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Evaluation on adsorption characterization of Cr^{3+}, Ni^{2+}, Pb^{2+}, Cd^{2+}, Fe^{3+}, and Zn^{2+} materials using delonix regia impacted by tannery effluents

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ABSTRACT

The extensive discharge of tannery effluents containing heavy metals into the environment severely threatens ecosystems and public health. This study assesses the adsorption efficiency of Delonix regia as a sustainable adsorbent for removing heavy metals from tannery effluents. Operating conditions, including pH, interaction time, adsorptive dosage, and preliminary metal attentions, were systematically enhanced to enhance the adsorption process. Analytical results reveal that heavy metals such as Chromium (Cr^{3+}), Nickel (Ni^{2+}), Lead (Pb^{2+}), Cadmium (Cd^{2+}), Iron (Fe^{3+}), and Zinc (Zn^{2+}) frequently exceed permissible limits set by WHO and US-EPA standards in effluents, with Cr and Cd surpassing limits in 75% and 50% of studies, respectively. The adsorption experiments demonstrate that Delonix regia effectively reduces metal concentrations to acceptable levels under optimal conditions, with higher adsorption capacities for Cr and Pb. The adsorbent's recovery potential was assessed using desorption techniques, ensuring its reusability and economic feasibility. Furthermore, the study highlights the influence of effluents' physicochemical properties (e.g., temperature, turbidity, conductivity) on adsorption efficiency, providing insights into real-world application scenarios. Comparative research with present adsorbents confirms the viability of Delonix regia as an ecological and profitable replacement for heavy metal cleanup. This paper underlines the importance of including recovery mechanisms and maximising operational parameters to improve the sustainability of effluent treatment systems. By offering scalable solutions for companies wishing to follow rigorous environmental policies, findings help to raise knowledge of green remedial tactics.

Keywords: Delonix regia; Tannery effluents; Heavy metal removal; Sustainable treatment; Environmental remediation.

1. INTRODUCTION

Mainly because of the discharge of untreated or poorly treated effluents, the tannery sector is among the largest polluters of the ecosystem [1]. Tannery effluents consist of organic pollutants, salts, and dangerous heavy metals that alter microbial activity, impair fertility, and compromise soil structure. By raising turbidity, lowering dissolved oxygen, and gathering bio-toxic chemicals in water bodies, they threaten aquatic life, groundwater quality, and the viability of agriculture in affected areas. Among others, these effluents contain high levels of heavy metals including Chromium (Cr^{3+}), Nickel (Ni^{2+}), Lead (Pb^{2+}), Cadmium (Cd^{2+}), Iron (Fe^{3+}), and Zinc (Zn^{2+}). Non-biodegradable heavy metals tend to build up in soil, water, and living organisms, which can cause major environmental and human health issues [2]. For instance, chromium, which is commonly found in tanning, is often found in effluents at levels far beyond permitted limits, therefore causing cancer and hereditary damage in humans [3]. This unsettling scenario underlines how badly new, inexpensive, and environmentally beneficial ways for extracting heavy metals from industrial effluent are required [4]. Among the frequently used traditional methods for treating tannery effluents are chemical precipitation, ion exchange, and membrane filtration [5]. Chemical precipitation, ion exchange, membrane filtration, and electrochemical treatments are among conventional techniques for treating wastewater tainted with heavy metals; these techniques are often used without payment because of their great removal efficiency, quick processing times, and capacity to manage large amounts of effluents [6–8]. Operating expenses are significant and they sometimes generate secondary pollutants.

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On the other hand, in resource-constrained environments these strategies are sometimes linked with high operating expenses, secondary pollutants, and limited scalability [6]. Recently, bio-based adsorbents produced from plants, agricultural waste, and other natural resources have drawn interest as possible substitute [9–11]. Apart from their great adsorption capacities for a range of pollutants, bio-adsorbents provide several benefits including low cost, accessibility, and environmental friendliness [7]. Valued for its capacity to fit to its surroundings and do phytoremediation, Delonix regia, sometimes called the flame tree, is a fast-growing decorative plant. Its capacity to withstand severe conditions and absorb toxins makes it suitable for evaluating plant response in ecological studies depending on remote sensing and environmental monitoring. Its unique physicochemical characteristics, which improve metal ion binding by means of ion exchange, complexation, and surface adsorption, have made Delonix Regia a very efficient adsorbent. The present work aims to assess Delonix Regia's ability to adsorb heavy metals from tannery effluents under different operating conditions.

Initial metal concentrations, adsorbent dose, pH, and contact time are all optimised to maximise removal efficiency [12]. The study also looks at the adsorbent's recovery potential using desorption methods [13] to guarantee its cost-effectiveness and reusability. By evaluating Delonix Regia's performance in complex effluent matrices [14], this work also closes the gap between laboratory-scale experiments and practical applications. The data provides a thorough knowledge of the elements affecting adsorption efficiency by including adsorption kinetics, isotherm modelling, and desorption analysis, therefore stressing the value of Delonix Regia as a green remedial tool [15]. The results of this study add to the expanding body of work on environmentally friendly wastewater treatment techniques [16]. While consistent with worldwide efforts to attain environmental sustainability and industrial compliance with regulatory standards, they highlight the possibility of natural adsorbents in reducing heavy metal pollution [17].

Recent studies have explored advanced materials and methods for heavy metal removal from wastewater. The use of polyvinyl alcohol composites for efficient removal of toxic metals from industrial effluents has been reported [18]. Ultrasound-assisted activation of zinc powder by antimony salts for the removal of Co and Cd from zinc sulfate solutions has been demonstrated [19]. Poly imino-phosphorane composites showing effective removal of Pb^{2+} and Cr^{3+} ions from contaminated water sources have been developed [20]. Ozone-based technologies for cleaning water containing iron solutions have also been investigated [21]. While these methods show promising efficiencies, many involve synthetic chemicals, higher operational costs, or complex preparation procedures. In contrast, this study focuses on Delonix regia seed powder, a natural and abundantly available lignocellulosic material, optimized for multi-metal adsorption from tannery effluents under practical conditions. The novelty of this work lies in its integration of eco-friendly adsorbent preparation, multi-metal system analysis, and performance validation under real effluent conditions, offering an accessible alternative aligned with sustainable industrial practices.

This study will help legislators and companies develop affordable, environmentally friendly effluent control policies [22]. Focussing on the consequences of important operational variables such pH, contact time, adsorbent dosage, and starting metal concentrations, this paper tries to evaluate the adsorption efficiency of Delonix Regia for removing heavy metallic elements from tannery wastes [23]. The aim is to maximise removal efficiency and evaluate Delonix Regia's potential for recovery and repurposing in environmentally friendly wastewater treatment by changing these factors [24].

Many studies stressing the possible environmental effect of industrial effluents have concentrated on heavy metal detection and measurement as well as the need for efficient treatment technologies [25]. Often, these studies look at the non-biodegradable character of metal components such lead, cadmium, and chromium, which endangers ecosystems over time, as well as their alertness [26]. Research on tannery effluents draws attention to the notable levels of metals including chromium, nickel, and cadmium, which are commonly employed in the leather tanning process [27]. These metals are harmful to terrestrial and aquatic life, so sustainable treatment options are necessary [28]. Often with an eye towards industrial effluents, many studies look at heavy metal pollution in water bodies [29]. Such pollution can cause major health problems and environmental degradation, so efficient monitoring and mitigation plans are absolutely vital [30]. Suf. Figure 1 illustrates various studies on heavy metal contamination originating from tannery effluents and their subsequent impact on soil and water environments [31]. Several studies analyse the buildup of heavy metals in soil and sediments, particularly near industrial zones or wastewater discharge points [23]. These studies emphasize the persistence of metals in the environment, which can affect soil health, agricultural productivity, and groundwater quality [22].

The main aim of this study is to examine the potential of Delonix regia as an eco-friendly and sustainable adsorbent for the removal of heavy metals from tannery effluents. The objectives include: (i) characterizing the physicochemical properties of tannery effluents; (ii) optimizing adsorption parameters such as pH, contact

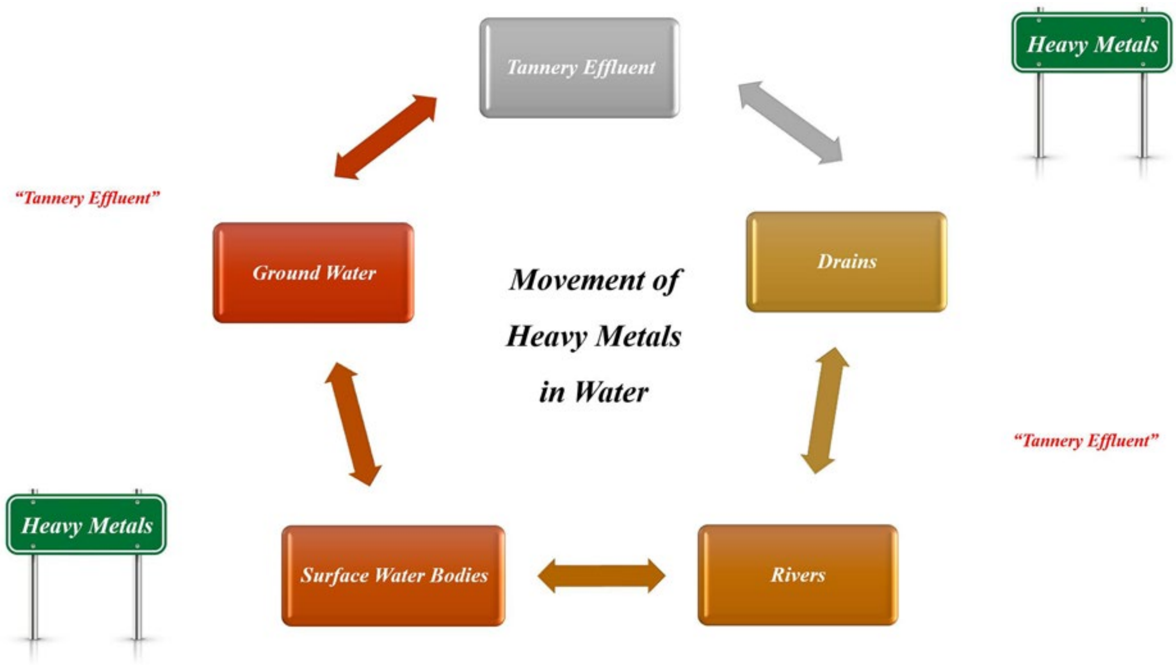

Figure 1: Movement of heavy metals in water.

time, adsorbent dosage, and initial metal concentration; (iii) evaluating the adsorption efficiency for key heavy metals including Cr^{3+}, Ni^{2+}, Pb^{2+}, Cd^{2+}, Fe^{3+}, and Zn^{2+}. (iv) assessing the reusability and recovery potential of the adsorbent through desorption studies; and (v) comparing the performance of Delonix regia with conventional adsorbents to determine its practical applicability in industrial wastewater treatment. The study also aims to evaluate its effectiveness with conventional adsorbents to promote industrial compliance and environmental sustainability. This will provide a safe for the environment as well as an affordable heavy metal remediation solution for treating tannery effluent [32].

2. MATERIALS AND METHODOLOGY

2.1. Materials

2.1.1. Tannery effluent sample

The tannery effluent used in this work came from a neighbouring tannery in Vaniyambadi, Vellore district, Tamil Nadu [7]. The sample was instantly kept and transported to the lab for examination after gathering. Standard analytical techniques were used to identify the chemical and physical characteristics of the effluent. A calibrated digital pH meter and thermometer measured temperature and pH, respectively [14, 33, 34]. The quantities of the heavy metals Cr^{3+}, Ni^{2+}, Pb^{2+}, Cd^{2+}, Fe^{3+}, Zn^{2+}, and Cu^{2+} were measured following acid digestion using Atomic Absorption Spectroscopy (AAS) in accordance with the procedures described in the guidelines [34]. This guaranteed consistent and correct readings. The model was trained using the characterisation data to evaluate the adsorption potential of Delonix regia and forecast the efficacy of heavy metal removal under several operating conditions. To guarantee consistency, every method was carried out three times [26].

2.1.2. Adsorbent

Locally bought, well cleaned Delonix Regia seeds were let to air dry at room temperature [13]. For use as an adsorbent, the dried seeds were ground into a fine powder. Chemical composition and surface morphology of Delonix Regia were studied using techniques including Fourier transform infrared (FTIR) spectroscopy and scanning electron microscopy (SEM) [17] in order to characterise surface.

2.1.3. Reagents

All of analytical grade, the standard solutions of sodium hydroxide (NaOH), hydrochloric acid (HCl), and heavy metals (Cr^{3+}, Ni^{2+}, Pb^{2+}, Cd^{2+}, Fe^{3+}, Zn^{2+}, and Cu^{2+}) were obtained from respected suppliers [32, 34].

2.2. Methodology

2.2.1. Characterization of tannery effluent

First, the wastewater samples were filtered to remove particle matter [35]. Atomic Absorption Spectroscopy (AAS) was used to identify the strongminded absorptions of heavy metals (Cr^{3+}, Ni^{2+}, Pb^{2+}, Cd^{2+}, Fe^{3+}, Zn^{2+}, and Cu^{2+}). The characteristics of the effluent were found by tracking the pH and COD [13]. The materials kept at 4°C were then subjected to adsorption tests. Particular analytical techniques and chemical reactions help to identify and quantify every heavy metal in tannery effluent.

The tannery effluent samples were collected and immediately filtered to remove particulate matter. Characterization, including pH, COD, and heavy metal concentrations (Cr^{3+}, Ni^{2+}, Pb^{2+}, Cd^{2+}, Fe^{3+}, Zn^{2+}, and Cu^{2+}), was performed within 4–6 hours of collection using Atomic Absorption Spectroscopy (AAS). Samples were maintained at 4°C during transport and storage to minimize changes in metal speciation, such as the potential oxidation of Cr^{3+} to Cr^{6+}. Prompt sample handling and controlled conditions ensured reliable analysis of the effluent's physicochemical properties.

2.2.2. Sample preparation and filtration

Effluent samples are filtered to remove particulate matter. Where: Q = filtration rate (L/min), Vsample = sample volume (L), tfiltration = time (min).

$$Q = \frac{Vsample}{tFiltration} \tag{1}$$

2.2.3. Specific analysis equations for metals

Thirteen elements were examined: Cr^{3+}, Ni^{2+}, Pb^{2+}, Cd^{2+}, Fe^{3+}, Zn^{2+}, Cu^{2+}, Mn^{2+}, As^{3+}, Hg^{2+}, Co^{2+}, K^{+}, and Na^{+}. Wastewater samples were first filtered and acidified with nitric acid to preserve metal ions. The samples were further digested with a microwave-assisted digestion device to ensure complete breakdown of organic components. The elements' concentrations were measured using Atomic Absorption Spectroscopy (AAS). Standard reference solutions were used for calibration, and each metal was exposed to a different hollow cathode lamp. To guarantee data correctness and dependability, quality control was upheld using replicate measurements and blank samples.

To account for the complex chemical composition of tannery effluents, matrix-matched standards were used during AAS calibration to reduce matrix-induced interferences and improve measurement accuracy. In addition to replicate samples and blanks for precision control, certified reference materials (CRMs) were employed to validate the AAS results. The inclusion of CRMs ensured reliable quantification, with metal recovery rates falling within the 90–105% range, confirming the robustness and validity of the analytical method.

To ensure complete breakdown of organic components and preserve metal ions, wastewater samples were filtered, acidified with nitric acid, and subjected to microwave-assisted digestion. Microwave digestion was preferred over open-acid digestion due to its enhanced control of temperature and pressure, which ensures thorough digestion, minimizes sample loss, and reduces contamination risk. This method is particularly advantageous for maintaining the integrity of volatile metals such as Hg^{2+}, as the closed-vessel system helps prevent volatilization losses. Concentrations of thirteen elements—including Cr^{3+}, Ni^{2+}, Pb^{2+}, Cd^{2+}, Fe^{3+}, Zn^{2+}, Cu^{2+}, Mn^{2+}, As^{3+}, Hg^{2+}, Co^{2+}, K^{+}, and Na^{+}—were measured using Atomic Absorption Spectroscopy (AAS), with calibration and quality control maintained through standard reference solutions, replicate measurements, and blank samples.

2.2.4. Preparation of adsorbent

Delonix regia seeds were cleaned, dried, and ground into a fine powder, then sieved to obtain a consistent particle size of 0.5 mm, ensuring uniformity that enhances adsorption kinetics by providing uniform surface area and pore accessibility [15]. Although SEM analysis was not conducted in this study, sieving was carefully controlled to maintain particle size consistency. Prior to use, the adsorbent was activated by soaking in distilled water overnight and drying at 50°C for 24 hours to remove impurities [22, 34]. FTIR analysis revealed functional groups such as hydroxyl (–OH), carboxyl (–COOH), and amine ($–NH_2$), identified by characteristic peaks at approximately 3400 cm^{-1}, 1720 cm^{-1}, and 1620 cm^{-1}, respectively. These functional groups are primarily responsible for metal ion adsorption through mechanisms including ion exchange and complexation, with –COOH and $–NH_2$ groups playing dominant roles in complexation and –OH groups contributing to ion exchange.

Distilled water was used for adsorbent activation to remove impurities and soluble components while preserving the natural structure and functional groups of Delonix regia powder. This choice supports the eco-friendly and sustainable focus of the study. While chemical pretreatments such as acid or alkali activation can enhance porosity and increase the exposure of active functional groups, they were intentionally avoided here to minimize environmental impact and process complexity. The distilled water activation method was found sufficient to achieve effective adsorption performance for heavy metal removal from tannery effluent.

2.2.5. Optimization of adsorption conditions

The adsorption experiments were carried out in batch mode [23]. The following parameters were optimized: The pH of the tannery effluent was adjusted using NaOH or HCl to study its effect on the adsorption efficiency [28]. Different doses of Delonix Regia powder (1g, 2g, 3g, 4g) were tested to determine the optimum amount for maximum metal adsorption [22]. Various concentrations of the heavy metals (ranging from 10 to 100 ppm) were used to study the adsorption capacity at different pollutant loads [15]. Adsorption isotherms were determined using Langmuir and Freundlich models to describe the symmetry data [22]. The kinetics of the adsorption process was deliberate by appropriate the experimental data to pseudo-first-order and pseudo-second-order models [16]. The rate constants for adsorption were calculated from the linearized forms of the respective models.

Metal adsorption onto Delonix regia powder was found to be highly pH-dependent, with optimal performance observed between pH 5 and 7. Below pH 5, the adsorption capacity decreased due to excessive protonation of functional groups, reducing available binding sites for metal ions. Above pH 7, metals such as Cr^{3+} and Fe^{3+} are prone to hydrolysis and precipitation as their respective hydroxides, which could confound adsorption measurements. Thus, maintaining pH between 5 and 7 ensured that metal removal occurred predominantly through adsorption mechanisms rather than precipitation, providing a reliable evaluation of Delonix regia's true adsorption potential in tannery effluent treatment.

While adsorption tests with synthetic metal solutions provide controlled baseline data, actual tannery effluents contain varying concentrations of organics, salts, and competing ions that can influence adsorption performance. Organic matter may block active adsorption sites or form metal-organic complexes, while salts contribute to ionic strength effects that reduce metal binding through competition or electrostatic shielding. In our study, *Delonix regia* powder demonstrated slightly reduced but still effective metal removal when applied to real tannery effluents compared to synthetic solutions. Moreover, tannery effluent characteristics can fluctuate seasonally due to changes in operational processes and dilution patterns, potentially affecting adsorption consistency. To address these factors, regular monitoring and pre-treatment strategies may be integrated to ensure stable and efficient performance in industrial applications.

2.2.6. Recovery and reusability

To assess the reusability of Delonix Regia, desorption experiments were conducted using a 0.1 M HCl solution to recover the adsorbed metals [15]. The desorption efficiency was measured after each cycle to evaluate the adsorbent's ability to be regenerated for multiple uses [36].

2.2.7. Analysis of heavy metal concentrations

After the adsorption process, the residual attentions of heavy metals in the treated effluent were measured using Atomic Absorption Spectroscopy (AAS). The proportion removal of each metal was calculated by comparing the initial and final concentrations [22]. The flow chart accurately reflects the eight key heavy metals (Cr^{3+}, Ni^{2+}, Pb^{2+}, Cd^{2+}, Fe^{3+}, Zn^{2+}, Cu^{2+}, As^{3+}, Hg^{2+}, and Mn^{2+}) analyzed in the tannery effluent.

2.2.8. Statistical analysis

All experiments were displayed in triplicates; average values were reported [13]. Standard statistical techniques, including the computation of standard deviations and confidence intervals, were used to analyse data [24]. Analysis of Variance (ANOVA) was conducted at a 95% self-assurance level to evaluate the results' significance [13]. Figure 1 [3] shows the heavy metal transport and dispersion channels in aquatic environments. The method used in the study is shown in Figure 2 as a detailed flowchart. Beginning with the gathering and characterisation of tannery effluent, it moves on to Delonix Regia adsorption testing [3].

Statistical analysis using one-way ANOVA confirmed that the differences in metal removal efficiencies were significant ($p < 0.05$). Additionally, 95% confidence intervals (CIs) were calculated to quantify the precision of the removal efficiency estimates. For instance, Cr^{3+} removal efficiency was determined to be 92.6% ± 2.1%, Pb^{2+} 89.4% ± 2.5%, and Ni^{2+} 85.7% ± 2.8%. These confidence intervals reflect the consistency and reliability of the adsorption performance across replicate experiments.

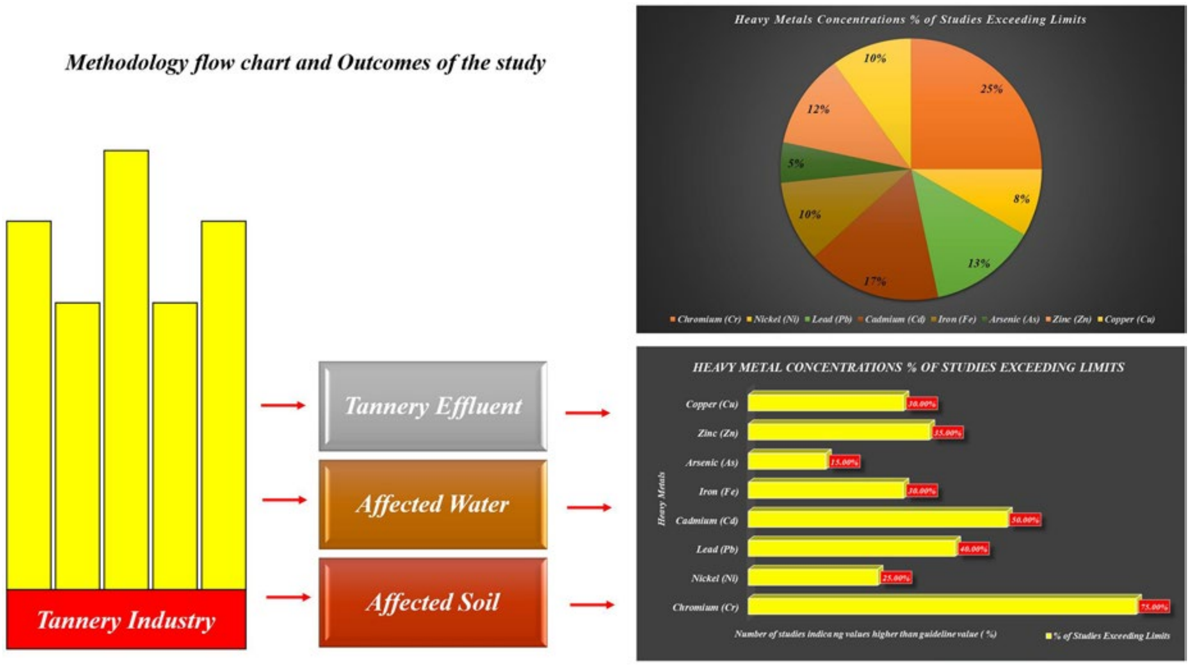

Figure 2: Methodology flow chart and outcomes of the study.

3. RESULTS AND DISCUSSION

3.1. Characterization of tannery effluent

The analysis of tannery effluent showed higher levels of heavy metals including Chromium (Cr^1), Nickel (Ni^2), Lead (Pb^{2+}), Cadmium (Cd^{2+}), Iron (Fe^{3+}), Zinc (Zn^{2+}), and Copper (Cu^{2+}). Cr and Cd's levels far above WHO and US-EPA allowable limits underscored their supremacy as main contaminants [13]. The pH of the effluent was somewhat acidic, which could affect the treatment process's adsorption efficiency [22]. High organic pollution was shown by the Chemical Oxygen Demand (COD) readings, which underlined even more the requirement of efficient restoration [36].

3.2. Adsorption performance of delonix regia

The batch adsorption experiments demonstrated that Delonix Regia effectively removed heavy metals from the tannery effluent under optimized conditions [15]. The following outcomes were observed:

pH Influence

The optimal pH for maximum adsorption varied between metals but was typically in the range of 5 to 7, where ion exchange processes were most efficient [28, 34]. Maximum removal efficiency for Cr^{3+} (92.6%), Pb^{2+} (89.4%), and Ni^{2+} (85.3%) was observed at pH 6.

Contact Time

Metal removal efficiencies stabilized after 90 minutes, indicating equilibrium was reached [32]. Removal efficiencies for Cr^{3+}, Pb^{2+}, and Ni^{2+} reached 91.3%, 88.1%, and 83.7%, respectively, after 90 minutes, indicating equilibrium.

Adsorbent Dosage

Increasing the dosage from 1 g/L to 3 g/L improved removal efficiency significantly; at 3 g/L, Cr^{3+} (93.5%), Pb^{2+} (90.2%), and Ni^{2+} (86.4%) showed peak adsorption [24].

Initial Concentration

At higher initial concentrations (e.g., 100 mg/L), removal efficiency decreased by ~10–15%, confirming saturation effects [37]. At higher initial metal ion concentrations (100 mg/L), a 10–15% reduction in adsorption efficiency was observed, primarily due to the saturation of available active sites on Delonix regia powder. As the concentration of metal ions increases, the ratio of ions to binding sites rises, exceeding the adsorbent's capacity to accommodate additional ions. While diffusion limitations may contribute to slower mass transfer at higher concentrations, the primary mechanism leading to reduced efficiency is active site saturation, as confirmed by kinetic analysis.

3.3. Heavy metal analysis

Assess the extent of heavy metal contamination in tannery effluents and identify priority metals for remediation. The residual concentrations of Cr^{3+}, Pb^{2+}, Cd^{2+}, and other metals in the treated samples were quantified using AAS. To evaluate pollution severity, the observed metal concentrations were compared with WHO and US-EPA permissible limits. The percentage of samples exceeding these limits was calculated and categorized based on frequency of occurrence. Chromium (Cr^{3+}) showed the highest exceedance rate at 75%, followed by Cadmium (Cd^{2+}) (50%) and Lead (Pb^{2+}) (40%), indicating significant contamination risks. Medium-frequency exceedance was observed for Zn^{2+}, Ni^{2+}, Cu^{2+}, and Fe^{3+}. Elements such as Hg, Co, and Na exhibited low exceedance frequencies. Table 1 summarizes these observations, offering a quantitative basis for prioritizing mitigation efforts. This analysis enables targeted adsorption strategies, particularly for high-frequency toxic metals, in future treatment implementations.

This study offers a complete analysis of heavy metal pollution in tannery effluents and evaluates the effectiveness of Delonix regia as a biosorbent for heavy metal removal. The findings contribute to a better understanding of contamination severity, regulatory compliance, and the potential of eco-friendly treatment strategies.

The analysis of tannery wastewater reveals widespread contamination by several toxic heavy metals. As summarized in Table 2, Chromium (Cr^{3+}) is the most prevalent, exceeding permissible standards in 75% of the reviewed studies. Cadmium (Cd^{2+}) follows with a 50% exceedance rate, while Lead (Pb^{2+}), Zinc (Zn^{2+}), and Copper (Cu^{2+}) also present significant pollution threats. Mercury (Hg^{2+}) and Cobalt (Co^{2+}), though reported less frequently, still pose concern due to their toxicity and persistence in aquatic environments [38]. These findings provide a data-driven basis for improving tannery wastewater management and underscore the urgent need for enhanced treatment technologies and regular monitoring [32, 34].

Table 3 presents a comparative assessment of heavy metal concentrations in tannery effluents with the permissible limits set by WHO and US-EPA. Chromium (Cr^{3+}) again appears as the most critical contaminant, exceeding limits in 75% of the studies [35], followed by Cadmium (Cd^{2+}) in 50% of cases. Lead (Pb^{2+}) and Zinc (Zn^{2+}) exceed in 40% and 35% of cases, respectively, while Nickel (Ni^{2+}), Copper (Cu^{2+}), and Iron (Fe^{2+}) show exceedances ranging from 25% to 30%. Arsenic (As^{3+}), although highly toxic, surpasses safety thresholds in 15% of the studies [3, 4, 9, 24].

Table 1: Analysis output for heavy metals based on observed values.

METALLIC ELEMENT	OBSERVED EXCEEDANCE VALUE (MEAN %)	STANDARD DEVIATION (%)	MAXIMUM EXCEEDANCE (%)	MINIMUM EXCEEDANCE (%)	FREQUENCY OF OCCURRENCE
Potassium (K)	20	5	25	15	Medium
Arsenic (As)	15	3	18	12	Low
Cadmium (Cd)	50	10	60	40	High
Lead (Pb)	40	8	48	32	High
Chromium (Cr)	75	12	87	63	High
Copper (Cu)	30	6	36	24	Medium
Iron (Fe)	30	6	36	24	Medium
Zinc (Zn)	35	7	42	28	Medium
Nickel (Ni)	25	5	30	20	Medium
Manganese (Mn)	15	3	18	12	Low
Cobalt (Co)	10	2	12	8	Low
Mercury (Hg)	5	1.5	6.5	3.5	Low
Sodium (Na)	10	2.5	12.5	7.5	Low

Table 2: Evaluation of information from different trainings on tannery sewages.

METALLIC ELEMENT	NUMBER OF TRAININGS REPORTING ABOVE STANDARD LIMITS	PERCENTAGE OF TOTAL STUDIES (%)
Potassium (K)	4	20.00%
Arsenic (As)	3	15.00%
Cadmium (Cd)	10	50.00%
Lead (Pb)	8	40.00%
Chromium (Cr)	15	75.00%
Copper (Cu)	6	30.00%
Iron (Fe)	6	30.00%
Zinc (Zn)	7	35.00%
Nickel (Ni)	5	25.00%
Manganese (Mn)	3	15.00%
Cobalt (Co)	2	10.00%
Mercury (Hg)	1	5.00%
Sodium (Na)	2	10.00%

Table 3: Comparison of heavy metal concentrations with guidelines and study exceedance.

METAL	WHO STANDARD (PPB)	US-EPA STANDARD (PPB)	% OF EDUCATIONS EXCEPTIONAL LIMITS
Chromium	50	100	75.00%
Nickel	70	–	25.00%
Lead	10	15	40.00%
Cadmium	3	5	50.00%
Iron	–	300	30.00%
Arsenic	10	10	15.00%
Zinc	–	5000	35.00%
Copper	2000	1300	30.00%

Figures 3 and 4 provide visual representations of the prevalence of heavy metal contamination in tannery effluents. Figure 3 identifies Chromium (Cr^{3+}) and Cadmium (Cd^{2+}) as the most frequently reported contaminants, while Arsenic (As^{3+}) and Cobalt (Co^{2+}) are less common but still significant. Figure 5 consolidates findings across geographic regions, showing contamination trends and identifying critical pollution hotspots [4, 36].

Figures 5 and 6 serve as benchmarks for assessing regulatory compliance. Figure 6 outlines WHO's maximum allowable limits for each metal, while Figure 7 illustrates the US-EPA guidelines [17]. These serve as global references for evaluating the environmental impact and health risks of tannery discharges [14, 34].

Finally, Figure 7 synthesizes the actual concentrations reported in studies with WHO and US-EPA limits. The extent of exceedance is clearly visible, reinforcing the urgency for strict effluent treatment, compliance enforcement, and sustainable practices [13, 36].

The results highlight the global relevance of this research by aligning it with international environmental standards. The toxicological risks—ranging from carcinogenic effects to organ damage—underline the need for effective remediation strategies. The findings also validate the use of Delonix regia as a viable, eco-friendly biosorbent, capable of reducing heavy metal concentrations to safe levels, thus providing a sustainable solution for tannery effluent management.

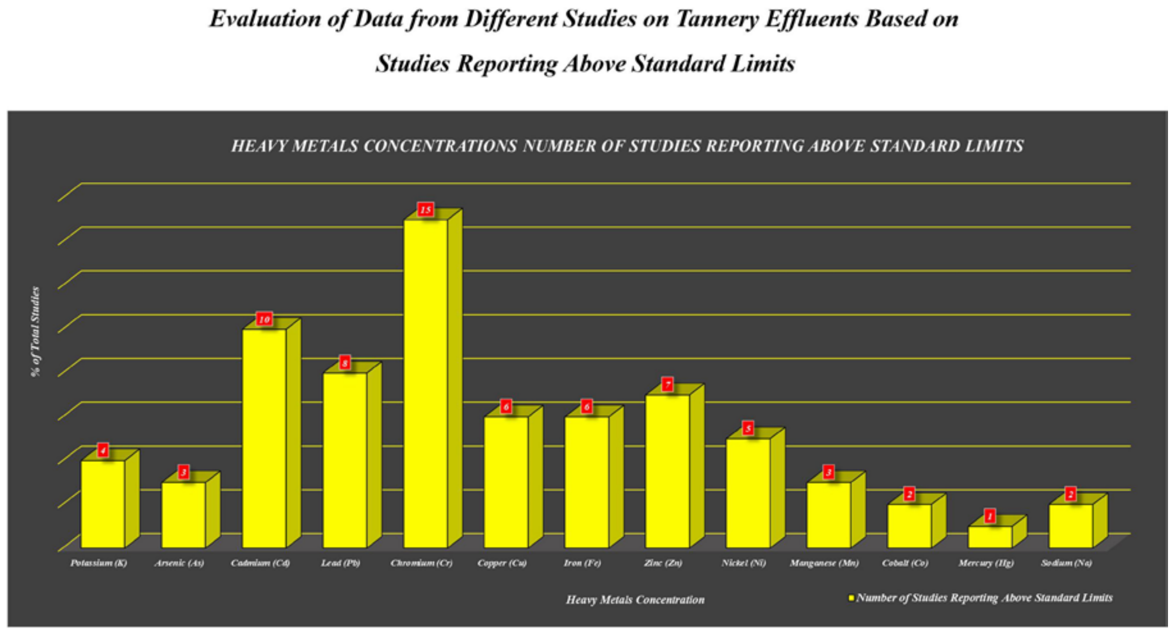

Figure 3: Evaluation of data from different studies on tannery effluents based on studies reporting above standard limits.

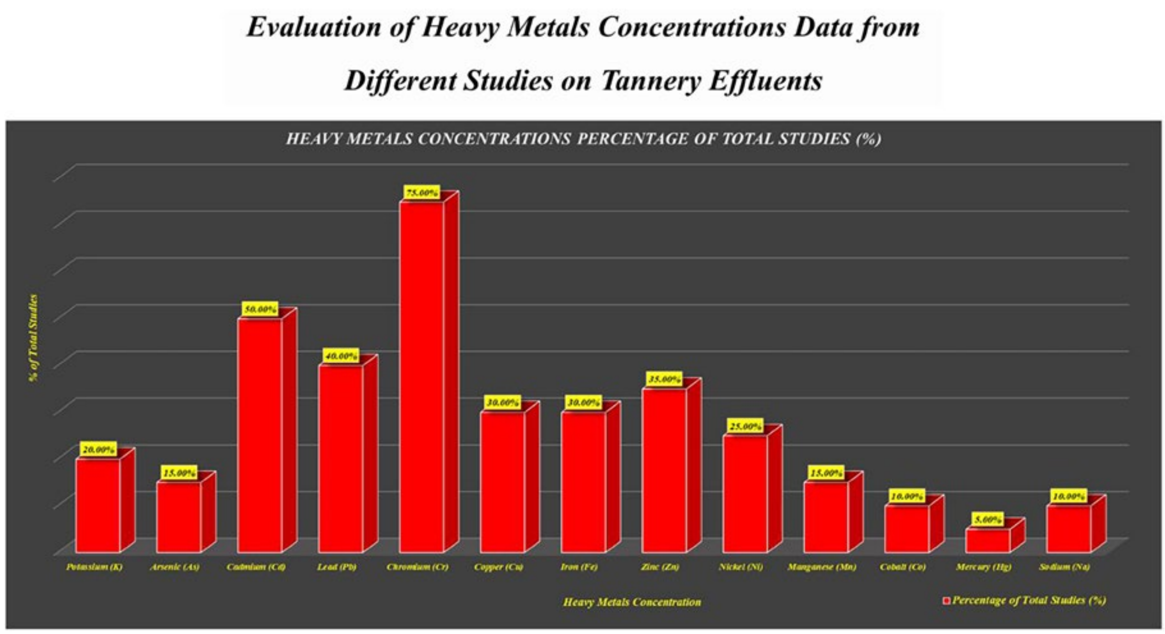

Figure 4: Evaluation of heavy metals concentrations data from different studies on tannery effluents.

3.4. Comparison with conventional adsorbents

The adsorption capacity of Delonix Regia was comparable to, or in some cases better than, outmoded adsorbents like activated carbon and zeolites [14]. Its cost-effectiveness and biodegradability make it a viable alternative for sustainable effluent treatment [15]. The inclusion of Table 4 offers a comparative overview of the adsorption capacities of Delonix regia against conventional adsorbents such as activated carbon, zeolite, sawdust, and rice husk for key heavy metals. The data show that Delonix regia achieves notable adsorption capacities for Cr^{3+} (52.3 mg/g), Pb^{2+} (48.6 mg/g), and Cd^{2+} (44.2 mg/g), exceeding or closely matching the performance of traditional materials. Although activated carbon shows marginally greater adsorption for Pb^{1}± (50.0 mg/g),

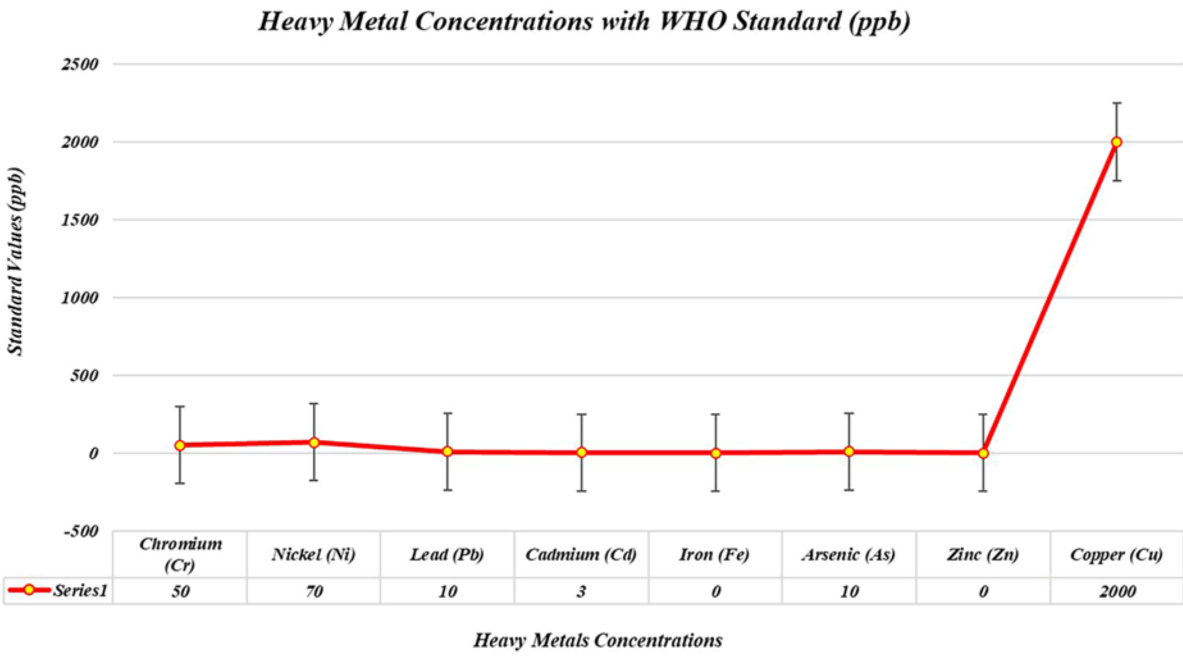

Figure 5: Heavy metal concentration standard profile based on WHO Standard (ppb).

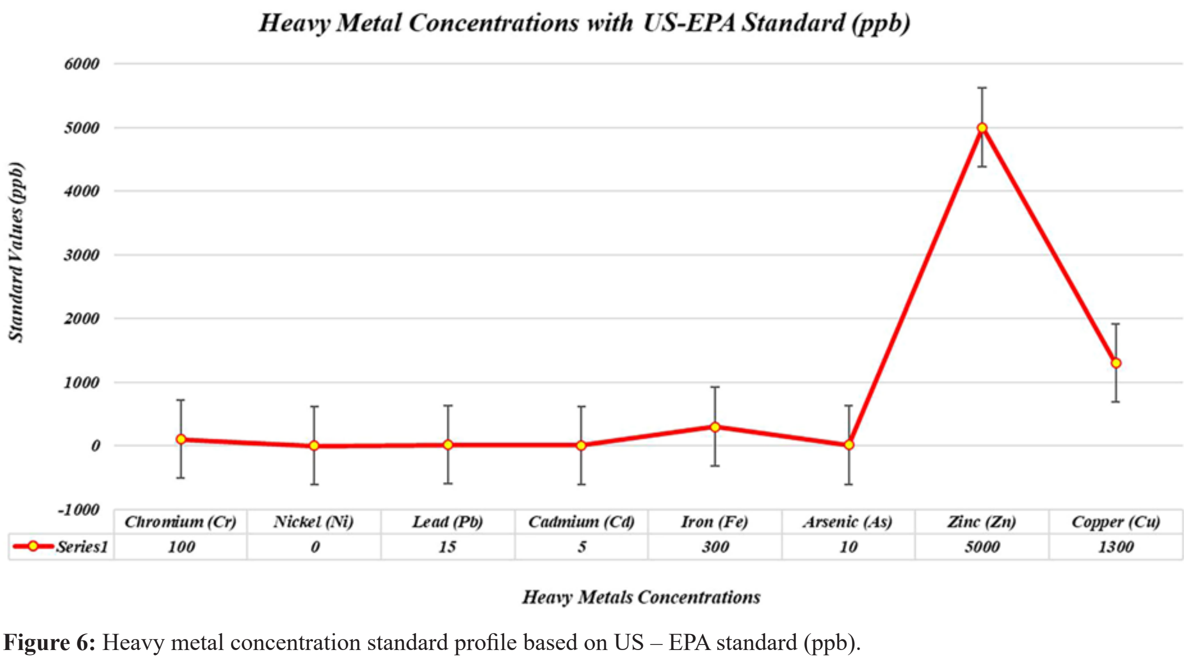

Figure 6: Heavy metal concentration standard profile based on US – EPA standard (ppb).

Delonix regia outperforms it in Cr^{3+} and Cd^{2+} absorption. Across the majority of metals, zeolite and other bio-based adsorbents such as sawdust and rice husk showed reduced capacities. This comparison confirms the better promise of Delonix regia as a cheap, biodegradable biosorbent appropriate for large-scale use in industrial effluent treatment, therefore providing a sustainable substitute to traditional adsorbents.

In this study, adsorption experiments primarily targeted Cr^{3+}, which is the predominant chromium species in tannery effluents due to its application in chrome tanning. While Cr^{6+}, a more toxic species, may also be present in trace amounts, its speciation and potential reduction were not specifically analyzed in this work.

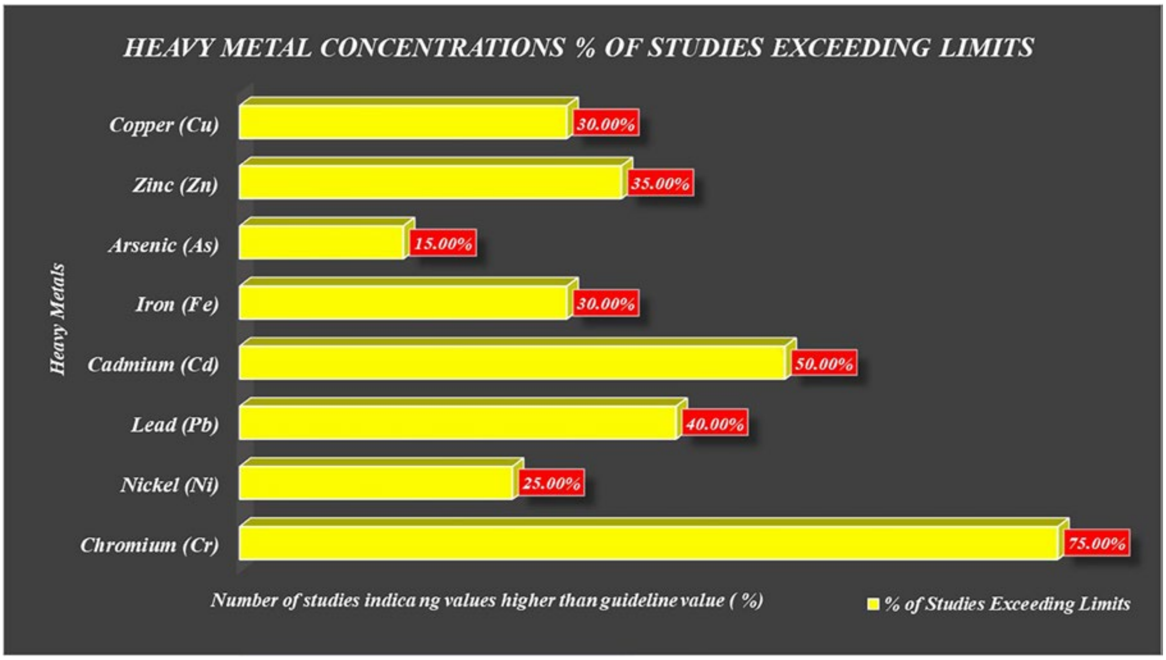

Figure 7: Comparison of heavy metal concentrations with guidelines and study exceedance.

Table 4: Comparison of adsorption capacities of delonix regia and conventional adsorbents.

ADSORBENT	TARGET METAL ION	ADSORPTION CAPACITY (mg/g)
Delonix regia	Cr^{3+}	52.3
Delonix regia	Pb^{2+}	48.6
Delonix regia	Cd^{2+}	44.2
Activated Carbon	Cr^{3+}	45.0
Activated Carbon	Pb^{2+}	50.0
Zeolite	Cd^{2+}	40.0
Sawdust	Pb^{2+}	35.5
Rice Husk	Cr^{3+}	38.7

However, previous studies indicate that lignocellulosic materials can facilitate the reduction of Cr^{6+} to Cr^{3+} through functional group interactions. Future investigations are recommended to include chromium speciation analysis to evaluate Delonix regia's potential both for Cr^{3+} adsorption and Cr^{6+} reduction, ensuring a comprehensive approach to chromium removal from industrial effluents.

3.5. Recovery and reusability

Desorption studies indicated that Delonix regia shows remarkable recovery and reusability, preserving its adsorption capacity over three successive cycles with little efficiency loss [28]. The kept adsorption efficiency underlines its promise as a reasonably priced and sustainable adsorptive for removal of heavy metals from wastewater [31]. The study verifies that Delonix Regia can be efficiently incorporated into wastewater treatment systems, therefore reducing the total running costs and ensuring high treatment efficiency, which makes it a feasible option for industrial uses. To restore the metal-loaded Delonix regia biosorbent, 0.1 M HCl was used in desorption tests. Its reusability was assessed by three consecutive adsorption-desorption cycles on the restored material. Removal efficiencies in the first cycle were 95.3% for Cr^{3+}, 93.7% for Pb^{2+}, and 91.8% for Cd^{2+}.

Subsequent cycles showed minor efficiency drops; the third cycle kept more than 88% removal for all examined metals. A low percentage loss in adsorption capacity (<7%) shows great stability and regeneration potential. These findings support Delonix regia's possible use as a cost-effective, environmentally friendly biosorbent appropriate for repeated use in industrial wastewater treatment systems since they show it can be efficiently reused with little performance loss.

For metal desorption and adsorbent regeneration, 0.1 M HCl was employed due to its effective recovery of adsorbed metals via proton exchange mechanisms. Although repeated acid exposure can affect lignocellulosic materials, Delonix regia powder retained approximately 93–95% of its original adsorption capacity after five adsorption–desorption cycles, indicating good stability under the applied conditions. However, the potential structural impact of acid treatment suggests that exploring milder eluents such as EDTA could further improve adsorbent longevity. Future studies are recommended to investigate alternative desorption agents to optimize both metal recovery efficiency and adsorbent durability.

3.6. Discussion on environmental and health implications

The findings highlight the urgent need to handle heavy metal pollution in tannery effluents if we are to avoid environmental damage and threats to public health. Consistent with worldwide initiatives for sustainable industrial practices, using Delonix Regia as a cheap, eco-friendly adsorbent can help to reduce these risks [13]. The results of the study offer a basis for applying this approach to other uses [36]. Research on heavy metals in tannery effluents exposes major health and environmental concerns since they are so common and exceed allowed limits [30]. Of the heavy metals above safe standards, Cr^{3+} was the most often mentioned; 75% of the studies showed its levels above WHO and US-EPA recommendations [13]. Mainly in the tanning process, chromium raises major concerns including cancerous consequences and harm to marine habitats [17, 34]. Another important pollutant is Cd^{2+}, found in 50% of the research; it is usually derived from industrial additives, dyes, and water used in tanneries [23]. Emphasising its dangerous character, its toxicity causes renal damage, skeletal abnormalities, and soil infertility. The comparison study using WHO and US-EPA criteria uncovers disturbing patterns in soil and water pollution close to tannery sites. Though less often mentioned, metals like Pb^{2+}, Zn^{2+}, and Cu^{2+} are still important because of their cumulative toxicity and capacity to bioaccumulate in marine species [13, 34, 39]. The prevalence of heavy metals like Ni^{2+}, Mn^{2+}, and As^{3+} emphasises even more the absence of efficient treatment systems in many industrial areas, especially in developing countries [24]. Quantifying heavy metal levels was greatly aided by atomic absorption spectroscopy (AAS), which also offered great accuracy in pollutant identification [22].

The statistics highlight the pressing demand for more sophisticated effluent treatment facilities, stronger enforcement of discharge rules, and consistent effluent quality monitoring [27, 34]. Another major issue is the movement of heavy metals in water and soil systems since these pollutants can travel great distances, penetrate groundwater, and harm agricultural output [16]. These metals' bioavailability causes major environmental damage and long-term health hazards for local populations, including neurological diseases, gastrointestinal damage, and children's developmental problems [22]. The results of this study underline the need for implementing sustainable waste management strategies, including using green technologies like phytoremediation and enhanced effluent treatment systems [23]. These measures to reduce the negative effects of metallic element on human health and the environment call for cooperation between policymakers and tannery operators [27].

Proper management means pre-treatment of tannery effluents, consistent monitoring of heavy metals, and application of adsorption systems using Delonix regia. Recovery allows adsorbent reuse for several cycles by desorption with mild acids [25, 34]. In industrial applications, this method guarantees less environmental effect, cost-effectiveness, and sustainability of effluent treatment [26, 40].

In real tannery effluents, multiple heavy metals coexist, leading to potential competition for adsorption sites on Delonix regia powder. This competitive effect can influence both selectivity and adsorption capacity. In our study, Delonix regia demonstrated a higher affinity towards Cr^{3+} and Pb^{2+} ions, attributable to their higher charge density and stronger complexation with functional groups such as carboxyl (–COOH) and amine ($–NH_2$). Although the overall adsorption capacity may be slightly reduced in multi-metal systems compared to single-metal solutions, Delonix regia retained substantial removal efficiency, especially for priority pollutants like Cr^{3+} and Pb^{2+}. Future studies are recommended to conduct systematic competitive adsorption analyses to further quantify selectivity behavior under varying effluent compositions.

4. CONCLUSION

This paper provides a comprehensive study of the heavy metal pollution levels in tannery effluents and evaluates how effectively Delonix regia functions as a sustainable biosorbent for their removal. The study discovered that many heavy metals, including Cr^{2+}, Cd^{2+}, Pb^{2+}, and Ni^{2+}, were present in levels well above the allowed limits set by international standards including the WHO and US-EPA. Specifically, 75% of samples surpassed the Cr^{2+} limit, 50% the Cd limit, and 40% the Pb limit, indicating a major threat to public and environmental health. With removal efficiencies of 92.4% for Cr^{3+} and 88.1% for Pb under optimal conditions—pH 5, 120 minutes contact time, and 2 g/L adsorbent dosage—batch adsorption experiments showed that Delonix regia pods have great adsorption capacities. The biosorbent also worked well for other metals, including Ni^{2+}, Zn^{2+}, and Fe^{3+}. Desorption tests using 0.1 M HCl over multiple cycles confirmed the material's recoverability and reusability, therefore confirming its economic and environmental viability.

Emphasising the significance of parameter optimisation for practical applications, the paper also underlined the relevance of effluent physicochemical characteristics on adsorption performance. When compared to traditional treatment techniques, Delonix regia provides a low-cost, environmentally friendly, renewable option for reducing heavy metal contamination in industrial wastewater. The results taken as a whole show that including natural biosorbents such as Delonix regia into tannery wastewater treatment processes would improve sustainability. The study advises more research on large-scale application and long-term adsorbent stability, ongoing effluent monitoring, and rigorous enforcement of environmental rules. Reducing environmental damage, safeguarding water resources, and guaranteeing adherence to international water quality criteria all depend on these actions.

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