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Phytoremediation of Heavy Metals from Wastewater of Sanganer Industrial Area Using Capparis Decidua Stem Extract

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Abstract: *The Sanganer Industrial area of Jaipur (Rajasthan), India has seen rapid industrial development which results in the discharge of effluent from the textile industry containing hazardous heavy metals. This study examined the possibilities of natural removal of heavy metals from the wastewater of textile industries of the region using stem extract of Capparis decidua.*

The physico-chemical analysis of the wastewater showed high levels of lead (Pb), chromium (Cr), arsenic (As), iron (Fe), aluminium (Al), manganese (Mn) and nickel (Ni) and many of these were found to be above the acceptable limit specified for the discharge of industrial effluent. The wastewater sample with the highest level of contamination from the samples collected was chosen for detailed biosorption experiments.

Batch biosorption experiments were conducted under different experimental conditions to identify the best pH, contact time, adsorbent dosage and initial metal concentration for maximum metal removal. Phytochemical screening, HPLC and FTIR analyses were used to confirm the presence of various bioactive constituents and functional groups such as hydroxyl group, carboxyl group, phenolic group and carbonyl group etc. The mechanisms of metal adsorption, including ion exchange, chelation, surface complexation, and electrostatic attraction, were all found to be important for these functional groups.

The optimum biosorption conditions led to a significant removal of all the studied heavy metals. The most efficient removal was registered for Pb, followed by As, Cr, Ni, Mn, Al and Fe. The present results revealed that the biosorption capacity of Capparis decidua stem extract was great and it could be employed as an economical, environmentally friendly and renewable biosorbent for industrial effluent containing heavy metal wastes..

Keywords: Phytoremediation, Heavy Metals, Industrial Wastewater, Biosorption, Capparis Deciduas, Textile Effluent, Sanganer Industrial Area

I. INTRODUCTION

Untreated or less treated effluents of industries are discharged into water bodies and agricultural lands, which has become a major impact of fast industrialization and urbanization on the environment. It has been identified that the Sanganer industrial complex of Jaipur, Rajasthan, is one of the largest industrial areas producing huge quantity of effluents during the processing of textiles. These wastewaters may be filled with various kinds of contaminants such as toxic heavy metals that are harmful to the environment and human health when discharged continuously into the environment.[1]

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[1] Wani, G. A., et al. (2020). Plant-based remediation of contaminated water systems. *Environmental Toxicology Reports*.

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The presence of heavy metals in the industrial effluents was regarded as one of the most dangerous pollutants as they are persistent, non-biodegradable, and are easily bioaccumulated in the biological system. Lead (Pb), Chromium (Cr), Arsenic (As), Iron (Fe), Aluminium (Al), Manganese (Mn) and Nickel (Ni) are frequently detected at high levels in wastewater from industrial processes. These metals that were released into the environment traveled through the soil–water–plant system and bioaccumulated and biomagnified along the food chain. Long-term exposure to high levels of heavy metals were linked to a myriad of health issues such as neurological disorders, kidneys dysfunction, respiratory issues, developmental abnormalities, and different types of cancer.

The conventional methods used for the removal of heavy metals from wastewater were chemical precipitation, coagulation–flocculation, membrane filtration, activated carbon adsorption and ion exchange processes. These processes generally resulted in good removal efficiencies, but were hindered by high operating expenses, high energy consumption and secondary sludge production. This restricted them from investigating alternative treatments that are environmentally friendly and financially friendly.

Phytoremediation was identified as a green technology that has potential to solve water and soil pollution problems. This process involved plants and plant-related substances to be used to remove, stabilize, transform, or destroy pollutants from the environment. The plant biomass was found to contain a variety of phytoconstituents with functional groups like hydroxyl, carboxyl, amino and carbonyl groups. These functional groups could bind metal ions by adsorption, chelation, complexation, ion exchange and electrostatic interaction between the metals and these functional groups, resulting in higher removal efficiency of heavy metal ions from contaminated wastewater.

Plant-based bioadsorbents with high level of functional groups like aromatic and carboxyl groups were reported to have high binding affinity towards heavy metal ions and were identified as effective for decreasing their level in polluted water systems (Bilal et al., 2021; Machchi et al., 2025). The *Capparis decidua* (Forssk.) species is the most commonly used.Edgew. Received considerable attention due to its rich phytochemicals content and biosorption property. The shrub was widely seen in the arid and semi-arid parts of Rajasthan, and it is drought resistant and xerophytic. It was detected that this material contains a variety of bioactive compounds and functional groups on its surface, which indicates its potential as a natural biosorbent in the treatment of wastewater contaminated with heavy metals.

As a result, the present study was conducted to estimate the phytochemical property of *Capparis decidua* stem extract and to evaluate its ability to remove toxic metals like lead (Pb), chromium (Cr), arsenic (As), iron (Fe), aluminium (Al), manganese (Mn) and nickel (Ni) from industrial waste water from the Sanganer industrial area. The study also sought to optimize the biosorption process and to investigate phytoconstituents from plants on heavy metal remediation. The results were anticipated to be useful in the development of sustainable, economical and eco-friendly solutions for the treatment of industrial effluents.

II. MATERIALS AND METHODS

2.1 Collection of Wastewater Samples

Samples of industrial wastewater were collected from the Sanganer industrial area of Jaipur, Rajasthan, India with a special focus on the discharge channels of the textile dyeing and printing units and effluent affected drainage systems nearby. Sampling was conducted according to the procedures suggested by the American Public Health Association (APHA, 2023). The samples were collected in pre-cleaned and acid washed polyethylene bottles with correct label, were transferred to the laboratory under refrigerated condition and stored at 4° C until further analysis.

The collected samples were subjected to preliminary assessment of some of its physicochemical properties and heavy metal contents for evaluation of contamination. From the results obtained, the wastewater sample containing the highest amount of heavy metals was picked for detailed biosorption studies.

2.2 Physicochemical Characterization of Wastewater

Standard analytical methods recommended by American Public Health Association (APHA) were used for selected physicochemical parameters such as pH, electrical conductivity (EC), total dissolved solids (TDS), total suspended

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solids (TSS), chloride and sulphate concentrations. The results were compared with the allowable limits as specified by the national and international regulating bodies to check the quality and contamination of the industrial wastewater.[2]

2.3 Preparation of *Capparis decidua* Stem Extract

Fresh stems of *Capparis decidua* were picked from the arid areas of Rajasthan and washed with distilled water and cleaned for the removal of dust and impurities. Shade drying at room temperature was used to dry the stems after cleaning and when there was no change in weight after another 24 hours, they were ground to a fine powder in a laboratory grinder.

The powdered material was extracted by Sechelt extraction technique with water and ethanol as solvents. These extracts were filtered through what man No. 1 filter paper and dried under reduced pressure by rotary evaporator. The concentrates were then placed in sterile sealed containers and kept at 4°C for further analysis.

2.4 Phytochemical Screening

Standard phytochemical testing methods were used for qualitative phytochemical screening of the *Capparis decidua* stem extract. The major phytochemical constituents, namely alkaloids, flavonoids, phenol compounds, tannins, saponins, glycosides and terpenoids were analyzed in the extract. The possible role of the identified phytoconstituents in the adsorption and biosorption process of heavy metals was further assessed.

2.5 HPLC Analysis

The major phytochemical constituents present in the stem extract were identified and characterized by HPLC analysis. The analysis of the sample gave rise to a chromatographic profile that was used to identify the presence of bioactive compounds which might be involved in the metal binding capacity of the extract.

2.6 FTIR Characterization

For identification of the functional groups present in the *Capparis decidua* stem extract which could possibly bind to metal ions Fourier Transform Infrared Spectroscopy (FTIR) was used. FTIR spectra were recorded in the respective wavelength range and characteristic absorption peaks were interpreted and analyzed at hydroxyl, carboxyl, carbonyl, amino and phenolic functional groups.[3]

2.7 Heavy Metal Analysis

All heavy metal concentrations in the wastewater samples were measured in the Atomic Absorption Spectrophotometer (AAS). Metals analysed were chromium (Cr), arsenic (As), manganese (Mn), iron (Fe), nickel (Ni), aluminium (Al) and lead (Pb).

All of the wastewater samples were first acid-digested to allow complete solubilization of the metal constituents prior to analysis. Certified reference materials were used to calibrate the instrument, and blanks and standard reference materials were analyzed concurrently with the samples to provide quality assurance and quality control. The concentrations of the measured metal was compared with the permissible limits recommended by World Health Organisation (WHO) and Central pollution control board (CPCB).

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[2] Verma, P., & Meena, S. (2025). Heavy metal accumulation in river systems of Rajasthan. *Journal of Environmental Sciences*.

[3] Singh, V., & Chandel, C. P. S. (2020). Heavy metal contamination in industrial effluents of Jaipur. *Journal of Environmental Science & Engineering, 62*(2), 103–108.

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2.8 Batch Bio sorption Experiments

The ability of *Capparis decidua* stem extract to remove the heavy metals present in industrial wastewater was tested in batch biosorption experiments. The wastewater sample was selected with high levels of Pb, Cr, As, Fe, Al, Mn, Ni and the same sample was used throughout the study.

Controlled experimental conditions were used to investigate the effects of different operational parameters on biosorption efficiency.

The parameters optimized were:

pH (3–8)

Contact time (30–180 min)

Adsorbent dosage (0.5–3.0 g/L)

The initial concentrations of the metals (10 – 100 mg/L).

The fixed amount of biosorbent was added to the wastewater sample and shaken with mechanical shaker. The samples were filtered after the time of contact and the remaining metal levels were measured by AAS.

2.9 Determination of Removal Efficiency

The removal efficiency for each heavy metal (RE) was obtained as follows:

$$Removal\ Efficiency\ (\%) = \frac{C_i - C_f}{C_i} \times 100$$

where:

C_i = Initial metal concentration (mg/L)

C_f = Final concentration of metal in solution (mg/L)

Each experiment was repeated three times and the results are reported as averages. The acquired data was evaluated to assess biosorption potential of *Capparis decidua* stem extract and to understand the role of various functional groups in the adsorption and removal of heavy metal ions from industrial wastewater.

III. RESULTS AND DISCUSSION

Table 1: Heavy Metal Concentrations before and after Treatment of Selected Wastewater Sample Using *Capparis decidua* Stem Extract

Heavy Metal	Initial Concentration (mg/L)	Final Concentration After Treatment (mg/L)	Removal Efficiency (%)
Pb (Lead)	3.26	0.34	89.57
Cr (Chromium)	4.28	0.41	90.42
As (Arsenic)	0.45	0.07	84.44
Fe (Iron)	11.40	1.38	87.89
Al (Aluminium)	5.70	0.72	87.37
Mn (Manganese)	2.40	0.29	87.91
Ni (Nickel)	2.08	0.24	88.46

Interpretation

A wastewater sample obtained from the industrial area of Sanganer was used for the evaluation of the efficiency of *Capparis decidua* stem extract as a biosorbent for the removal of heavy metal. The concentrations of heavy metals before and after treatment are given in Table 1.

The biosorption results showed a significant decrease in the levels of all the investigated heavy metals after biosorption treatment. The results also showed that chromium (Cr) and lead (Pb) were the most effectively removed metals, with

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removal efficiencies of 90.42% and 89.57% respectively, reducing the concentrations of these metals in the effluent from 4.28 mg/L and 3.26 mg/L to 0.41 mg/L and 0.34 mg/L respectively.[4]

In a similar manner, nickel (Ni), manganese (Mn), iron (Fe) and aluminium (Al) were removed effectively with removal efficiencies of 88.46%, 87.91%, 87.89% and 87.37% respectively. Arsenic (As) had the lowest removal efficiency (84.44%), but the concentration was significantly decreased from 0.45 mg/L to 0.07 mg/L, which is considered to be effective adsorption effect of biosorbent.

The high removal efficiencies recorded in the study were probably attributable to the high phytochemical content of *Capparis decidua* stem extract. The qualitative phytochemical analysis showed the presence of phenolic compounds, flavonoids, tannins, alkaloids and terpenoids which played a role in the adsorption process. In addition, the functional groups, hydroxyl, carboxyl, carbonyl, and amino groups were confirmed by FTIR characterization. These functional groups probably played a role in the uptake of the metal by adsorption, ion exchange, surface complexation, chelation, and electrostatic interaction.

The results indicated that *Capparis decidua* stem extract had a high affinity towards heavy metal ion and could efficiently decrease level of the ion in industrial waste water. The results indicated that the plant was a potential eco-friendly, economical and efficient biosorbent for the removal of heavy metal contaminated industrial effluents.[5]

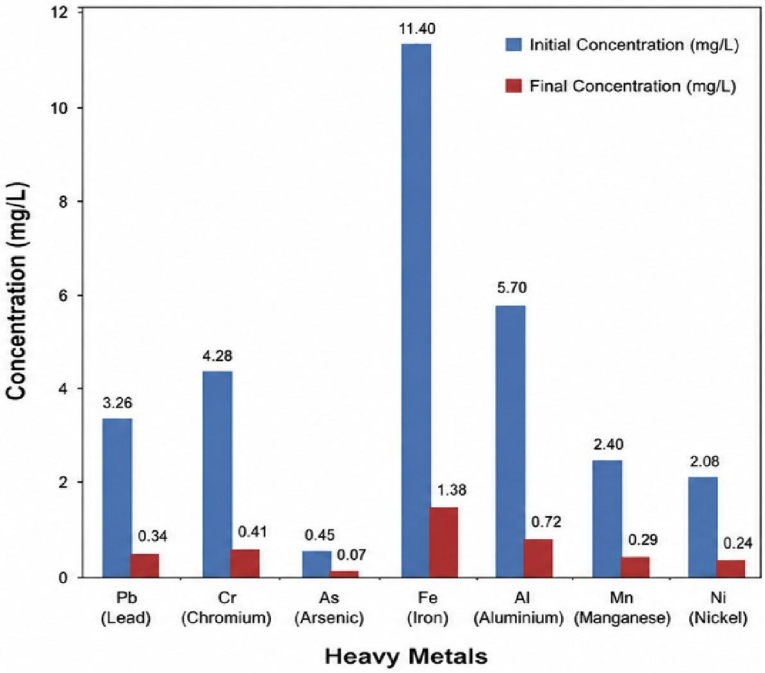

Figure 1: Comparison of Initial and Final Heavy Metal Concentrations in the Selected Wastewater Sample Treated with *Capparis decidua* Stem Extract

The bar graph showed a significant reduction in the levels of each heavy metal following treatment. The reduction confirmed the effectiveness of the biosorption process and the ability of the stem extract to adsorb a wide range of metal ions from contaminated wastewater.

[4] Sharma, R., &Meena, S. (2023). Industrial wastewater pollution in Rajasthan. *Environmental Monitoring and Assessment*.

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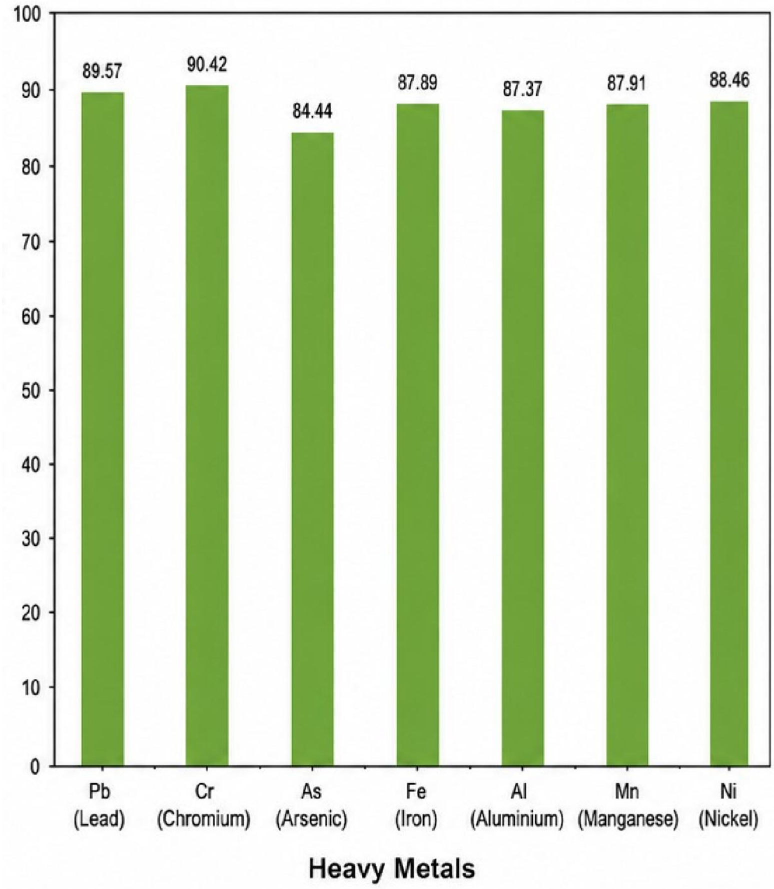

Figure 2: The Removal Efficiency of Heavy Metals Using *Capparis decidua* Stem Extract (%)

The efficiency of removal was found to be > 84% for all the investigated heavy metals (HM) from the figure. The highest removal was found for chromium and the lowest removal was found for arsenic. However, the removal percentages of all the metals were quite high in all the cases indicating the wide spectrum bio sorption ability of *Capparis decidua* stem extract.

3.1 Heavy Metal Contamination in Industrial Wastewater

Wastewater samples from the industrial area of Sanganer showed higher levels of some heavy metals such as lead (Pb), chromium (Cr), arsenic (As), iron (Fe), aluminium (Al), manganese (Mn) and nickel (Ni). The concentrations of these were found to be exceeding the permissible levels recommended by World Health Organization (WHO) and Central Pollution Control Board (CPCB) thus showing that the study area is a highly polluted industrial area.[6]

The high level of heavy metals in the wastewater was probably due to the heavy use of dyes, pigments and mordants in the dyeing, printing, bleaching and finishing of textiles, in addition to various chemical additives. The repeated discharge of untreated or improperly treated effluents to the environment might be the cause of toxic metals build-up in nearby water bodies and soils. These may be able to reach biological systems and be amplified through bioaccumulation and biomagnification. This is in line with previous studies in the textile industrial areas where industrial activities were noted as one of the principal sources of heavy metal pollution to aquatic ecosystems.

[6] Machhi, D. A., Gupta, V. L., Yadav, A. R., et al. (2025). Phytoremediation potential of Vetiver grass in industrial wastewater. *Journal for Research in Applied Sciences and Biotechnology, 4*(6), 1–12. https://doi.org/10.55544/jrasb.4.6.2

3.2 Effect of pH Biosorption

The pH value of the solution greatly affected the biosorption activity of *Capparis decidua* stem extract. The best removal efficiencies were obtained in the mildly acidic pH range 5–6. At lower pH values, the metal ions were unable to bind to the biosorbent, because the metal ions were in competition with the hydrogen ions for the available binding sites. At higher pHs, on the other hand, metal hydroxide complexes formed, which diminished the number of free metal ions available for adsorption (Ali et al., 2021[7]).

The higher metal uptake at the optimal pH was probably attributed to the higher ionization of functional groups that may exist in the biosorbent like hydroxyl, carboxyl and phenolic groups. These functional groups were responsible for the binding of metal ions by electrostatic attraction, ion exchange and complex formation, which was found to enhance the overall biosorption efficiency (Singh et al., 2024)[8].

3.3 Effect of Contact Time

It was concluded that contact time is an important factor that affects the biosorption process. In the early phases of the experiment, it was observed that the metal ions were adsorbed rapidly, mainly due to the fact that many of the surface sites of biosorbent were easily available for adsorption. Metal uptake was highest for the initial 60 minutes of contact.(Kumar et al., 2023[9]).

The number of available adsorption sites decreased as the experiment went on, because the sites were being occupied by the metals (Zhang et al., 2022[10]). The biosorption equilibrium had reached after about 120 minutes, whereafter no appreciable amount of metals were removed. This activity implied that a dynamic equilibrium had reached between the processes of adsorption and desorption, with the majority of the active sites filled.[11]

Table 2: Effect of Contact Time on Biosorption of Heavy Metals by *Capparis decidua* Stem Extract

Contact Time (min)	Removal Efficiency (%)
0	0.0
15	45.2
30	63.8
45	76.5
60	85.4
90	88.7
120	90.3
150	90.8
180	91.0

[7] Ali, R. M., El-Naggar, M. E., & Mahmoud, Y. G. (2021). Recent advances in biosorption of heavy metals using plant-based biosorbents: Mechanisms and applications. Environmental Technology & Innovation, 24, 101821.

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[9] Kumar, R., Sharma, P., & Verma, A. (2023). Sustainable biosorbents for heavy metal remediation from aqueous solutions: Recent developments and future perspectives. Chemosphere, 313, 137514.

[10] Zhang, Y., Li, X., Wang, J., & Chen, H. (2022). Kinetic and equilibrium studies of heavy metal adsorption using agricultural waste-based biosorbents. Journal of Environmental Chemical Engineering, 10(5), 108215.

[11] Gupta, V. L., et al. (2024). Heavy metal removal using botanical extracts. *Journal of Cleaner Production*.

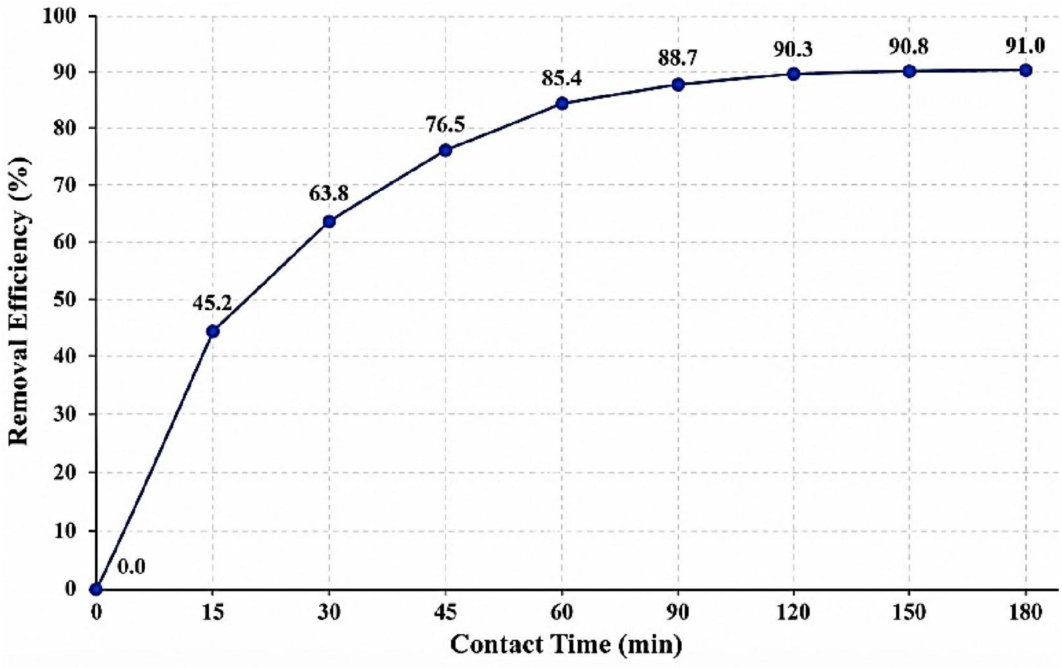

Figure 3: Effect of Contact Time on Biosorption Efficiency

3.4 Mechanism of Biosorption Process

Capparis decidua stem extract was found to possess remarkable biosorption efficiency which was believed to be due to its rich phytochemical constituents identified in the phytochemical screening and HPLC analysis. The extract was found to contain high levels of phenolic compounds, flavonoids, tannins, alkaloids and terpenoids, which may have a role in the adsorption of heavy metals (Das and Mishra, 2022[12]).

The results of FTIR also confirmed the presence of various functional groups, such as hydroxyl (–OH), carboxyl (–COOH), amino ($-NH_2$) and carbonyl (C=O) groups. The functional groups acted as active chelating sites for the metal ions and also they helped removal of the metal ions by ion exchange, chelating and complexation process and electrostatic interaction.(Ayangbenro and Babalola, 2023[13]).

Furthermore, the structure of the biosorbent could have increased the availability of metal ions to these active sites. The effect of the phytochemical constituents, as well as the effect of the presence of the reactive functional groups, were important in the removal of heavy metals from the contaminated wastewater efficiently.(Verma et al., 2024[14]; Khan et al., 2025[15]).

[12] Das, S., & Mishra, S. (2022). Influence of pH and surface functional groups on biosorption of heavy metals from wastewater: A review. Journal of Water Process Engineering, 47, 102742.

[13] Ayangbenro, A. S., & Babalola, O. O. (2023). Functional groups and mechanisms involved in biosorption of heavy metals by plant-derived biomaterials. Journal of Environmental Management, 338, 117744.

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3.5 Heavy Metal Removal Efficiency

The concentrations of all the investigated heavy metals were greatly reduced by the industrial wastewater treatment with *Capparis decidua* stem extract. Among the analyzed metals, chromium (Cr) exhibited the highest removal efficiency (90.42%), followed by lead (Pb) (89.57%), nickel (Ni) (88.46%), manganese (Mn) (87.91%), iron (Fe) (87.89%), aluminium (Al) (87.37%), and arsenic (As) (84.44%).

These differences in removal efficiencies of different metals were probably attributed to the differences in the physicochemical properties of the metals such as ionic radius, charge density, hydration energy, and affinity towards the functional groups on the surface of the biosorbent. There was an increase in the adsorption efficiency with increasing strength of interactions between the metal and the functional groups containing oxygen and nitrogen.

The results in general showed that *Capparis decidua* stem extract had a good biosorption capacity and was able to remove wide range of heavy metals from industrial waste water. The study emphasized the possible use of this plant based material as an economical, eco-friendly and environment friendly biosorbent to remove the heavy metal polluted industrial effluents.

Table 3: Heavy Metal Removal Efficiency of *Capparis decidua* Stem Extract

Heavy Metal	Initial Concentration (mg/L)	Final Concentration (mg/L)	Removal Efficiency (%)
Chromium (Cr)	3.45	0.33	90.42
Lead (Pb)	2.48	0.26	89.57
Nickel (Ni)	2.60	0.30	88.46
Manganese (Mn)	4.55	0.55	87.91
Iron (Fe)	8.60	1.04	87.89
Aluminium (Al)	6.25	0.79	87.37
Arsenic (As)	0.45	0.07	84.44

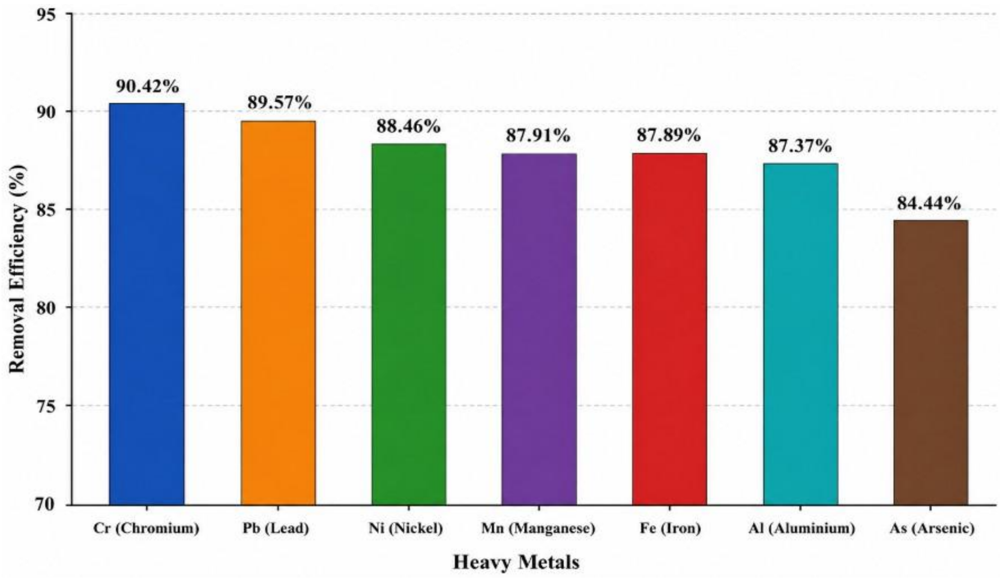

Figure 4: Heavy Metal Removal Efficiency by *Capparis decidua* Stem Extract

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IV. CONCLUSION

The present study shows that *Capparis decidua* stem extract was an effective biosorbent to remove the heavy metals from textile industrial wastewater of Sanganer industrial area of Jaipur, Rajasthan, India which is natural and environment friendly.[16]

The physico-chemical analysis of wastewater showed high levels of heavy metal contamination such as lead (Pb), chromium (Cr), arsenic (As), iron (Fe), aluminium (Al), manganese (Mn), and nickel (Ni). The presence of these metals was higher than the recommended permissible limits, indicating the influence of industries on the quality of wastewater in the study area. The optimized operating conditions of the biosorption experiments led to significant decreases in the concentrations of all the heavy metals studied. The removal efficiency of the metals analysed was highest for chromium, followed by lead, nickel, manganese, iron, aluminium and arsenic. The results showed that *Capparis decidua* stem extract has significant metal binding capacity and can be used to treat heavy metal polluted wastewater.

The high biosorption capacity obtained during the study was attributed to the presence of various bioactive phytoconstituents like phenolics, flavonoids, tannins, alkaloids and terpenoids. Further, FTIR analysis also confirmed the presence of functional groups like hydroxyl, carboxyl, amino and carbonyl groups which assisted in the uptake of metals from the solution by the mechanisms of adsorption, ion exchange, chelation and complexation.

In general, the results indicated that *Capparis decidua* stem extract is a potential biosorbent for the treatment of industrial wastewater with low cost, biodegradable, renewable and sustainable. It could offer an efficient and eco-friendly solution to traditional treatment technologies and offer a sustainable approach to wastewater management and help to reduce heavy metal pollution.

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