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SORPTION OF HEAVY METAL IONS FROM WASTEWATER USING LOCALIZED ALGAE

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Abstract: This study presents a comparative analysis of the dynamics of copper and zinc heavy metal ion uptake (sorption) from an aqueous medium using immobilized and free cells of the microalga *Chlorella vulgaris*. Experimental results demonstrated that immobilized cells exhibit superior efficiency, mechanical strength, and long-term stability in removing metal ions compared to free cells. Furthermore, using modern analytical techniques, maps showing the local distribution of elements and copper ions on the surface and within the internal structures of the microalgal cells were analyzed, confirming the role of active functional groups in the cell wall in binding metals. The findings indicate the potential for the effective practical application of these biological materials in processes for removing heavy metals from industrial wastewater.

Keywords: *Chlorella vulgaris*, microalgae, immobilization, sorption, heavy metals, wastewater, biosorption.

INTRODUCTION

The rapid development of industrial sectors today—particularly the expansion of non-ferrous metallurgy, mechanical engineering, electroplating, and the chemical industry—is exacerbating the problem of environmental pollution, specifically the contamination of natural water bodies with heavy metal ions. Heavy metals such as copper (Cu^{2+}), zinc (Zn^{2+}), cadmium, lead, and nickel are highly toxic to living organisms even at low concentrations; they disrupt the stability of aquatic ecosystems and pose serious risks to human health. Consequently, the treatment of wastewater to remove heavy metals using effective, economically viable, and environmentally safe methods is a pressing scientific and practical challenge.

Although traditional treatment methods (such as chemical precipitation, ion-exchange resins, membrane filtration, and electrochemical processes) are highly efficient, their high energy requirements, generation of secondary toxic waste, and high costs act as limiting factors. Therefore, in recent years, there has been a sharp increase in the demand for sorption technologies (biosorption) utilizing biological agents, including microorganisms and microalgae. The microalga *Chlorella vulgaris* possesses the ability to effectively bind heavy metal ions due to its high growth rate, widespread distribution, and the unique chemical composition of its cell wall (characterized by the presence of functional groups such as carboxyl, hydroxyl, amino, and phosphate). However, the use of free (non-immobilized) microalgal cells in industrial-scale wastewater treatment processes presents technological challenges, such as the difficulty of subsequent separation from the water and a lack of resistance to hydrodynamic shear forces. One of the most effective solutions to this problem is the immobilization of microalgal cells within specialized matrices. Immobilized cells provide mechanical stability, enable reuse, and enhance the overall stability of the sorption process.

The aim of this study is to investigate the sorption dynamics of copper (Cu^{2+}) and zinc (Zn^{2+}) ions from an aqueous medium using both immobilized and free cells of *Chlorella vulgaris*, and to evaluate the mechanisms of local metal distribution on the cell surface using modern analytical techniques.

LITERATURE REVIEW

The removal of heavy metal ions from wastewater using biological methods has become a significant area of research in recent years, driven by the need to develop environmentally safe and economically viable technologies. In particular, microalgae are being investigated as promising biosorbents because functional groups present on their cell walls—such as carboxyl, hydroxyl, amino, and phosphate groups—possess the ability to bind with metal ions. Studies summarizing the potential of microalgae for heavy metal ion removal have highlighted their high capacity for biosorption and their selectivity toward various metal ions [3, 9, 10, 12].

The microalga *Chlorella vulgaris* is one of the most extensively studied biological agents for the sorption of heavy metal ions. Research conducted by Fraile et al. examined the sorption characteristics of *C. vulgaris* biomass regarding Cu, Zn, Cd, and Ni ions in both single-component and binary-component solutions. The authors demonstrated that

the extent of metal ion sorption depends on the type of metal and the composition of the solution [1]. These results demonstrate the potential of using *Chlorella vulgaris* biomass to treat wastewater containing multiple heavy metal ions simultaneously.

Al-Rub et al. investigated the biosorption of copper ions by *Chlorella vulgaris* in single-, binary-, and ternary-component metal solutions. The study evaluated the effects of contact time, biosorbent dosage, equilibrium pH, and the presence of Pb and Zn ions on Cu^{2+} sorption. The results indicated that the biosorption of copper ions was significantly dependent on pH and biosorbent dosage [2]. It was also found that the presence of competing ions, such as Pb^{2+} and Zn^{2+} , reduced Cu^{2+} sorption. This highlights the necessity of considering competitive mechanisms during the sorption process when multiple metal ions are simultaneously present in wastewater [2, 7].

Cho et al. studied the biosorption of heavy metal ions by *Chlorella vulgaris* and demonstrated that the microalga's cell surface plays a crucial role in this process [13]. The interaction between metal ions and active sites on the cell surface can occur rapidly during the initial stage of biosorption. From this perspective, the composition of functional groups on the microalgal cell wall and their metal-ion binding characteristics are among the key factors determining the sorbent's efficiency.

Immobilizing microalgae further expands the technological possibilities for their application in wastewater treatment. Research by Ahmad, Bhat, and Buang utilized both free *Chlorella vulgaris* cells and those immobilized in a Ca-alginate matrix for the sorption of Fe^{2+} , Mn^{2+} , and Zn^{2+} ions. The results demonstrated that immobilized microalgae can serve as effective biosorbents for the removal of metal ions [4]. Furthermore, immobilization facilitates the separation of biomass from the aqueous medium, its reuse, and its retention within the technological process.

Studies directly comparing free and immobilized forms of *Chlorella vulgaris* have also investigated the potential for removing Ni^{2+} and Cu^{2+} ions using cells entrapped in Ca-alginate. Studies by Ahmad et al. have reported the high-level recovery of these ions from low-concentration metal solutions and identified competition for binding sites between free and immobilized cells during the overall sorption of metal ions [13]. These results provide a significant scientific basis for the practical application of immobilized microalgae.

Competition between heavy metal ions also plays a crucial role in the biosorption process involving *Chlorella vulgaris*. Al-Rub et al. investigated the effects of Cu^{2+} and Zn^{2+} ions on Pb^{2+} biosorption and found that the presence of Cu^{2+} significantly reduced Pb^{2+} sorption [7]. In that study, the sorption process was evaluated using various isotherm models, with the Sips model providing the best fit for the experimental data. These results highlight the importance of considering the combined effects of multiple metal ions—rather than just a single metal—when treating actual wastewater.

To better understand the mechanisms of the sorption process associated with the cell wall, subsequent research has also extensively examined the cellular composition of microalgae and their metal-binding characteristics. In particular, the relationship between the cell wall composition of *Chlorella vulgaris* and its metal-ion-binding properties has been investigated, demonstrating that functional groups within the cell wall play a crucial role in metal sequestration [5, 11]. These findings provide insight into the mechanisms by which microalgae sorb heavy metal ions at the molecular level.

In contemporary literature, the heavy metal sorption properties of microalgae—not only regarding laboratory-prepared model solutions but also from the perspective of wastewater treatment—are being evaluated. Salsali, Parker, and Sattar investigated the potential to reduce Cu and Zn ion concentrations in wastewater—following secondary treatment—using microalgae [8]. These studies demonstrate the feasibility of integrating microalgae into biological wastewater treatment processes.

In recent years, there has also been an increase in analytical studies summarizing the heavy metal biosorption properties of microalgae. Leong and Chang analyzed modern mechanisms and technological approaches for the bioremediation of heavy metals using microalgae, evaluating them as a promising biological resource for removing heavy metals from aquatic environments [10]. Meanwhile, Ubando et al. analyzed development trends in this field based on numerous scientific studies regarding heavy metal biosorption by microalgae [9]. Additionally, Kumar et al. highlighted the high sorption potential of algal biomass while summarizing various algal biosorbents, sorption isotherms, kinetic models, and heavy metal removal mechanisms [12].

RESEARCH METHODOLOGY

During the study, strains of the microalga *Chlorella vulgaris* were cultivated under laboratory conditions in a specialized nutrient medium. Biopolymer matrices were used to immobilize the microalgal cells; the cells were mixed at a uniform concentration to form gel-like granules of a specific diameter, ensuring stability against physiological dissolution.

Model wastewater solutions containing specific concentrations of copper (based on $\text{CuSO}_4 \cdot 5\text{H}_2\text{O}$) and zinc (based on $\text{ZnSO}_4 \cdot 7\text{H}_2\text{O}$) ions were used for the experimental studies. To investigate the kinetics of the sorption

process, specific quantities of immobilized and free *Chlorella vulgaris* cells were added to the metal salt solutions. Experiments were conducted under constant agitation over a defined time interval (0 to 25 hours).

Residual concentrations of copper (Cu^{2+}) and zinc (Zn^{2+}) ions in the solution were measured at specific time intervals. The dynamics of changes in metal ion concentrations and sorption efficiency were recorded using specific physicochemical analysis methods.

Additionally, microscopic and elemental analyses were performed to determine the localization and accumulation of copper ions within the *Chlorella vulgaris* cell structures. Maps showing the local distribution of $^{12}\text{C}^-$, $^{12}\text{C}^{14}\text{N}^-$, $^{31}\text{P}^-$, and $^{63}\text{Cu}^-$ secondary ions on the cell surface and within its interior were obtained, enabling an in-depth assessment of the interaction between functional groups in the cell wall and metal ions.

ANALYSIS AND RESULTS

During the study, the time-dependent dynamics of the uptake (sorption) of copper (Cu^{2+}) and zinc (Zn^{2+}) heavy metal ions from an aqueous medium by immobilized and non-immobilized (free) cells of the microalga *Chlorella vulgaris* were investigated. The experimental results obtained are presented in Figure 1 (Figure 1).

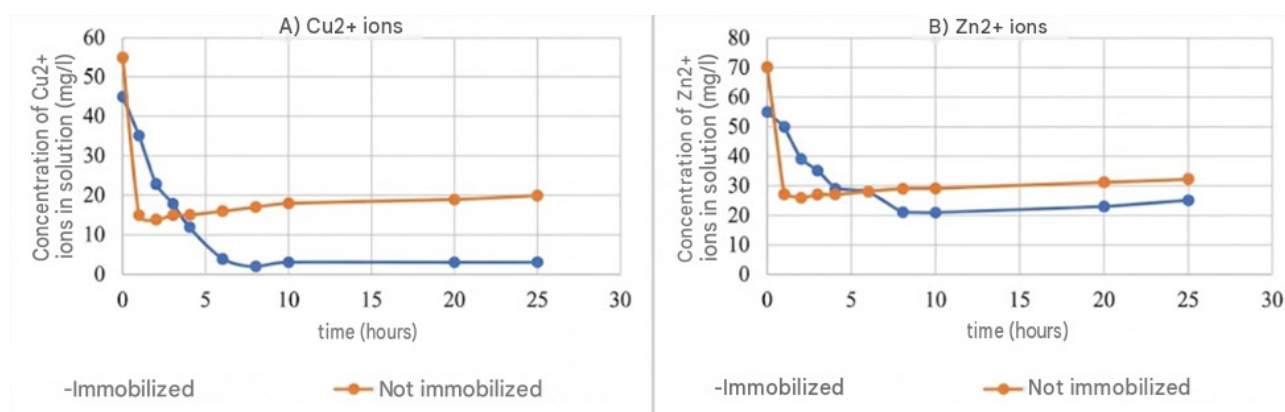


Figure 1. Decrease in metal concentration after the use of immobilized and non-immobilized *Chlorella vulgaris* cells: A) Cu^{2+} and B) Zn^{2+}

As shown in Figure 1, Graph A, immobilized *Chlorella vulgaris* cells demonstrated higher efficiency and stability than free cells in removing Cu^{2+} ions from the solution. A sharp decrease in metal ion concentration was observed for both forms during the initial 2–4 hours of the process. This phenomenon is attributed to rapid physicochemical interactions—specifically, ion exchange and complex formation—between the metal ions and active functional groups (carboxyl, hydroxyl, amino, and phosphate groups) on the cell walls.

With free cells, the sorption process was initially rapid; although the Cu^{2+} concentration in the solution dropped to 14 mg/L by the third hour, equilibrium was subsequently disrupted, causing the concentration to rise slightly and stabilize at around 20 mg/L. This behavior is linked to the mutual agglomeration (clumping) of free cells during mass transfer or the occurrence of partial desorption. In contrast, immobilized cells maintained a stable sorption process, reducing the Cu^{2+} concentration in the solution to a minimum value ($\approx 2\text{--}3$ mg/L) after 6–8 hours and sustaining this level until the end of the experiment. Figure 1B illustrates the sorption dynamics of Zn^{2+} ions, revealing distinct characteristics for both immobilized and free cells. Free cells rapidly took up Zn^{2+} ions during the initial 2 hours, reducing the concentration from ~ 70 mg/L to ~ 26 mg/L; however, in subsequent stages, sorption capacity reached saturation, and the concentration stabilized within the 28–32 mg/L range.

In contrast, immobilized *Chlorella vulgaris* cells took up Zn^{2+} ions more gradually but achieved a greater and more stable level of removal. A steady decline was observed over the first 10 hours, with the metal concentration in the solution dropping to $\sim 20\text{--}22$ mg/L and remaining stable until the end of the experiment. The presence of the immobilization matrix ensures uniform cell distribution, improves hydrodynamic conditions, and facilitates the formation of strong, long-term bonds between metal ions and active sites.

To gain a deeper understanding of the mechanisms behind the intracellular binding and accumulation of copper (Cu^{2+}) ions, the distribution of ions within the *Chlorella vulgaris* cells was analyzed. The resulting images are presented in Figure 2 (Figure 2).

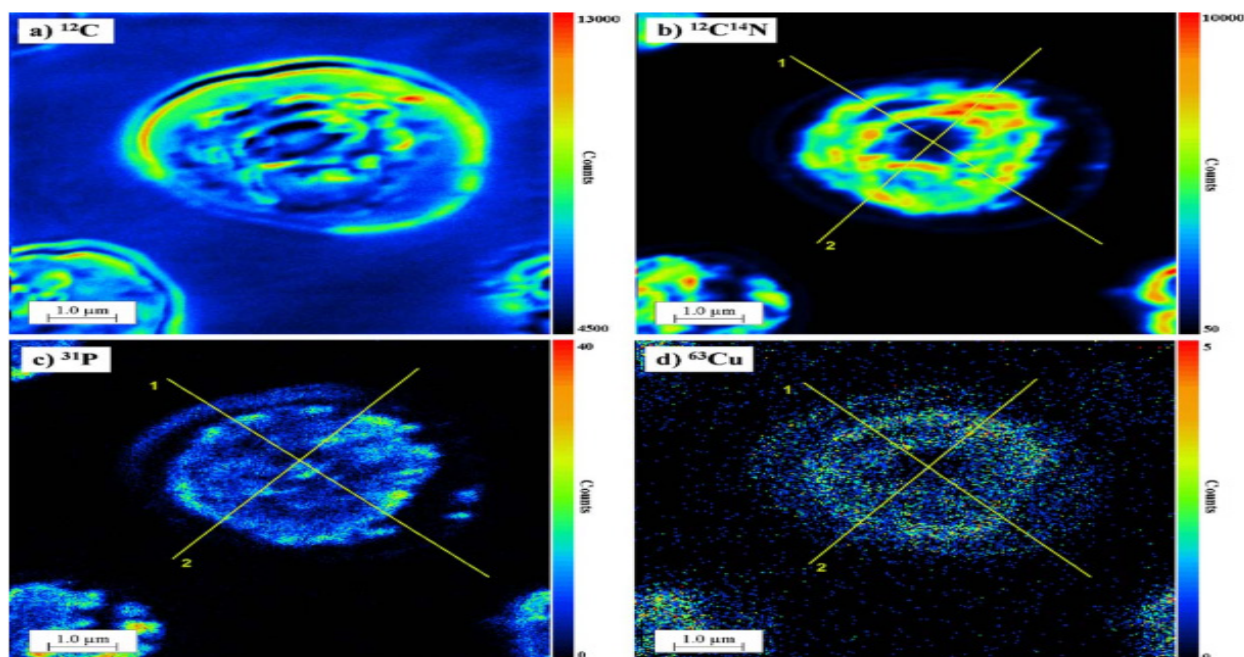


Figure 2. Images showing the distribution of $^{12}\text{C}^-$, $^{12}\text{C}^{14}\text{N}^-$, $^{31}\text{P}^-$, and $^{63}\text{Cu}^-$ secondary ions across the entire *Chlorella vulgaris* cell: a) ^{12}C , b) $^{12}\text{C}^{14}\text{N}$, c) ^{31}P , d) ^{63}Cu .

As shown in images (a) and (b) of Figure 2, carbon (^{12}C) and carbon-nitrogen ($^{12}\text{C}^{14}\text{N}$) ions are evenly distributed throughout the cellular structure, clearly delineating the microalga's overall organic matrix—specifically, the cell wall and the main cytoplasmic framework.

The distribution of phosphorus (^{31}P) ions reveals high concentrations localized at specific points (zones of intense growth along the line). This pattern is closely associated with regions containing intracellular nucleic acids, phospholipids, and energy-rich compounds (ATP).

The map reflecting the presence and localization of copper ions (^{63}Cu) confirms the metal's distribution across the cell surface and its partial penetration into internal structures. The fact that the intensity of the ^{63}Cu signal aligns with the cell's outer shell and phosphorus-rich (^{31}P) regions demonstrates that heavy metals form strong coordination compounds or complexes with phosphate, amino, and carboxyl groups in the cell wall.

Overall, the results regarding macroscopic sorption dynamics and microscopic ion distribution fully confirm that the immobilized form of the *Chlorella vulgaris* microalga exhibits high efficiency, mechanical strength, and stable biomolecular-level binding characteristics in processes designed to remove heavy metal ions (Cu^{2+} and Zn^{2+}) from industrial wastewater.

CONCLUSION AND RECOMMENDATIONS

The results of this study fully confirmed that the immobilized form of the microalga *Chlorella vulgaris* exhibits superior efficiency, mechanical strength, and long-term stability compared to free cells in the process of removing copper and zinc heavy metal ions from industrial wastewater. The study revealed that rapid physicochemical interactions—involving ion exchange and complex formation mediated by active functional groups (carboxyl, hydroxyl, amino, and phosphate groups) on the cell surface—occur during the initial hours of the sorption process. Furthermore, analyses of ion distribution scientifically substantiated that metal ions form stable coordination complexes with the cell wall and phosphorus-rich internal structures. The use of an immobilization matrix effectively eliminated the issues of desorption and agglomeration observed over time with free cells, thereby demonstrating the technology's superiority. These findings provide a solid foundation for the widespread practical application of this biological material in environmentally safe, cost-effective, and highly efficient biosorption technologies.

References

1. Fraile, A., Penche, S., González, F., Blázquez, M. L., Muñoz, J. A., & Ballester, A. (2005). Biosorption of copper, zinc, cadmium and nickel by *Chlorella vulgaris*. *Chemistry and Ecology*, 21(1), 61–75. <https://doi.org/10.1080/02757540512331334933>
2. Al-Rub, F. A. A., El-Naas, M. H., Ashour, I., & Al-Marzouqi, M. (2006). Biosorption of copper on *Chlorella vulgaris* from single, binary and ternary metal aqueous solutions. *Process Biochemistry*, 41(2), 457–464. <https://doi.org/10.1016/j.procbio.2005.07.018>

3. Mehta, S. K., & Gaur, J. P. (2005). Use of algae for removing heavy metal ions from wastewater: progress and prospects. *Critical Reviews in Biotechnology*, 25(3), 113–152. <https://doi.org/10.1080/07388550500248571>
4. Ahmad, A., Bhat, A. H., & Buang, A. (2018). Enhanced biosorption of transition metals by living *Chlorella vulgaris* immobilized in Ca-alginate beads. *Environmental Technology*, 40(14), 1793–1809. <https://doi.org/10.1080/09593330.2018.1430171>
5. Soto-Ramírez, R., Lobos, M.-G., Córdova, O., Poirrier, P., & Chamy, R. (2021). Effect of growth conditions on cell wall composition and cadmium adsorption in *Chlorella vulgaris*: A new approach to biosorption research. *Journal of Hazardous Materials*, 411, 125059. <https://doi.org/10.1016/j.jhazmat.2021.125059>
6. de Abreu, F. C. P., da Costa, P. N. M., Brondi, A., Pilau, E. J., Gozzo, F. C., Eberlin, M. N., Trevisan, M. G., & Garcia, J. S. (2014). Effects of cadmium and copper biosorption on *Chlorella vulgaris*. *Bulletin of Environmental Contamination and Toxicology*, 93(4), 405–409. <https://doi.org/10.1007/s00128-014-1363-x>
7. Al-Rub, F. A. A., El-Naas, M. H., Ashour, I., & Al-Marzouqi, M. (2007). Effect of competitive interference on the biosorption of lead(II) by *Chlorella vulgaris*. *Chemical Engineering and Processing: Process Intensification*, 46(12), 1391–1399. <https://doi.org/10.1016/j.cep.2006.11.003>
8. Salsali, H., Parker, W. J., & Sattar, S. A. (2014). Heavy metal removal (copper and zinc) in secondary effluent from wastewater treatment plants by microalgae. *ACS Sustainable Chemistry & Engineering*, 2(2), 130–137. <https://doi.org/10.1021/sc400289z>
9. Ubando, A. T., Africa, A. D. M., Maniquiz-Redillas, M. C., Culaba, A. B., Chen, W.-H., & Chang, J.-S. (2021). Microalgal biosorption of heavy metals: A comprehensive bibliometric review. *Journal of Hazardous Materials*, 402, 123431. <https://doi.org/10.1016/j.jhazmat.2020.123431>
10. Leong, Y. K., & Chang, J.-S. (2020). Bioremediation of heavy metals using microalgae: Recent advances and mechanisms. *Bioresource Technology*, 303, 122886. <https://doi.org/10.1016/j.biortech.2020.122886>
11. Wang, L., Liu, J., Filipiak, M., Mungunkhuyag, K., Jedynak, P., Burczyk, J., Fu, P., & Malec, P. (2021). Fast and efficient cadmium biosorption by *Chlorella vulgaris* K-01 strain: The role of cell walls in metal sequestration. *Algal Research*, 60, 102497. <https://doi.org/10.1016/j.algal.2021.102497>
12. Mahlangu, D., Mphahlele, K., De Paola, F., & Mthombeni, N. H. (2024). Microalgae-mediated biosorption for effective heavy metals removal from wastewater: A review. *Water*, 16(5), 718. <https://doi.org/10.3390/w16050718>
13. Ahmad, A., Bhat, A. H., & Buang, A. (2001). Removal of Ni and Cu from single and binary metal solutions by free and immobilized *Chlorella vulgaris*. *European Journal of Protistology*, 37(3), 261–271. <https://doi.org/10.1078/0932-4739-00813>

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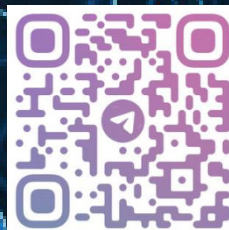
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