addition to its nutritional significance, *A. platensis* exhibits strong adaptability to alkaline, nutrient-rich environments and possesses remarkable metal-sorption capacities (Murli et al, 2014). These attributes make it an effective agent for bioremediation, capable of mitigating heavy metal and pollutant contamination in wastewater (Cretescu et al, 2023; Nawaz et al., 2023). Consequently, *A. platensis* has achieved global relevance as a sustainable and multifunctional organism with wide-ranging applications in nutrition, biotechnology, and environmental management.

Various physiological parameters were assessed, including growth, pigments, protein, carbohydrates, oxidative stress markers (SOR), lipid peroxidation (MDA), antioxidant enzymes (SOD, POD), and non-enzymatic antioxidants (proline) to evaluate oxidative stress and antioxidant responses in *A. platensis*. The goal is to enhance our understanding of how copper affects the physiology and adaptation of *A. platensis*, thereby exploring novel perspectives in the research field**.**

Materials and Methods

Organism and culture conditions

Arthrospira platensis, a multicellular blue-green microalga, was obtained from the National Repository for microalgae and cyanobacteria -freshwater (NRMC-F) Bharathidasan University, Tiruchirappalli, India. The axenic and homogenous cultures of *A. platensis* were kept in Zarrouk's medium, pH 7.8 (Zarrouk, 1966), in a thermostatically-controlled culture growth chamber at 25±2 ◦C within the range of photosynthetically active radiation (PAR, 400–700 nm), constant light intensity of 75 µmol photon $m^{-2}s^{-1}$ and 50% relative humidity with a 16:8 h of light: dark cycle. Every experiment was carried out in triplicate using cells in the early exponential phase (optical density (0.11) measured at 750 nm absorbance).

Mode of copper treatment and growth inhibition test

For the present study, a heavy metal, i.e., Copper (Cu), was added as CuCl (MW = 99.00 g/mol; purity = 99%; Sigma Aldrich) to the culture. Initially, range-finding screening experiments were used to identify the dose range to understand the survival behaviour of cyanobacteria against Cu. After this exponentially grown, cultures were exposed to selected doses of Cu, i.e. 0.6, 1.2, 1.8, and 2.4 µg/mL in Zarrouk medium. A control set, consisting of cultures grown without the addition of Cu treatment, was included in the same experimental settings to establish a baseline for comparison. All the cells were maintained in 150 mL conical flasks under PAR range in a culture growth chamber at 25 ± 2°C for 96 h to assess the impact of Cu exposure on different physiological and biochemical parameters of *A. platensis*.

Morphological Analysis

Determination of *A. platensis* Growth (biomass)

Growth was measured by optical density and dry cell mass (DCW) after 96 hours of experiment of *A. platensis* cells. The absorbance of a well-mixed culture sample is measured at 750 nm using a UV-VIS spectrophotometer (Evolution 201, Thermo Scientific). For the estimation of growth biomass (dry cell mass), all the samples were centrifuged (4000g for 10 min) and oven dried at 90 ^{0}C for 24h to remove all the moisture. Finally, an electronic balance (Metler Toledo ME204, India) was used to determine the sample's dry weight.

Estimation of Chlorophyll a, Carotenoid, and Phycobiliproteins

To analyse the content of photosynthetic pigments, i.e. chlorophyll a (Chl a), carotenoids (Car) and Phycobiliproteins in *A. platensis*, pigment extraction methods were employed. During the early exponential phase, a five-millilitre culture was taken and centrifuged at 10000×g for ten minutes (Eppendorf, Centrifuge 5920). Following the discarding of the supernatant, the pellets were suspended in 100% methanol, thoroughly mixed, and left overnight at 4 °C to extract the pigment. Subsequently, each sample was centrifuged at 5000×g for 10 minutes. To determine chlorophyll a and carotenoids, optical density was measured using a UV-VIS

spectrophotometer (Evolution 201, Thermo Scientific) at 665 and 450 nm (Porra et al., 1989 and Goodwin, 1954), respectively. In order to assess phycobiliproteins, the Bennett and Bogorad (1973) method was used; cell pellets were treated with one or two drops of toluene, left overnight, and extracted in phosphate buffer (pH 7.0). Moreover, by following multiple freeze-thaw cycles, the phycobiliprotein contents, i.e. allophycocyanin (APC), phycocyanin (PC), and phycoerythrin (PE), were measured spectrophotometrically by the absorbance of the supernatant at 652, 615, and 562 nm, respectively.

Determination of Oxidative Stress Biomarkers: Superoxide radical, and Malondialdehyde

The method of Elstner and Heupal (1976) was used to quantify the amount of superoxide radical (SOR; $O_2^{\bullet-}$). A standard curve was prepared with the prime solutions of $NaNO_2^-$ and H_2O_2 to estimate the accumulation of Oxide radicals. Similarly, using Packer and Heath's technique (1968), degradation of lipids was measured as lipid peroxidation in terms of malondialdehyde (MDA) equivalent in both control and treated samples. An extinction coefficient of 155 mM^{-1} cm^{-1} was used to determine the MDA concentration.

Determination of the Antioxidant Defense System

To assess the antioxidant defense response, both treated and untreated samples were centrifuged at 5,000×g for 10 minutes, and the obtained cell pellets were used to estimate each of the enzymatic and non-enzymatic activities.

Enzymatic antioxidants

Superoxide dismutase (SOD) and peroxidase (POD) activity were measured using the Giannopolitis and Ries (1977) and Gahagan et al. (1968) methods, respectively. The amount of enzyme needed to accomplish 50% inhibition of NBT (nitro blue tetrazolium) reduction under the specified experimental conditions was defined as one unit of superoxide dismutase (SOD) activity. The NBT photoreduction, leading to the production of purple formazone, was monitored through a spectrophotometer at 560 nm and compared to the control. Similarly, POD activity was calculated by using an extinction value of 25.5 mM^{-1} cm^{-1}. The increase in absorbance resulting from pyrogallol oxidation was assessed at 430 nm for two minutes. The amount of enzyme required to catalyze the oxidation of one nmol of pyrogallol per minute was defined as one unit of enzyme activity.

Non-enzymatic antioxidants

The amount of Proline (Pro), termed as non-enzymatic antioxidant activity, was quantified by measuring the absorbance of the chromophores containing the layer of the reaction mixture at 520 nm, according to the method of Bates et al. (1973). The quantity of formed proline was determined with the support of their standard curve.

Measurement of biochemical constituents (Carbohydrates and Proteins)

To assess the carbohydrate content in *A. platensis*, the Anthrone method was employed (Dubois et al., 1956), with main glucose as the standard for calibration. A 40 mL sample was hydrolyzed in a hot water bath for 2 h by adding 5 mL of 2.5N HCl. After cooling at room temperature, the solution was inactivated with Na_2CO_3 until effervescence ended. Further, it was diluted with 100 mL of distilled water and then centrifuged. For the assay, 4 mL of Anthrone reagent was mixed with 1 mL of the supernatant and heated in a boiling water bath for 8 minutes. Once cooled, the optical density was measured at 630 nm. To calculate the protein content in the biomass of each sample, the bovine serum albumin standard method was utilised (Lowry et al.,1951).

Statistical analysis

Statistical analysis was done by using SPSS software (ver. 16.0, Chicago, USA), employing one-way analysis of variance (ANOVA) followed by the Post Hoc test. The data displayed consist of means ± standard errors of three independent replicates.

Results and Discussion

Growth responses of *A. platensis* exposed to copper stress

The exposure of Cu had a significant and dose-dependent inhibitory effect on the growth of *A. platensis*. To assess the biomass of *A. platensis*, the dry cell weight (DCW) was utilised as a quantitative measure, which is a reliable indicator of cellular mass. At low levels, copper seemed to promote growth in the first two days, possibly because the algae need it for metabolism or because they formed substances that reduce metal toxicity. However, after 96 hours of exposure, the growth measurement in terms of dry weight was notably reduced by 7, 32, 50 and 56% in response to 0.6, 1.2, 1.8, and 2.4 µg/mL treatments, respectively, compared to the untreated control (Fig. 1A). The least decline was observed at 0.6 µg/ml, which suggests negligible stress. However, at higher doses (between 1.2, 1.8, and 2.4 µg/ml), the growth curve exhibited a dramatic decline ($P < 0.05$), indicating a significant level of physiological stress (Fig. 1B).

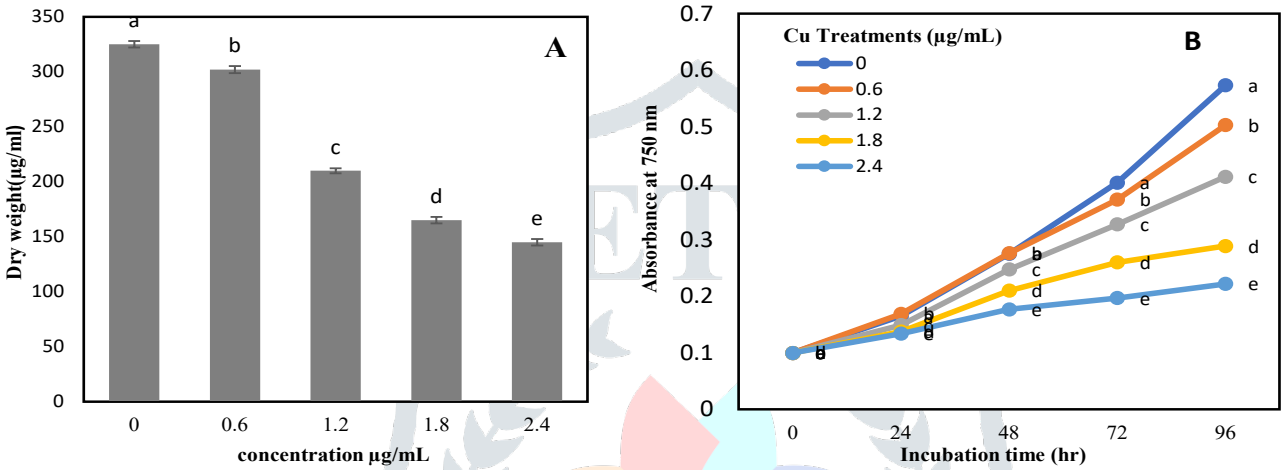

Fig. 1 Impact of different Cu concentrations on growth biomass (A) and dose-dependent curve (B) of *A. platensis* after 96 h of incubation. Data are mean ± standard error of three independent experiments. Bars followed by different letters show a significant difference (P<0.05) among treatments.

Photosynthetic Pigment Analysis

Chlorophyll a and phycocyanin serve as the primary light-harvesting pigments in cyanobacteria. The marked reduction in pigment levels indicates that copper exposure impairs the photosynthetic system of *A. platensis*. After 96 hours of treatment, copper at the tested concentrations caused a decline in chlorophyll a content by 9%, 38%, 60%, and 69%, respectively. In cyanobacteria, PBPs (phycobiliproteins) comprise three major pigments: phycocyanin (PC), allophycocyanin (APC), and phycoerythrin (PE). Amongst the three pigments of Phycobiliproteins, PC content is more prone to damage and shows a greater reduction under the tested doses, as it exhibits reductions of 11, 14, 37, and 40% in *A. platensis*. A similar trend was also recorded for Carotenoid, APC and PE content, which was found to decrease in a dose-dependent manner (Fig. 2).

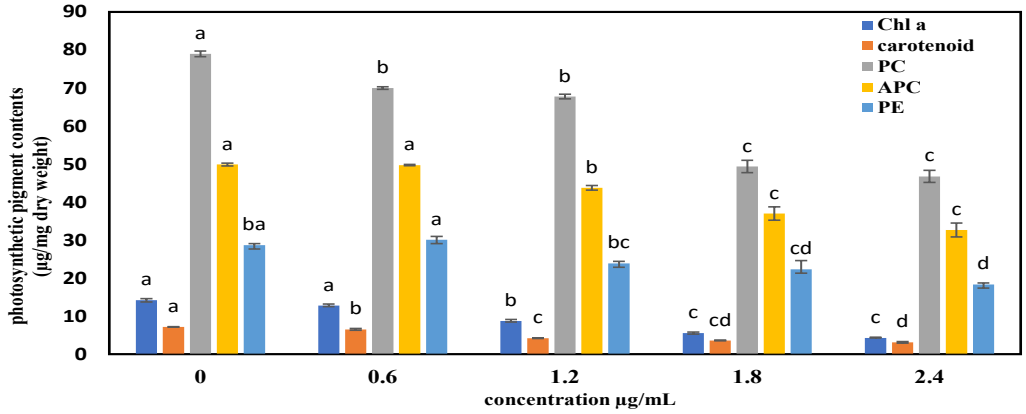

Fig. 2 Impact of different Cu concentrations on chlorophyll *a* (Chl a), carotenoids and phycobiliproteins (PC, APC and PE) contents of *A. platensis* after 96 h of incubation. Data are mean ± standard error of three independent experiments. Bars followed by different letters show a significant difference (P<0.05) among treatments.

Oxidative damage

The results illustrate the significant (P<0.05) impact of Cu on the induction of oxidative stress biomarkers (SOR and MDA) in *A. platensis* (Fig. 3A and 3B). The amount of $O_2^{\bullet-}$ radicals and MDA in *A. platensis* was not significantly affected by lower concentration treatments when compared to the control. However, it was found to rise in a dose-dependent manner at higher doses, approximately 24%, 48%, 62%, and 158%, respectively, compared to control samples. MDA (Malondialdehyde) equivalents, a byproduct of lipid peroxidation, were used to quantify lipid peroxidation, which indicates oxidative damage in cyanobacteria. The results showed that Cu enhanced the MDA equivalents content by 10, 37, 67, and 55%, compared to the control values. The induction of $O_2^{\bullet-}$ and MDA equivalents contents in *A. platensis* in response to Cu exposure indicates the detrimental effects on cellular health and oxidative status.

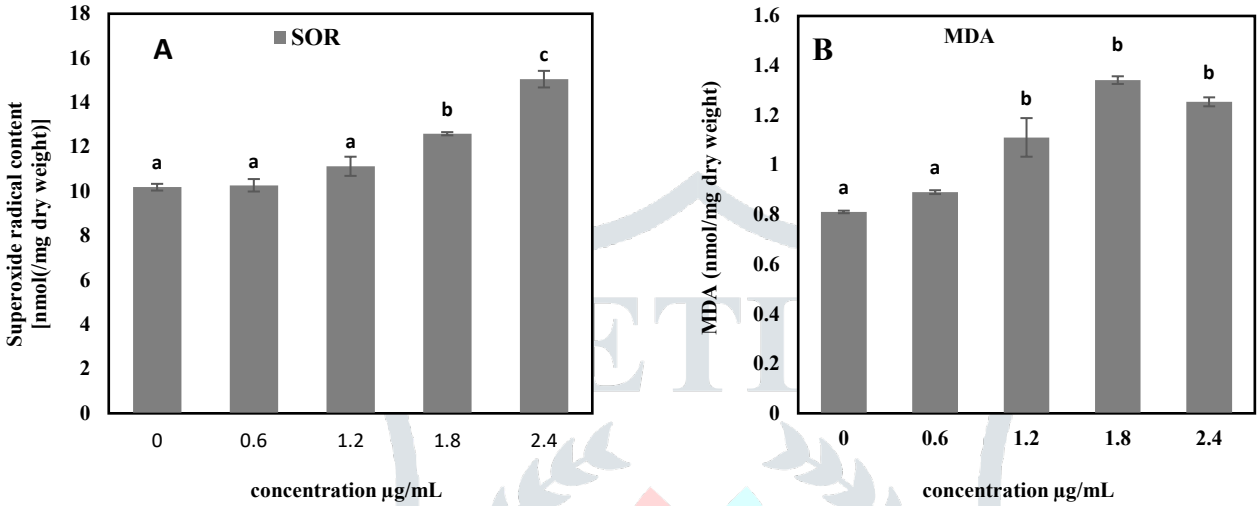

Fig. 3 Impact of different Cu concentrations on superoxide radical (SOR; A) and MDA equivalents (MDA; B) level of *A. platensis* after 96 h of incubation. Data are mean ± standard error of three independent experiments. Bars followed by different letters show a significant difference (P<0.05) among treatments.

Enzymatic Antioxidant Activities

Enzymatic antioxidant activities, such as SOD (Superoxide dismutase) and POD (peroxidase), were often analysed to measure the effect of oxidative stress caused by Cu in *A. platensis.* The SOD and POD activity in the tested cyanobacteria under Cu exposure has been depicted in Fig. 4A and 4 B. Our result points out that at lower concentrations (0.6 µg/ml) of Cu, enzymatic activities are very low; however, as the concentration increases, SOD and POD activity was enhanced (P<0.05) by 18, 19, 30% and 14, 167, 172% respectively, in *A. platensis*, over the control values. These enzyme activities act as indicators of the antioxidant defense and detoxification capacities of *A. platensis* under copper stress.

Non-enzymatic antioxidant activity (Proline)

The increase in proline accumulation under stress conditions represents an adaptive response that functions either by detoxifying reactive oxygen species (ROS) through metal chelation or by acting as a non-enzymatic antioxidant. Proline, an α-amino acid, has a well-established role in stress physiology. Proline content showed a slight increase of 18.2% and 32% at low doses of Cu in *A. platensis*, which was significantly (P < 0.05) decreased by 27% and 25% after 96 h of treatment at high doses (Fig. 4C).

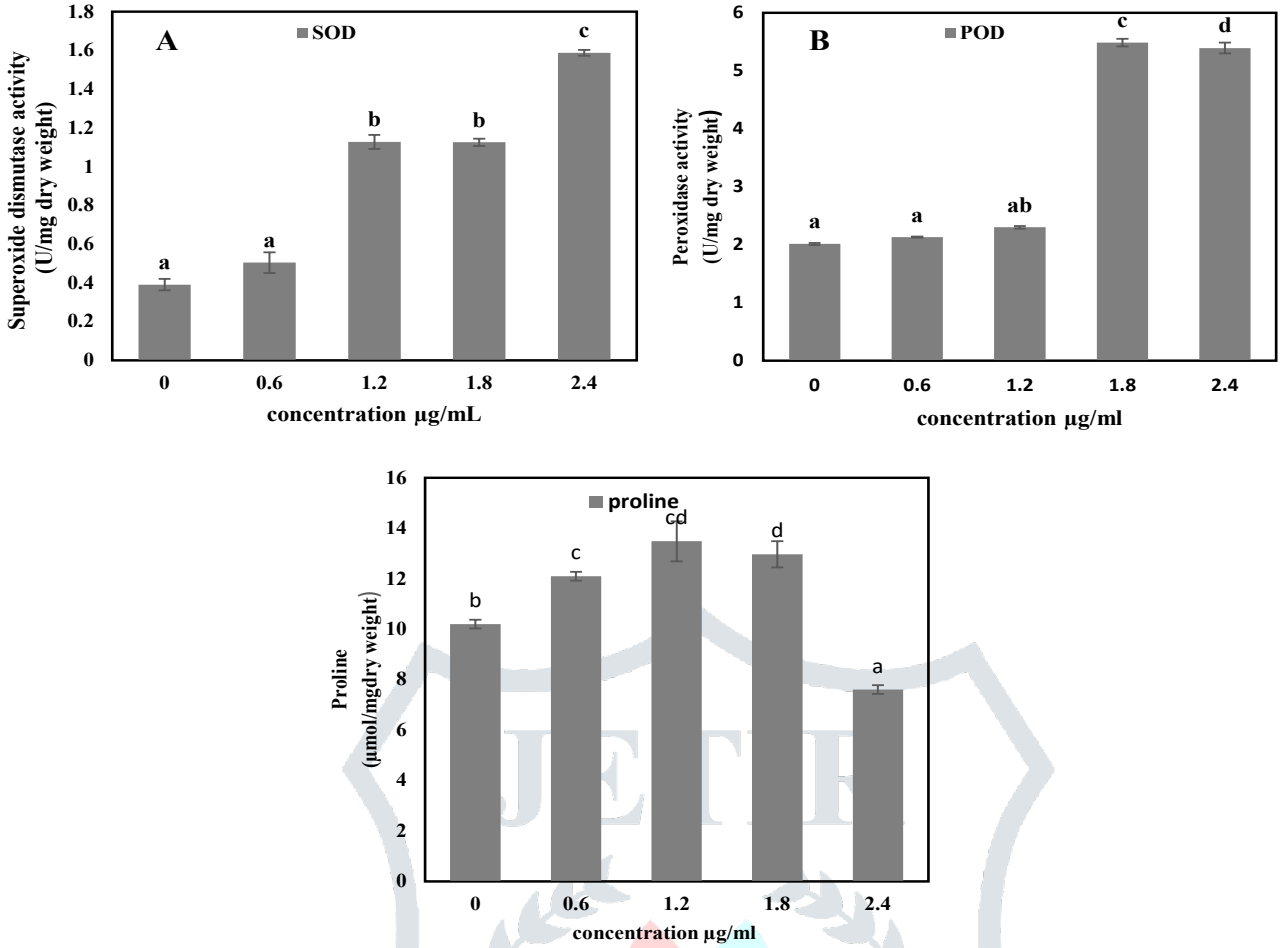

Fig. 4 Impact of different Cu concentrations on SOD (A), POD (B) and Proline (C) contents of *A. platensis* after 96 h of incubation. Data are mean ± standard error of three independent experiments. Bars followed by different letters show a significant difference (P<0.05) among treatments.

Effect on primary biomolecule (Carbohydrate and protein)

The results showed a slight increase in carbohydrate and protein contents in *A. platensis* by 8% and 0.5%, respectively, at the lowest copper concentration after 96 hours of exposure compared to the control. However, at higher copper doses, both carbohydrate and protein levels significantly ($p < 0.05$) decreased by 18%, 30%, and 31%, and by 25%, 32%, and 48%, respectively, relative to the control (Fig. 5A and 5B). This decline in macromolecular content underscores the toxic impact of copper on *A. platensis*, as carbohydrates and proteins are essential for fundamental cellular processes, including growth and cell division.

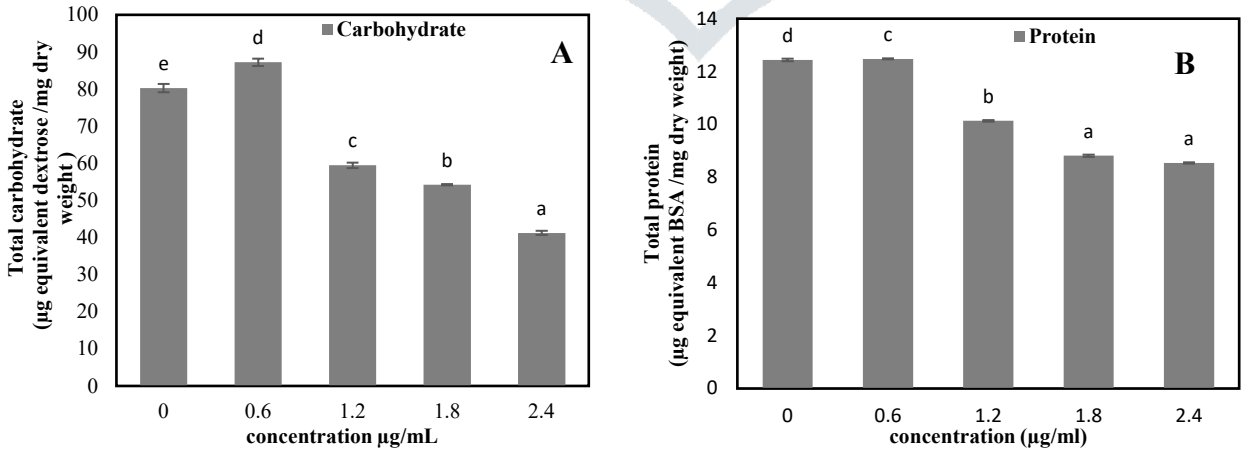

Fig. 5 Impact of different Cu concentrations on Carbohydrate (A) and protein (B) content of *A. platensis* after 96 h of incubation. Data are mean ± standard error of three independent experiments. Bars followed by different letters show a significant difference (P<0.05) among treatments.

Table 1. Impact of Cu stress on photosynthetic pigment contents, oxidative damage, antioxidant activity, and biochemical components of *A. platensis* after 96 h exposure.

Concentration (µg ml^{-1})	Photosynthetic pigment contents (µg mg^{-1} Dry weight)					Oxidative damage (nmol mg^{-1} Dry weight)		Antioxidant activity (nmol mg^{-1} Dry weight)			Biochemical components (µg mg^{-1} Dry weight)	
	Chlorophyll a (Chl a)	Carotenoid (Car)	Phycocyanin (PC)	Allophycocyanin (APC)	Phycoerythrin (PE)	Superoxide radical (SOR)	Malondialdehyde (MDA)	Superoxide dismutase (SOD)	Peroxidase (POD)	Proline	Carbohydrate	protein
0	14.20 ±0.43	07.21 ±0.05	78.96 ±0.74	49.90 ±0.03	28.71 ±0.37	10.12± 0.14	0.81±0.00	0.39±0.02	2.01±0.01	10.20± 0.17	80.27 ±1.10	12.44± 0.05
0.6	12.81 ±0.28	06.55 ±0.21	70.01 ±0.34	49.74 ±0.17	30.11 ±0.58	10.26± 0.28	0.89±0.00	0.50±0.05	2.12±0.01	12.10± 0.17	87.23 ±0.90	12.48± 0.01
1.2	08.72 ±0.23	04.23 ±0.05	67.79 ±.58	43.77 ±0.58	23.90 ±0.55	11.10± 0.43	1.11±0.07	1.12±0.03	2.30±0.02	13.48± 0.72	59.50 ±0.71	10.13± 0.02
1.8	05.55 ±0.27	03.62 ±0.09	49.41 ±1.6	36.99 ±1.87	22.34 ±2.29	12.59± 0.07	1.34±0.01	1.12±0.02	5.48±0.06	12.91± 0.51	54.23 ±0.11	8.81±0.04
2.4	04.29 ±0.02	03.14 ±0.17	46.78 ±1.5	32.68 ±1.71	18.38 ±2.23	15.04± 0.37	1.25±0.01	1.58±0.01	5.39±0.09	7.60±0.17	41.27 ±0.51	8.54±0.020

Data are means±standard error (±SE) of three replicates (n=3).

Discussion

This study investigates the complex interaction between copper stress and the photosynthetic apparatus of *A. platensis*, elucidating the physiological alterations and adaptation behaviour brought on by heavy metal exposure. Under copper stress, *A. platensis* exhibits distinct patterns that define its toxicity margin and associated physiological changes. At a low copper concentration of 0.6 µg/mL, *A. platensis* exhibited an initial increase in growth during the first two days, followed by a gradual decline over the 96-hour exposure period. The calculated effective concentration (EC50) for copper after 96 hours was approximately 1.8 µg/ml, indicating the concentration at which growth inhibition becomes significant. These results align with findings of Kaamoush et al. (2022), who described that Cu^{2+} treatment at 1.0 mg/L enhanced culture growth by day two, whereas higher concentrations (2.5 mg/L) led to reduced growth and along decrease in biomass by day four. *A. platensis* to elevated copper concentrations for up to 96 hours resulted in a marked suppression of growth, with dry weight reductions ranging from 7% to 56% ($P < 0.05$) compared to the control (Fig. 1). These results nearly agree with the findings of many authors; Studies of Rudi et al (2024), Ali A. Al-Homaidan (2014) and Nalimova et al (2005) suggest a dose-dependent response of cyanobacterial growth to copper exposure, with stimulatory effects at lower concentrations and toxicity at elevated levels due to inhibition of metabolic activity. This pronounced inhibition corresponds to copper's well-documented toxic effects, primarily mediated through oxidative stress pathways (Zinicovscaia et al, 2022).

Copper stress exerts multifaceted impacts on the photosynthetic pigment composition of *A. platensis*, highlighting the intricate interplay between light-harvesting processes and photoprotective responses. Progressive reductions in pigment contents (Chl a, Car, and Phycobiliproteins) occur in a dose-dependent manner, corroborating previous observations in *Arthrospira* species by Kaamoush et al. (2022) and Mohy El. Din, Soad. (2017). Chloroplasts, which are especially vulnerable to oxidative stress, are among the earliest organelles to display structural and functional deterioration, resulting in substantial declines in chlorophyll a

content (9–69%, P <0.05) (Fig. 2), in agreement with findings by Gomaa et al. (2023). The pronounced toxicity of copper at elevated concentrations is likely attributable to its oxidative properties, which foster the generation of reactive oxygen species and consequent pigment degradation, findings consistent with those of Cepoi et al. (2020). Ultimately, such stress impairs photosynthetic efficiency and energy production, undermining cell physiology and survival, as also documented by Zinicovscaia et al. (2022).

The observed dose-dependent increase in SOR (oxidative stress-related parameter) values, approximately 24%, 48%, 62%, and 158% (P < 0.05) (Fig. 3A), compared to controls, indicates escalating cellular stress in *A. platensis* under higher copper doses. Similarly, the measured enhancement of malondialdehyde (MDA) equivalents by 10%, 37%, 67%, and 55% (P <0.05) (Fig. 3B) at rising copper concentrations highlights intensified lipid peroxidation, a marker of oxidative membrane damage (Table 1). These results are consistent with those of Cepoi et al. (2020); according to their findings, dose-dependent pro-oxidative effects and generation of reactive oxygen species may elucidate copper toxicity in the microalgae *A. platensis*. Elevated copper triggers oxidative damage, as evidenced by increased MDA levels and associated biochemical disruptions. The statistical support underscores the reliability of the observed trends.

The enzymatic defense activities in *A. platensis* significantly increase with rising copper concentrations, reflecting a robust antioxidant response to mitigate copper-induced oxidative stress. While SOD and POD activities are low at 0.6 µg/mL copper concentration, however rise substantially (up to 30% and 172%, respectively, P <0.05) (Fig. 4A and 4B) with increasing concentration, compared to controls. Many other investigations have shown results that are comparable to ours and suggest that heavy metals stimulate enzyme activity (SOD and POD) in *A. platensis* (Prasad et al, 2019; Tunca et al, 2020). This enhancement indicates activation of the microalga's defense system to eliminate reactive oxygen species and to safeguard cellular integrity and photosynthetic machinery under heavy metal stress by scavenging produced radicals (SOR) and H_2O_2 (Prasad et al, 2024). When *A. platensis* is exposed to low copper levels, a modest rise in proline (18.2% and 32%, P <0.05) is observed. This increase is a common stress response where proline functions as an osmo-protectant, stabilising proteins and membranes, and scavenging reactive oxygen species (ROS). After 96 hours at high copper doses, proline content decreases significantly (by 27% and 25%, $P < 0.05$) (Fig. 4C). The fluctuating proline dynamics reflect an adaptive cellular strategy: initial enhancement as a protective response at increasing stress, followed by depletion when stress becomes excessive and overwhelms *A. platensis'* defense capacity, resulting in cellular impairment. Rudi et al. (2024) and Zhou et al. (2022) report both an initial rise and subsequent fall in proline under increasing copper nanoparticle stress in *Arthrospira*, attributed to an exhaustion of the cells' adaptive mechanisms and altered osmolytes at higher doses.

Studies have shown that Carbohydrate levels and protein content of *A. platensis* are significantly reduced at higher copper concentrations. This reduction is primarily attributed to copper's ability to disrupt ribosomal activity, induce ROS, and cause oxidative damage to cellular machinery, impairing both transcriptional and translational processes. Mohy El Din et al. (2017) and Rudi et al. (2024) also demonstrated a sharp decline (P <0.05) (Fig. 5) in carbohydrate and protein with increasing copper concentration in *A. platensis*, confirming copper's potent toxicity. Many other studies have shown similar results to ours, which have an inhibitory impact on the carbohydrate and protein content of *A. platensis* on heavy metal exposure. (Cretscu et al., 2023; Nath et al., 2023; Prasad et al., 2019).

Conclusion

The present investigation concludes that *A. platensis* functions effectively as a bioindicator for assessing heavy metal stress. A key finding is that the elevated Cu levels impair its growth, biochemical components, and photosynthetic performance. These negative effects are mainly caused by the excessive production and accumulation of oxidative stress biomarkers (SOR, MDA equivalents), which reflect compromised cell membrane integrity and can lead to significant impairment of the physiological and functional efficiency of cyanobacterial cells. This damage was countered by heightened antioxidant detoxification activity. This research highlights the physiological, biochemical, and molecular adaptations of *A. platensis* under copper stress, providing valuable insights into its metal tolerance capacity. Given its nutritional and industrial importance, adopting sustainable and multidisciplinary approaches is essential for maintaining the production and utilisation of this resilient cyanobacterium in changing environmental conditions. Nevertheless, more research is desired to enlighten the molecular basis of metal toxicity and explore the synergistic interactions between cyanobacteria and heavy metals, to develop targeted strategies to reduce metal pollution.

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