Chittagong Univ. J. B. Sci. Vol. 13 (1&2): 86-92, 2025

Effects of cadmium, lead, zinc and copper on chlorophyll and protein content of rice (*Oryza sativa* L.)

Mazharul Islam* and Md. Golam Kibria

Department of Soil Science, University of Chittagong, Chattogram-4331, Bangladesh
*Corresponding author's email: rasenviro@cu.ac.bd

DOI: https://doi.org/10.3329/cujbs.v13i1.86250
Received: 16 October, 2025; Accepted: 3 November, 2025; Published: 15 December, 2025

Abstract
This study investigated the effects of cadmium (Cd), lead (Pb), zinc (Zn), and copper (Cu) on some biochemical constituents like chlorophyll, nitrogen and protein levels in rice. A pot experiment was conducted using agricultural loamy soil amended with graded concentrations of Cd, Pb, Zn, and Cu salts, with untreated soil serving as control. Rice leaf samples were collected after 45 days of transplantation in in-situ conditions and analyzed for chlorophyll content. Nitrogen and protein content in rice grains were determined after harvest at ripening. Results revealed significant ($p<0.05$) reductions in chlorophyll a, chlorophyll b, and total chlorophyll across all treatments, with Cd exerting the most severe inhibitory effect, followed by Pb, Cu, and Zn. Similarly, nitrogen and protein contents declined under metal exposure, with Cd and Pb causing the greatest reductions, while Zn and Cu showed comparatively moderate toxicity. These findings demonstrate that heavy metal stress disrupts pigment biosynthesis, nitrogen metabolism, and protein synthesis in rice, thereby compromising its physiological performance and nutritional quality.

Keywords: Heavy metal, crops, agroecosystem, nitrogen metabolism, protein synthesis and metal stress

Introduction

Heavy metal contamination in agricultural soils is an escalating concern, particularly in regions heavily reliant on industrial activities, urbanization, and agrochemical usage[1,2]. Among these metals, lead (Pb), cadmium (Cd), zinc (Zn), and copper (Cu) have emerged as significant pollutants, disrupting soil health and threatening crop productivity[3]. The toxic effects of these metals often manifest in plant physiological and biochemical processes, including chlorophyll synthesis and protein metabolism, which are critical for plant growth and yield[4].

Rice (*Oryza sativa* L.) is a staple food for over half of the world's population, is highly sensitive to environmental stressors, including heavy metal contaminated soils[5]. Chlorophyll, essential for photosynthesis, and protein content, critical for nutritional quality, are frequently impaired under metal stress[6,7]. Lead and cadmium, categorized as non-essential and highly toxic elements, are known to disrupt enzymatic activities and interfere with nutrient uptake. On the other hand, zinc and copper, although essential in trace amounts, become toxic at elevated concentrations, causing oxidative damage and protein denaturation in plants[8, 9].

Studies have highlighted the detrimental impact of lead and cadmium on chlorophyll synthesis, resulting in chlorosis and reduced photosynthetic efficiency. Cd is readily absorbed by rice plants, primarily through ion transporters like OsNRAMP5 and OsIRT1, disrupting root cell growth, photosynthesis, and enzyme activity while inducing reactive oxygen species (ROS) production and phytotoxicity[10]. Rice mitigates Cd stress via regional sequestration, chelation with phytochelatins, and antioxidative mechanisms[11,12]. Similarly, Pb toxicity impairs rice growth, reproductive development, and photosynthesis by disrupting ATP production, lipid peroxidation, and essential nutrient uptake, but rice deploys detoxification strategies such as Pb sequestration in vacuoles and activation of antioxidants[6]. For instance, Pb competes with essential cations such as calcium (Ca), magnesium (Mg), and potassium (K) for uptake by root cells, resulting in nutrient imbalances and physiological disorders. Pb was shown to replace Mg ions in chlorophyll molecules, directly affecting their stability and function[13]. Conversely, zinc and copper, while necessary for various enzymatic reactions and structural proteins, exhibit dual behavior. Excess zinc has been shown to hinder protein metabolism by disrupting nitrogen assimilation pathways[14]. Elevated copper levels lead to lipid peroxidation and protein degradation, exacerbating cellular damage in rice plants[15]. Cu stress affects root growth, photosynthesis, and nutrient absorption, with high Cu levels disrupting essential metal homeostasis and chloroplast ultrastructure, reducing yield and productivity[16]. Cu-induced oxidative stress also alters the TCA cycle, with significant down regulation of intermediates like citric and malic acids, severely impairing carbohydrate metabolism and rice growth[17].

Despite these findings, the synergistic or antagonistic interactions of these metals and their individual effects on rice remain largely unexplored. Furthermore, limited research has specifically examined how Pb, Cd, Zn, and Cu collectively influence chlorophyll and protein content in rice. These gaps hinder the development of comprehensive strategies for mitigating heavy metal toxicity in rice-based agroecosystems. The present study is to investigate the effects of lead, cadmium, zinc, and copper on chlorophyll, nitrogen and protein content in rice. Specifically, the main objectives are to:

(a) Assess the effect of individual metal exposures on chlorophyll a, chlorophyll b, and total chlorophyll content.

(b) Evaluate the effect of metals on the protein content of rice grains.

Materials and Methods

Experimental Design and Soil Preparation

Four separate controlled pot experiments with agricultural loamy soil, free from prior contamination was conducted at the Crop field of the Department of Soil Science, University of Chittagong, during mid-January 2022 to June 2022 to evaluate the effects of four heavy metals such as cadmium (Cd), lead (Pb), zinc (Zn), and copper (Cu) on the chlorophyll and protein content of rice (*Oryza sativa* L.). Soil was collected from the surface layer (0–15 cm), air-dried, and sieved through a 2 mm mesh. Physicochemical properties of the soil, including pH (5.32 gL^{-1}), electrical conductivity (128.1 μscm^{-1}), organic matter (1.41%), CEC (24.24 meq/100g), total nitrogen (0.5%), total phosphorus (0.07%), Cd (0.003 mg kg^{-1}), Pb (0.01 mg kg^{-1}), Zn (10 mg kg^{-1}) and Cu (6 mg kg^{-1}) respectively, were analyzed prior to treatment.

Five treatments consisted of a single heavy metal were added to the soil in the form of its respective salt that is cadmium as cadmium sulfate ($3CdSO_4 . 8H_2O$), lead as lead nitrate [$Pb(NO_3)_2$], zinc as zinc sulphate ($ZnSO_4 . 7H_2O$), and copper as copper sulphate ($CuSO_4 . 5H_2O$). Metal salts were thoroughly mixed with the soil to obtain Cd levels of 2, 4, 6, 8 and 10 mg kg^{-1} soil, Pb levels of 20, 40, 60, 80 and 100 mg kg^{-1} soil, Zn levels of 30, 60, 90, 120 and 150 mg kg^{-1} soil and Cu levels of 4, 8, 12, 16 and 20 mg kg^{-1} soil, respectively. A control treatment without heavy metal addition was also maintained in each experiment. Thus, six treatments were arranged in a randomized complete block design (RCBD) with three replications in each separate experiment.

Planting and Growth Conditions

Pre-germinated rice seeds (*Oryza sativa* L.) of variety BRRI -28 were transplanted into 4 kg capacity plastic pots containing the treated soils. One seedling was planted per pot. The pots were maintained under natural daylight in a research field. Soil moisture was maintained throughout the growth period by regular watering with tap water.

Duration of Exposure and Sampling

Plants were grown for a period about 120 days following transplantation[18]. At harvest, the fully expanded leaves were collected, rinsed with distilled water to remove surface contaminants, and immediately subjected to biochemical analyses. Leaf samples were analysed for chlorophyll content in fresh weight basis and rice grain were collected for analyzing nitrogen and protein content in dry weight basis.

Chlorophyll Analysis

Chlorophyll a, chlorophyll b, and total chlorophyll (Chl) contents were determined following the method of Arnon[19] an additional modified by Lichtenthaler and Wellburn[20]. Fresh leaf tissue (1 g) was homogenized in 100% acetone and centrifuged at 200 rpm for 1 hour and made volume up to 50 ml in the volumetric flask. The absorbance of the supernatant was measured at 645 nm and 662 nm using a UV–Vis spectrophotometer (Shimadzu UV-1800). Chlorophyll contents were calculated using following equations[21] and expressed as mg g^{-1} fresh weight.

$$Chl - a = \frac{11.75A_{662} - 2.35A_{645}}{W \times 1000} V$$

$$Chl - b = \frac{18.61A_{645} - 3.96A_{662}}{W \times 1000} V$$

Total Chl = (Chl a + Chl b)

Where, A = absorbance at specific wavelength, V = final volume of chlorophyll extract in 100% acetone, W = fresh weight of leaf tissue, Chl-a = *chlorophyll a*, Chl-b = *chlorophyll b* and Total Chl = *total chlorophyll*.

Total Nitrogen and Protein Analysis

Total nitrogen content was determined using the Kjeldahl digestion method[22]. Oven-dried 0.5 g ground rice grain was digested with concentrated sulphuric acid in the presence of a digestion catalyst (K_2SO_4: $CuSO_4.5H_2O$: Se = 100:10:1) and volume up to 100 ml in volumetric flask. The digested samples were distilled and titrated with dilute acid to quantify nitrogen content, expressed as a percentage of dry weight.

$$\% \text{ Total Nitrogen (TN)} = \frac{(T-B)\times f \times 0.014 \times 100ml\ volume \times 100}{w \times volume\ of\ extract\ used}$$

where, T = Sample titration value (mL) of standard H_2SO_4; B = Blank titration value (mL) of standard H_2SO_4; f = strength of H_2SO_4; W = Weight of rice grain in gram.

Protein content was estimated by multiplying total nitrogen values by a conventional factor of 6.25, assuming that nitrogen constitutes approximately 16% of plant protein. Percent of protein content was calculated with the following formula on a dry weight basis[23].

Protein % = % Nitrogen × 6.25 (conversion factor)

Statistical Analysis

The significance of differences among the means of the treatments were evaluated by one way Analysis of Variance (ANOVA) followed by Duncan's Multiple Range Test (DMRT) at the significance level of 5%. The statistical analyses were done using Excel, and SPSS version 20. All data were carefully examined for accuracy and consistency prior to statistical analysis.

Results and Discussion

Chlorophyll content

Figure 1 illustrates the impact of cadmium (Cd), lead (Pb), zinc (Zn), and copper (Cu) exposure on chlorophyll *a*, chlorophyll *b*, and total chlorophyll content in rice leaves, expressed in mg g^{-1}. Across all treatments, a general decline in chlorophyll content was observed in comparison to the control. Chlorophyll a showed the most pronounced reduction under Cd exposure, followed by Pb, Cu, and Zn. Chlorophyll b also declined under all heavy metal treatments, with Cd again having the most substantial inhibitory effect. Total chlorophyll content mirrored the trends observed for individual pigments, demonstrating the cumulative stress effect of heavy metals, particularly Cd and Pb. The reductions were statistically significant ($p<0.05$), indicating that heavy metal exposure, especially Cd, adversely affects chlorophyll biosynthesis in rice.

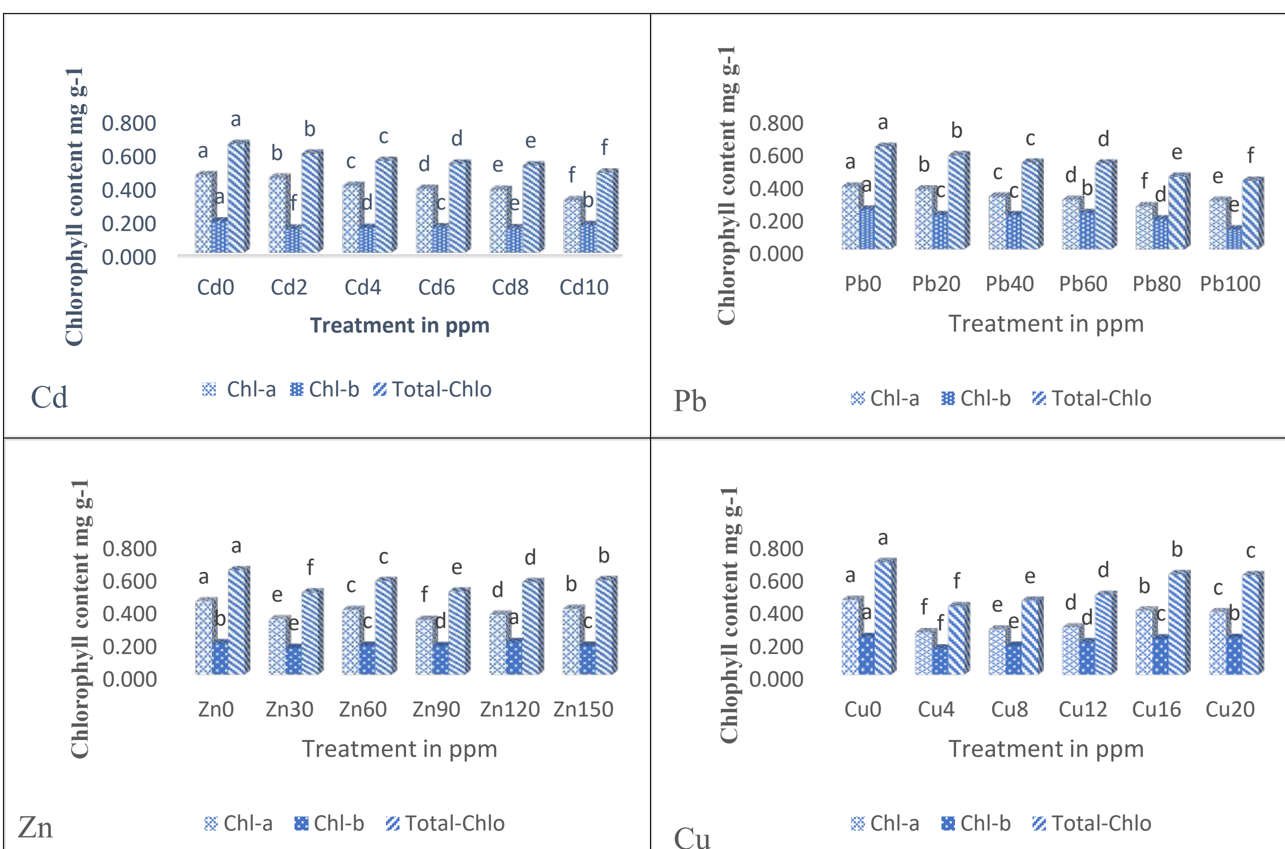

Figure 1. Effect of heavy metals (Cd, Pb, Zn and Cu) exposure on chlo-a, chlo-b and total chlo (mg g^{-1}) content in rice. Bars having same letter(s) are not significantly different among treatments by DMRT ($p\leq0.05$). [chlo-a = *chlorophyll a*, chlo-b = *chlorophyll b*, total chlo = *total chlorophyll*].

The observed decrease in chlorophyll content under heavy metal stress suggests a disruption in photosynthetic efficiency and pigment biosynthesis. Cadmium and lead, known for their phytotoxicity, likely interfere with chloroplast structure and enzymatic activity responsible for pigment formation[24, 25]. The significant decline in chlorophyll *a* under Cd exposure might be attributed to the inhibition of protochlorophyllide reductase or enhanced chlorophyll degradation pathways[26]. These findings are consistent with earlier studies by Rai *et al.*[27] who reported that Cd and Pb reduce chlorophyll content in various cereal crops, impairing photosynthesis and growth. The relatively lower reduction observed under Zn and Cu could be due to their dual role as both essential micronutrients and toxicants at higher concentrations[27].

Total Nitrogen Content

The total nitrogen content (%) in rice plants subjected to Cd, Pb, Zn, and Cu exposure (Figure 2). A consistent reduction in nitrogen content was recorded across all treatments relative to the control. The maximum decline in nitrogen content was observed under Cd treatment, followed closely by Pb. Zn and Cu also caused a measurable decline, but the reductions were less severe than those caused by Cd and Pb. All reductions were statistically significant ($p<0.05$), suggesting a systemic disruption of nitrogen assimilation or translocation under heavy metal stress.

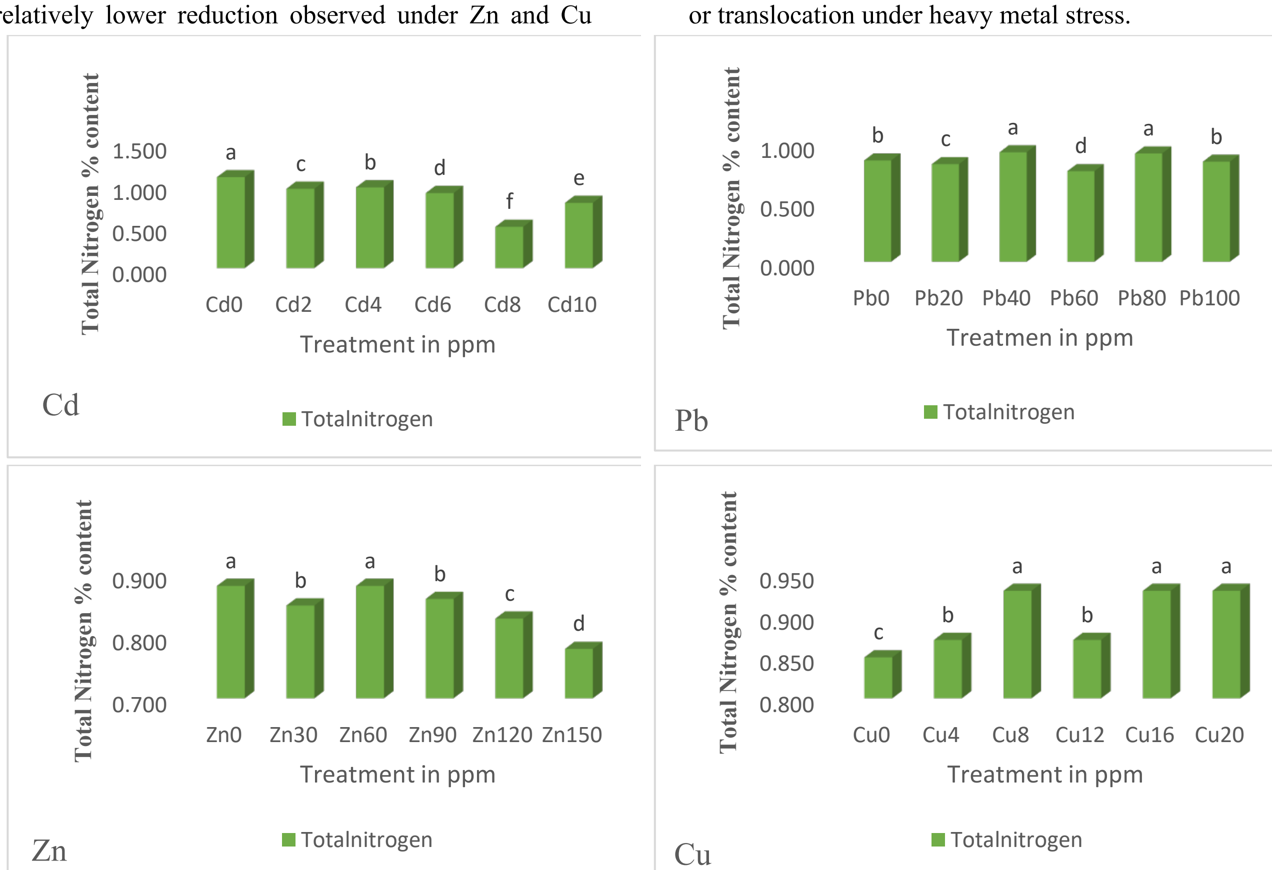

Figure 2. Effect of heavy metals (Cd, Pb, Zn & Cu) exposure on total nitrogen (%) content in rice. Bars having same letter(s) are not significantly different among treatments by DMRT ($p\leq0.05$).

Nitrogen is a critical macronutrient involved in amino acid and protein synthesis. The marked reduction in nitrogen content, especially under Cd and Pb stress, could be linked to impaired nitrate reductase activity and root uptake mechanisms[28, 29]. Cadmium is particularly notorious for causing root membrane damage, thereby limiting the plant's ability to absorb nutrients efficiently.

The results are in alignment with the work of Lebrazi *et al.*[30] who demonstrated that Cd toxicity limits nitrogen metabolism in rice by down regulating key enzymes and transporters. Similarly, Pb can inhibit nitrogen assimilation enzymes and displace essential cations, exacerbating nutritional deficiencies[31]. Zinc and copper, despite being essential for plant metabolism, become toxic at elevated levels and can disrupt nitrogen transport and metabolism[32, 33]. However, the relatively lower decline observed under Zn and Cu treatments might reflect a threshold effect, where toxicity is less pronounced due to their functional roles in enzymatic reactions.

Protein Content

The percentage of protein content in rice exposed to various heavy metals data is presented in figure 3. A downward trend in protein content was evident for all treatments compared to the control. The most substantial decrease was associated with Cd exposure, followed by Pb, Cu, and Zn. The protein content declined significantly ($p<0.05$), with Cd and Pb showing the most adverse effects.

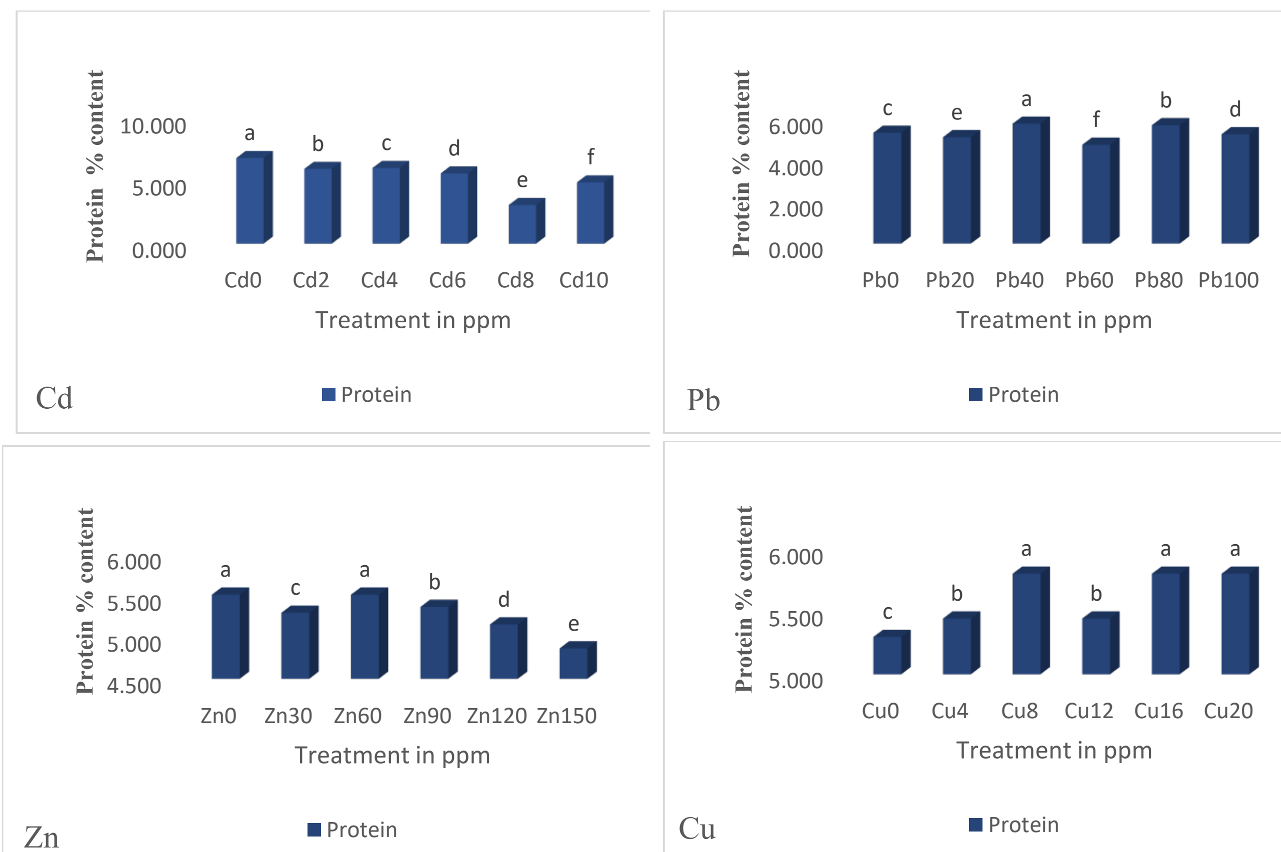

Figure 3. Effect of heavy metals (Cd, Pb, Zn and Cu) exposure on protein (%) content in rice.
Bars having same letter(s) are not significantly different among treatments by DMRT ($p\leq0.05$).

Protein synthesis is directly influenced by nitrogen availability and metabolic function. The decline in protein content under heavy metal exposure reflects a combination of impaired nitrogen uptake, altered gene expression, and disrupted cellular machinery. Cadmium and lead are known to inhibit ribosomal function and amino acid biosynthesis, thereby affecting protein assembly[34, 31].

The parallel decline in nitrogen and protein contents suggests that heavy metal toxicity compromises the nitrogen-to-protein conversion pathway. The result is supported by findings from Hasan *et al.*[35] who observed reduced protein levels in rice and wheat under similar metal stress conditions. The relatively lesser reduction in protein under Zn and Cu treatments may reflect the metals' role in maintaining enzymatic functions at lower concentrations, although chronic exposure remains detrimental[36, 33].

Overall, the decline in protein content under heavy metal stress raises serious concerns for nutritional quality and food security in contaminated areas.

Conclusion

This research highlights the detrimental effects of Cd, Pb, Zn, and Cu on key biochemical parameters in rice, including chlorophyll content, nitrogen concentration, and protein levels. Cadmium emerged as the most toxic metal, significantly impairing pigment biosynthesis and nitrogen metabolism. Lead followed a similar trend, while Zn and Cu exhibited moderate toxicity. These findings underscore the importance of monitoring heavy metal contamination in agricultural soils, particularly in rice-growing regions exposed to industrial and urban runoff. From a physiological and agronomic perspective, such contamination can compromise crop quality and yield, with downstream effects on human health and food systems. Therefore, it is recommended to evaluate long-term field responses to metal contamination under varied agronomic practices.

Acknowledgements

The authors would like to extend sincere thanks to the chairman of the Department of Soil Science, University of Chittagong, Bangladesh for providing all laboratory facilities. The authors also express their gratitude to the research and publication cell, University of Chittagong, Chattogram-4331, Bangladesh for funding to carry out this research work.

References

1. Tomczyk, P., Wdowczyk, A., Wiatkowska, B., and Szymańska-Pulikowska, A. 2023. Assessment of heavy metal contamination of agricultural soils in Poland using contamination indicators. *Ecological Indicators*. https://doi.org/10.1016/j.ecolind.2023.111161
2. Kibria, M. G., Ahammad, M. J., Islam, M., and Osman, K. T. 2013. Dynamics of cadmium and lead in some soils of Chittagong, Bangladesh. *IOSR J Environ Sci Toxico Food Technol*, 2(6), 64-71.
3. Li, L., Zhang, Y., Ippolito, J. A., Xing, W., Qiu, K., and Wang, Y. 2020. Cadmium foliar application affects wheat Cd, Cu, Pb and Zn accumulation. *Environmental Pollution*, **262,** 114-129. https://doi.org/10.1016/J.ENVPOL.2020.114329
4. Hu, Z., Zhao, C., Li, Q., Feng, Y., Zhang, X., Lu, Y., Ying, R., Yin, A. and Ji, W. 2023. Heavy Metals Can Affect Plant Morphology and Limit Plant Growth and Photosynthesis Processes. *Agronomy*, ***13***,2601. https://doi.org/10.3390/agronomy13102601
5. Kaur, R., Das, S., Bansal, S., Singh, G., Sardar, S., Dhar, H., and Ram, H. 2021. Heavy metal stress in rice: Uptake, transport, signaling, and tolerance mechanisms. *Physiologia plantarum*, **173(1),** 430–448. https://doi.org/10.1111/ppl.13491
6. Yin, M., Wang, S., Wang, Y., Wei, R., Liang, Y., Zuo, L., Huo, M., Huang, Z., Lang, J., Zhao, X., Zhang, F., Xu, J., Fu, B., Li, Z., and Wang, W. 2024. Impact of Abiotic Stress on Rice and the Role of DNA Methylation in Stress Response Mechanisms. *Plants (Basel, Switzerland)*, **13(19),** 2700. https://doi.org/10.3390/plants13192700
7. Chandra, R., and Kang, H. 2016. Mixed heavy metal stress on photosynthesis, transpiration rate, and chlorophyll content in poplar hybrids. *Forest Science and Technology*, **12(2)**, 55–61. https://doi.org/10.1080/21580103.2015.1044024
8. Faizan, M., Alam, P., Hussain, A., Karabulut, F., Tonny, S. H., Cheng, S. H., Yusuf, M., Adil, M. F., Sehar, S., Alomrani, S. O., Albalawi, T., and Hayat, S. 2024. Phytochelatins: Key regulator against heavy metal toxicity in plants. *Plant Stress*, **11,** 100355. https://doi.org/https://doi.org/10.1016/j.stress.2024.100355
9. Whitfield, J., Dy, V., McQuilty, R., Gu, Z., Heath, A. C., Montgomery, G. W., and Martin, N. G. 2010. Genetic Effects on Toxic and Essential Elements in Humans: Arsenic, Cadmium, Copper, Lead, Mercury, Selenium, and Zinc in Erythrocytes. *Environmental Health Perspectives*, **118(6)**, 776–782. https://doi.org/10.1289/EHP.0901541
10. Jiang, M., Jiang, J., Li, S., Li, M., Tan, Y., Song, S., Shu, Q., and Huang, J. 2020. Glutamate alleviates cadmium toxicity in rice via suppressing cadmium uptake and translocation. *Journal of Hazardous Materials*, **384**, 121319. https://doi.org/https://doi.org/10.1016/j.jhazmat.2019.121319
11. Riaz, M., Kamran, M., Rizwan, M., Ali, S., Zhou, Y., Núñez-Delgado, A., and Wang, X. 2021. Boron application mitigates Cd toxicity in leaves of rice by subcellular distribution, cell wall adsorption and antioxidant system. *Ecotoxicology and Environmenta lSafety*, **222**, 112540. https://doi.org/https://doi.org/10.1016/j.ecoenv.2021.112540
12. Zhang, X., Chen, H., Jiang, H., Lu, W., Pan, J., Qian, Q. and Xue, D. 2015. Measuring the damage of heavy metal cadmium in rice seedlings by SRAP analysis combined with physiological and biochemical parameters. J. Sci. Food Agric., **95**: 2292-2298. https://doi.org/10.1002/jsfa.6949
13. Ur Rahman, S., Qin, A., Zain, M., Mushtaq, Z., Mehmood, F., Riaz, L., Naveed, S., Ansari, M. J., Saeed, M., Ahmad, I., and Shehzad, M. 2024. Pb uptake, accumulation, and translocation in plants: Plant physiological, biochemical, and molecular response: A review. *Heliyon*, **10(6)**, e27724. https://doi.org/https://doi.org/10.1016/j.heliyon.2024.e27724

14. Stanton, C., Sanders, D., Krämer, U., and Podar, D. 2022. Zinc in plants: Integrating homeostasis and biofortification. *Molecular plant*, **15(1)**, 65–85. https://doi.org/10.1016/j.molp.2021.12.008
15. Rob, M. M., Akhter, D., Islam, T., Bhattacharjya, D. K., Shoaib Khan, M. S., Islam, F., and Chen, J. 2024. Copper stress in rice: Perception, signaling, bioremediation and future prospects. *Journal of Plant Physiology*, **302**, 154314. https://doi.org/https://doi.org/10.1016/j.jplph.2024.154314
16. Mir, A.R., Pichtel, J. and Hayat, S. 2021. Copper: uptake, toxicity and tolerance in plants and management of Cu-contaminated soil. *Biometals* **34**, 737–759. https://doi.org/10.1007/s10534-021-00306-z
17. Cao, H., Chen, D., Kuang, L., Yan, T., Gao, F., and Wu, D. 2023. Metabolomic analysis reveals the molecular responses to copper toxicity in rice (Oryza sativa). *Plant Physiology and Biochemistry*, **199**, 107727. https://doi.org/https://doi.org/10.1016/j.plaphy.2023.107727
18. Hossain, M., Biswas, P., and Islam, M. R. 2023. Cold-Tolerant and Short-Duration Rice (*Oryza sativa* L.) for Sustainable Food Security of the Flash Flood-Prone *Haor* Wetlands of Bangladesh. *Sustainability*, **15(24)**, 16873. https://doi.org/10.3390/su152416873
19. Arnon D. I. 1949. Copper Enzymes in isolated chloroplasts. Polyphenoloxidase in *Beta vulgaris*. *Plant physiology*, **24(1)**, 1–15. https://doi.org/10.1104/pp.24.1.1
20. Lichtenthaler, H. K., and Wellburn, A. R. 1983. Determinations of total carotenoids and chlorophylls a and b of leaf extracts in different solvents. *Biochem Soc Trans*. **11(5)**: 951-592. https://doi.org/10.1042/bst0110591
21. Škondrić, S., Kukavica, B., Trifković, T., and Mihajlović, D. 2025. A comparison of the biochemical parameters and micronutrient concentrations in the leaves of two Balkan endemic Scilla species from a karst area. *Comprehensive Plant Biology*, **49(1)**, 73-86. https://doi.org/10.2298/CPB2501073S
22. Bremner, J. M., and Mulvaney, C. S. 1982. Nitrogen-Total. In: Methods of Soil Analysis. Part 2. Chemical and Microbiological Properties; Page, A.L., Miller, R.H., Keeney, D.R., Eds.; American Society of Agronomy, Soil Science Society of America: Madison, WI, USA. pp. 595–624.
23. Gupta, S., Lakshmi, A. J., Manjunath, M. N., and Prakash, J. 2005. Analysis of nutrient and antinutrient content of underutilized green leafy vegetables. *LWT-Food Science and Technology*, **38(4)**, 339-345. https://doi.org/10.1016/j.lwt.2004.06.012
24. Goncharuk, E. A., and Zagoskina, N. V. 2023. Heavy metals, their phytotoxicity, and the role of phenolic antioxidants in plant stress responses with focus on cadmium. *Molecules*, **28(9)**, 3921. https://doi.org/10.3390/molecules28093921
25. Gomes, S. M. D. S., Lima, V. L. A. D., Souza, A. P. D., do Nascimento, J. J., and Nascimento, E. S. D. 2014. Cloroplast pigments as indicators of lead stress. *Engenharia Agrícola*, **34**, 877-884. https://doi.org/10.1590/S0100-69162014000500007
26. An, M., Wang, H., Fan, H., Ippolito, J. A., Meng, C., E, Y., Li, Y., Wang, K., and Wei, C. 2019. Effects of modifiers on the growth, photosynthesis, and antioxidant enzymes of cotton under cadmium toxicity. *Journal of Plant Growth Regulation*, **38(4)**, 1196-1205. https://doi.org/10.1007/s00344-019-09924-x
27. Rai, R., Agrawal, M., and Agrawal, S. B. 2016. Impact of heavy metals on physiological processes of plants: with special reference to photosynthetic system. In *Plant responses to xenobiotics.* pp. 127-140. Springer Singapore. https://doi.org/10.1007/978-981-10-2860-1_6
28. Seregin, I.V., and Ivanov, V.B. 2001. Physiological Aspects of Cadmium and Lead Toxic Effects on Higher Plants. *Russian Journal of Plant Physiology* **48**, 523–544. https://doi.org/10.1023/A:1016719901147
29. Hussain, S., Khaliq, A., Noor, M. A., Tanveer, M., Hussain, H. A., Hussain, S., Shah. T., and Mehmood, T. 2019. Metal toxicity and nitrogen metabolism in plants: an overview. *Carbon and nitrogen cycling in soil*, 221-248. https://doi.org/10.1007/978-981-13-7264-3_7
30. Lebrazi, S., and Fikri-Benbrahim, K. 2018. Rhizobium-legume symbioses: Heavy metal effects and principal approaches for bioremediation of contaminated soil. In *Legumes for soil health and sustainable management.* pp. 205-233. Springer Singapore. https://doi.org/10.1007/978-981-13-0253-4_7
31. Sharma, P., and Dubey, R.S. 2005. Lead Toxicity in Plants. *Brazilian Journal of Plant Physiology*, **17**, 35-52. http://dx.doi.org/10.1590/S1677-04202005000100004
32. Kaur, H., **and** Garg, N. 2021. Zinc toxicity in plants: a review. *Planta* 253, 129. https://doi.org/10.1007/s00425-021-03642-z
33. Yruela, I. 2009. Copper in plants: acquisition, transport and interactions. *Functional plant biology:* **36(5)**, 409–430. https://doi.org/10.1071/FP08288
34. Hasanuzzaman, M., Bhuyan, M. H. M. B., Zulfiqar, F., Raza, A., Mohsin, S. M., Mahmud, J. A., Fujita, M., and Fotopoulos, V. 2020. Reactive Oxygen Species and Antioxidant Defense in Plants under Abiotic Stress: Revisiting the Crucial Role of a Universal Defense Regulator. *Antioxidants*, **9(8)**, 681. https://doi.org/10.3390/antiox9080681
35. Hasan, M. K., Cheng, Y., Kanwar, M. K., Chu, X. Y., Ahammed, G. J., and Qi, Z. Y. 2017. Responses of plant proteins to heavy metal stress—a review. *Frontiers in plant science*, **8**, 1492. https://doi.org/10.3389/fpls.2017.01492
36. Nagajyoti, P.C., Lee, K.D. and Sreekanth, T.V.M. 2010. Heavy metals, occurrence and toxicity for plants: a review. *Environ Chem Lett* **8**, 199–216. https://doi.org/10.1007/s10311-010-0297-8