

Reduction of Heavy Metal Ions Cu^{2+} and Pb^{2+} in Electroplating Wastewater Using an Ion Exchange Column

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Abstract

Electroplating wastewater are hazardous because it contains heavy metals, such as copper and lead, at concentrations exceeding environmental standards. This study aimed to evaluate the effects of resin height and flow rate on the removal of Cu^{2+} and Pb^{2+} using an ion-exchange column packed with Dowex Amberlite IRC120 Na resin. The wastewater sample had an initial Cu concentration of 37,8 mg/L and Pb concentration of 3,33% mg/L, both above the applicable quality standard. The process was carried out using resin heights of 20, 25, 35, 45, and 55 cm and flow rates of 30, 55, 65, 75, and 80 mL/min with three recirculation cycles. The results showed that increasing resin height tended to improve metal removal, while lower flow rates provided longer contact time and better exchange performance. The best result was obtained at a resin height of 20 cm and a flow rate of 80 mL/min, with final concentrations of 0.014 mg/L for Cu^{2+} and 0.013 mg/L for Pb^{2+} . These results indicate that ion exchange is effective for reducing heavy metals in electroplating wastewater and meets the required discharge standard.

Keywords: *ion exchange, electroplating wastewater, copper, lead, resin height, dowex amberlite IRC120 Na resin*

Abstrak

Limbah cair elektroplating mengandung logam berat seperti tembaga (Cu^{2+}) dan timbal (Pb^{2+}) dengan kadar yang melebihi baku mutu lingkungan. Penelitian ini mengkaji efektivitas kolom *ion exchange* menggunakan resin Dowex Amberlite IRC120 Na untuk menurunkan kadar Cu^{2+} dan Pb^{2+} dalam limbah elektroplating nyata yang diperoleh dari UMKM "Sinar Permata", Surabaya. Variabel yang diteliti meliputi tinggi resin (20, 25, 35, 45, dan 55 cm) dan laju alir (30, 55, 65, 75, dan 80 ml/menit) dengan volume sampel 5000 ml dan resirkulasi sebanyak tiga kali. Kadar logam dianalisis menggunakan spektrofotometer serapan atom (SSA). Hasil penelitian menunjukkan bahwa peningkatan tinggi resin meningkatkan kapasitas pertukaran ion, sementara penurunan laju alir memperpanjang waktu kontak sehingga meningkatkan efisiensi penyerapan. Kondisi operasi terbaik dicapai pada tinggi resin 20 cm dan laju alir 80 ml/menit, dengan efisiensi penurunan Cu^{2+} sebesar 99,96% dan Pb^{2+} sebesar 99,61%, sehingga menghasilkan kadar akhir yang memenuhi baku mutu Peraturan Gubernur Jawa Timur Nomor 52 Tahun 2014. Kesetimbangan adsorpsi dimodelkan menggunakan isoterm Langmuir dengan nilai R^2 yang menguntungkan pada seluruh variabel.

Kata Kunci: *pertukaran ion, limbah elektroplating, tembaga, timbal, tinggi resin, resin dowex amberlite IRC120 Na*

1. Introduction

Electroplating is a metal finishing technique commonly applied across various industries, especially manufacturing industries to enhance corrosion resistance, surface appearance, hardness, and wear resistance of metal products [1]. Despite its industrial significance, electroplating activities generate substantial volumes of wastewater containing various hazardous substances, particularly dissolved heavy metals and chemical compounds such as copper (Cu^{2+}), lead (Pb^{2+}), chromium (Cr), nickel (Ni), zinc (Zn), and cyanide (CN^-), originating from plating baths, washing, and cleaning processes [2]. When discharged without adequate treatment, these pollutants deteriorate water quality, disrupt aquatic ecosystems, and accumulate through the food chain, posing serious threats to both environmental integrity and human health [3]. According to East Java Governor Regulation No. 52 of 2014, the maximum permissible concentrations for Cu^{2+} and Pb^{2+} in electroplating wastewater respectively are 0.6 mg/L and 0.1 mg/L.

Numerous technologies have been developed for heavy metal removal from industrial wastewater, including chemical precipitation, coagulation–flocculation, membrane filtration, adsorption, and ion exchange. [2]. Among these approaches, ion exchange has emerged as one of the most efficient methods

owing to its high selectivity toward dissolved metal ions, low operational cost, minimal secondary waste generation, and the possibility of resin regeneration. Ion exchange is a reversible chemical sorption process in which ions in solution are replaced by ions of the same charge bound to functional groups on a solid resin matrix [4]. Strong acid cation resins containing sulfonate functional groups ($R-SO_3^-$) are particularly suitable for heavy metal removal, as they selectively exchange their bound sodium ions (Na^+) with divalent metal cations such as Cu^{2+} and Pb^{2+} [5]. In this study, Dowex Amberlite IRC120 Na resin was selected as the ion exchange medium owing to its strong affinity for divalent heavy metal cations and its established performance in water treatment applications.

The performance of a continuous ion exchange column is influenced by several operating variables, particularly resin bed height, wastewater flow rate, and ion selectivity [6], [7], [8]. Resin bed height directly determines the number of active exchange sites in the column, with a higher bed height providing greater adsorption capacity and extended contact time. Flow rate controls the hydraulic residence time of the solution within the column, where lower flow rates generally improve removal efficiency by allowing longer contact between metal ions and the resin's active sites [8]. Furthermore, ion selectivity plays a critical role in determining the exchange sequence in multi-component systems, where Pb^{2+} is preferentially exchanged over Cu^{2+} due to its lower standard reduction potential based on the electrochemical activity series [9]. These parameters collectively determine the overall performance of the ion exchange column and must be carefully optimized for practical wastewater treatment applications.

Previous studies have demonstrated the feasibility of ion exchange for removing heavy metals from wastewater. Tan et al. reported Cu^{2+} removal efficiency of up to 99.14% using D001 strong acid resin in a batch system [10], while Zewail and Yousef achieved Pb^{2+} removal efficiencies of 98–99% using AMBERJET 1200 Na resin in a continuous column [11]. Ratnasari et al. showed that the highest Pb^{2+} removal was obtained at the lowest flow rate using Lewatit cation resin [7], and Pujiastuti et al. further demonstrated that increasing resin height significantly improved removal efficiency using Dowex Amberlite IRC120 Na resin on batik industrial wastewater treatment [8]. However, most of these studies were limited to a single operational variable or used synthetic wastewater, and those that simultaneously examined the combined influence of resin height and flow rate in continuous columns treating actual electroplating wastewater remain limited.

Understanding the behavior of adsorption equilibrium is important for characterizing the interaction between metal ions and resin surfaces. The Langmuir isotherm model is widely used to describe monolayer adsorption on homogeneous surfaces with a finite number of identical active sites [12]. The model assumes that adsorption occurs on energetically uniform sites distributed over a homogenous surface and that each site accommodates a single adsorbate species. Because ion exchange takes place at specific functional groups on the resin, Langmuir approach is considered suitable to evaluate adsorption behavior in this system. The Langmuir parameters, such as maximum adsorption capacity (q_{max}) and adsorption affinity constant (K_L), provide direct quantitative insights into the resin's adsorption performance. Therefore, this study aims to investigate the reduction of Cu^{2+} and Pb^{2+} in actual electroplating wastewater using a continuous ion-exchange column packed with Dowex Amberlite IRC120 Na resin, evaluate the combined effects of resin bed height and flow rate, and describe adsorption equilibrium behavior using the Langmuir isotherm model.

2. Research Methodology

Equipment and Materials

The ion exchange system consists of a cylindrical column with an inside diameter of 7 cm and a height of 70 cm, packed with the resin as shown in **Fig. 1**. Supporting components include a valve, a flow restrictor to maintain flow rates, a pump, a waste collection tank, and an effluent collection tank. The material used in this research was liquid wastewater from a small-scale electroplating workshop, "Sinar Permata" located in Surabaya, Indonesia. The strong acid cation resin used is Dowex Amberlite IRC120 Na.

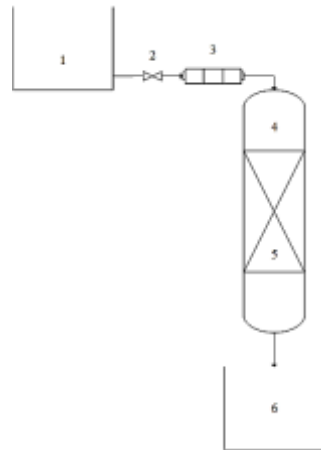


Fig. 1: Ion Exchange Column

Description:

1. Waste collection tank
2. Valve
3. Flow restrictor
4. Ion exchange column
5. Resin
6. Effluent collection tank

Procedure

Electroplating wastewater was analyzed using an atomic absorption spectrophotometer (AAS) to determine the initial concentrations of Cu^{2+} and Pb^{2+} . Dowex Amberlite IRC120 Na resin was weighed and packed into the column at designated bed heights of 20 cm, 25 cm, 35 cm, 45 cm, and 55 cm. A volume of 5000 ml of electroplating wastewater was then fed through the packed column at five flow rates: 30, 55, 65, 75, and 80 ml/min. The treated effluent was collected and recirculated through the column for three consecutive cycles to maximize ion exchange efficiency. Following the recirculation process, the effluent was reanalyzed for Cu^{2+} and Pb^{2+} concentrations using AAS. The removal efficiency (%) of each metal was calculated as follows [13]:

$$\% = \frac{C_0 - C_e}{C_0} \times 100\%$$

Where: C_0 and C_e represent the initial and equilibrium metal concentrations (mg/L), respectively.

Then, the amount of metal adsorbed per gram of resin at equilibrium (q_e , mg/g) was determined from the following [9]:

$$C = C_0 - C_e$$

$$q_e = \frac{x}{m} = C \times \frac{V}{m}$$

Where: C is the adsorbed metal concentration (mg/L), V is the sample volume (L), and m is the resin mass (g).

3. Results and Discussion

3.1 Electroplating wastewater analysis

The electroplating wastewater exhibited a pale blue-green appearance, a characteristic of dissolved heavy metal ions. Copper ions (Cu^{2+}) are known to impart a blue-green coloration, while lead ions (Pb^{2+}) contribute a bluish hue when in contact with the surrounding environment. The fading of this coloration following the ion exchange process served as a preliminary visual indicator of successful ion removal, as shown in **Fig. 2**. Before treatment, the wastewater was analyzed using Atomic Absorption Spectrophotometry (AAS) at the Environmental Agency Laboratory of East Java Province. The initial Cu^{2+} and Pb^{2+} concentrations were measured at 37.8 mg/L and 3.33 mg/L, respectively, both of which greatly exceeded the maximum permissible discharge limits of 0.6 mg/L for Cu^{2+} and 0.1 mg/L for Pb^{2+} as stipulated in East Java Governor Regulation No. 52 of 2014. These findings confirm the urgent necessity to apply an effective treatment method before environmental discharge, and ion exchange using Dowex Amberlite IRC120 Na resin was therefore selected as the treatment approach in this study.



Fig. 2: Electroplating wastewater (left) and treated effluent (right)

3.2 Influence of Resin Height

The effect of resin bed height on the amount of Cu^{2+} and Pb^{2+} adsorbed was evaluated at five bed heights of 20, 25, 35, 45, and 55 cm, as presented in Fig. 3 and Fig. 4. For Cu^{2+} , a sharp increase in the amount adsorbed was observed when resin height increased from 20 to 25 cm, followed by a gradual and less significant increase at heights of 35 to 55 cm. A similar trend was observed for Pb^{2+} : adsorption increased between 20 and 35 cm progressively, then plateaued at heights above 35 cm. The increase in metal ion removal observed at higher resin bed heights can be attributed to the increasing number of active exchange sites as resin volume increases, a greater resin bed height provides more sulfonate functional groups (R-SO_3^-) available for interaction with dissolved metal ions. As a result, the overall ion exchange of the system increases [14]. The gradual plateau observed at higher resin heights suggests that the resin was approaching saturation, with most active sites already occupied, and that additional resin contributed little to further removal.

This is consistent with the findings of Nuryoto et al., who reported that a greater amount of resin increases the number of active sites available for ion exchange [14]. Regarding ion selectivity, the results showed that Pb^{2+} was adsorbed preferentially over Cu^{2+} at lower resin heights, which is in agreement with the selectivity series of strong acid cation resins, where Pb^{2+} precedes Cu^{2+} due to its lower standard reduction potential (E°) in the electrochemical activity series, making it more reactive and more readily attracted to the sulfonate groups of the resin [15]. The highest Cu^{2+} and Pb^{2+} adsorption was obtained at a flow rate of 30 ml/min and a resin height of 20 cm, yielding final concentrations of 0.014 mg/L for Cu^{2+} and 0.013 mg/L for Pb^{2+} , with removal efficiencies of 99.96% and 99.61%, respectively. Importantly, all experimental conditions produced final Cu^{2+} and Pb^{2+} concentrations below the maximum allowable discharge limits stipulated in East Java Governor Regulation No. 52 of 2014 (0.6 mg/L for Cu^{2+} and 0.1 mg/L for Pb^{2+}), confirming that the ion exchange column with Dowex Amberlite IRC120 Na resin effectively treated the electroplating wastewater under all tested conditions.

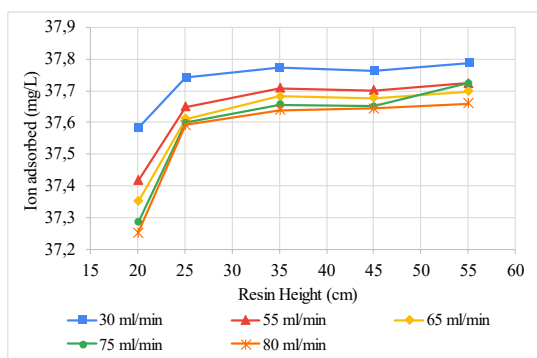


Fig. 3: Influence of Resin Height on the Concentration of Absorbed Cu^{2+} Ions at Various Waste Flow Rates

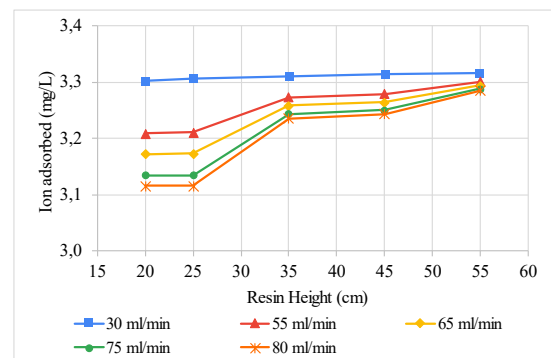


Fig. 4: Influence of Resin Height on the Concentration of Absorbed Pb^{2+} Ions at Various Waste Flow Rates

3.3 Influence of Flow Rate

The effect of flow rates on the amounts of adsorbed Cu^{2+} and Pb^{2+} was evaluated at the flow rates of 30, 55, 65, 75, and 80 ml/min, as presented in Fig. 5 and Fig. 6. For Cu^{2+} , the amounts of adsorbed ions slightly decrease and fluctuates with the resin bed height of 55 cm. The same occurs with Pb^{2+} , where the amounts of adsorbed ions declines slightly as the flow rate increases. Observation results show that the slower the flow rate, the greater the amount of Cu^{2+} and Pb^{2+} ions adsorbed [7]. Lower flow rates can exchange more ions because extended residence time facilitates ion diffusion toward the active sites and

improves the probability of ion exchange. Previous research has shown that the higher the ion concentration in a solution, the more ions the resin can bind [6]. The highest and lowest amounts of adsorbed Cu^{2+} ions, respectively, are 37,786 mg/L at 30 ml/min and 37,251 mg/L at 80 ml/min, whilst for Pb^{2+} , the highest and lowest amounts of adsorbed Pb^{2+} ions, respectively, are 3,317 mg/L at 30 ml/min and 3,116 mg/L at 80 ml/min.

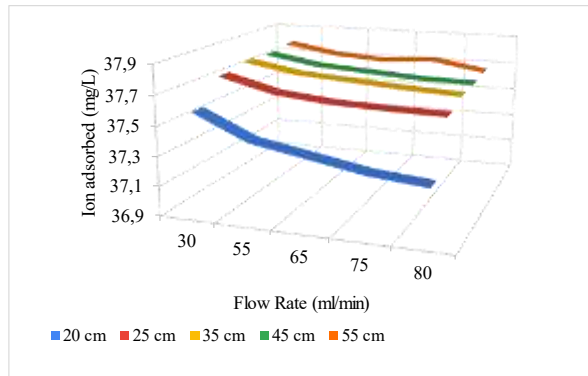


Fig. 5: Influence of Waste Flow Rate on the Concentration of Adsorbed Cu^{2+} Ions at Various Resin Heights

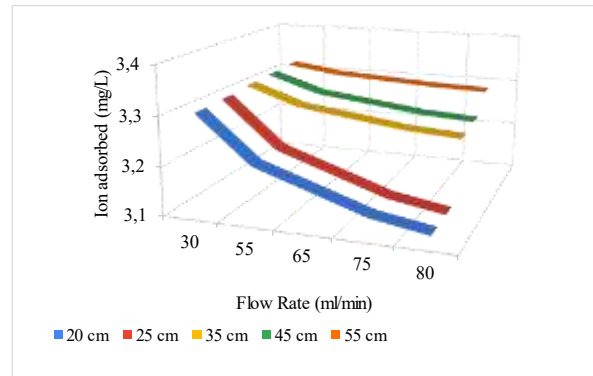


Fig. 6: Influence of Waste Flow Rate on the Concentration of Adsorbed Pb^{2+} Ions at Various Resin Heights

3.4 Langmuir Isotherm Adsorption

The Langmuir isotherm model was applied to describe the adsorption equilibrium behavior of Cu^{2+} and Pb^{2+} ions onto the Dowex Amberlite IRC120 Na resin. The Langmuir model was selected because the ion exchange mechanism on resin surfaces is theoretically consistent with its fundamental assumptions, namely that adsorption occurs on a homogeneous surface with a finite number of equivalent active sites, and that each site can accommodate only one ion species until monolayer coverage is achieved [16]. The linearized form of the Langmuir equation ($C_e/q_e = (1/q_{\max}) \cdot C_e + 1/(K_L \cdot q_{\max})$) was used to determine the maximum adsorption capacity (q_{\max}). The Langmuir affinity constant (K_L) from the slope and intercept of the C_e/q_e versus C_e plots, as presented in **Fig. 7-11** for Cu^{2+} and **Fig. 12-16** for Pb^{2+} : The Langmuir parameters for Cu^{2+} and Pb^{2+} are summarized in **Tables 1** and **2**, respectively.

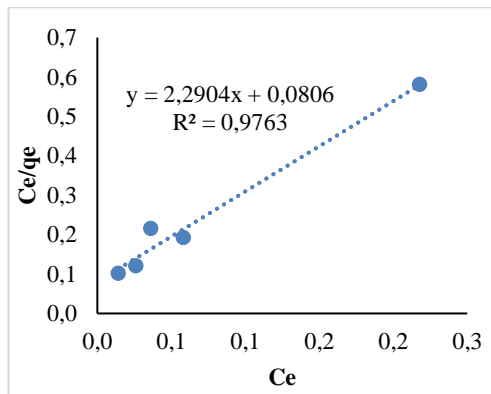


Fig. 7: Langmuir Isotherm Plot for Cu^{2+} at a Waste Flow Rate of 30 ml/min

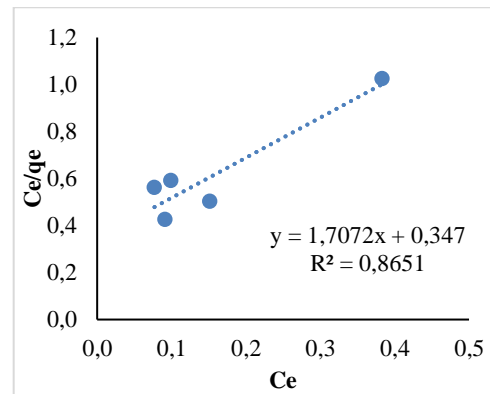


Fig. 8: Langmuir Isotherm Plot for Cu^{2+} at a Waste Flow Rate of 55 ml/min

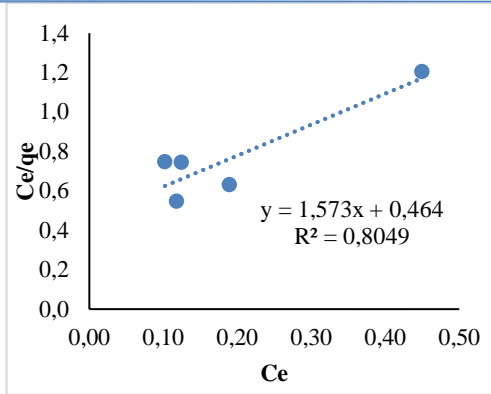


Fig. 9: Langmuir Isotherm Plot for Cu^{2+} at a Waste Flow Rate of 65 ml/min

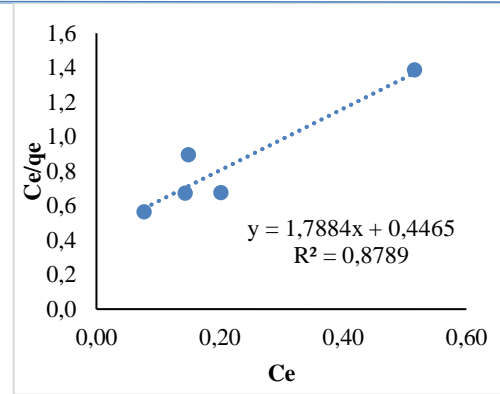


Fig. 10: Langmuir Isotherm Plot for Cu^{2+} at a Waste Flow Rate of 75 ml/min

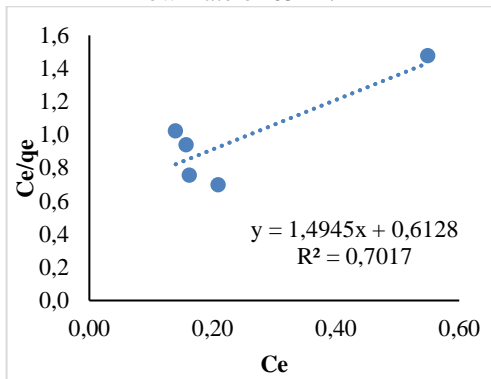


Fig. 11: Langmuir Isotherm Plot for Cu^{2+} at a Waste Flow Rate of 80 ml/min

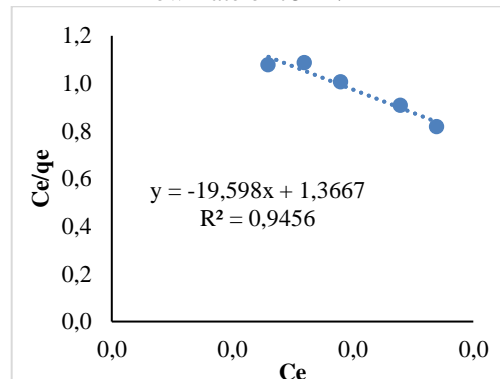


Fig. 12: Langmuir Isotherm Plot for Pb^{2+} at a Waste Flow Rate of 30 ml/min

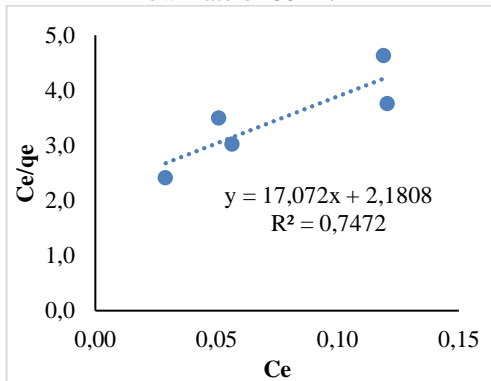


Fig. 13: Langmuir Isotherm Plot for Pb^{2+} at a Waste Flow Rate of 55 ml/min

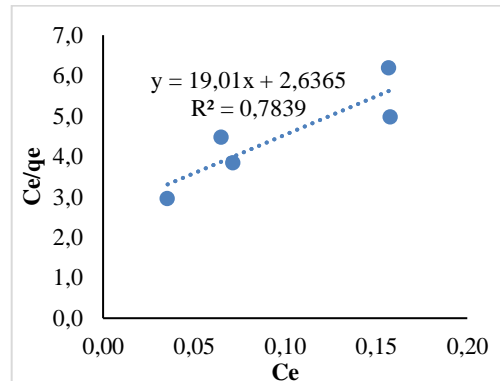


Fig. 14: Langmuir Isotherm Plot for Pb^{2+} at a Waste Flow Rate of 65 ml/min

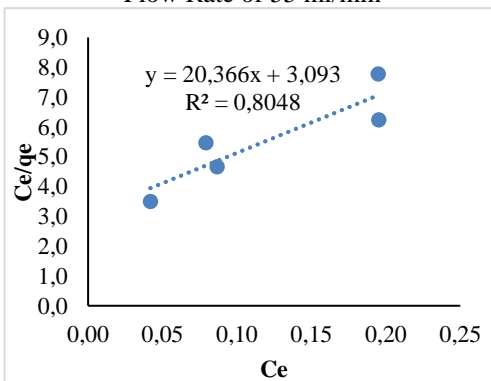


Fig. 15: Langmuir Isotherm Plot for Pb^{2+} at a Waste Flow Rate of 75 ml/min

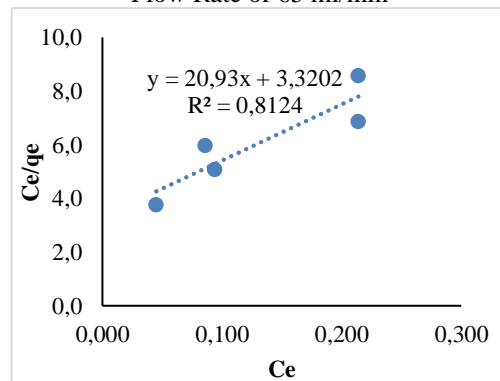


Fig. 16: Langmuir Isotherm Plot for Pb^{2+} at a Waste Flow Rate of 80 ml/min

Table 1. Langmuir Isotherm Parameters for Cu²⁺

Flow rate (ml/min)	a	b	Qm	K
30	2,2904	0,0806	0,4366	28,4169
55	1,7457	0,3351	0,5728	5,2095
65	1,5730	0,4640	0,6357	3,3901
75	1,8004	0,4413	0,5554	4,0798
80	1,4945	0,6128	0,6691	2,4388

Table 2. Langmuir Isotherm Parameters for Pb²⁺

Flow rate (ml/min)	a	b	Qm	K
30	-19,5980	1,3667	0,0510	14,3397
55	17,0720	2,1808	0,0586	7,8283
65	19,0100	2,6365	0,0526	7,2103
75	20,3660	3,0930	0,0491	6,5845
80	20,9300	3,3202	0,0478	6,3038

For Cu²⁺, the q_{\max} values showed a general increasing trend with increasing flow rate, ranging from 0.4366 mg/g at 30 ml/min to 0.6691 mg/g at 80 ml/min, with some fluctuation observed at intermediate flow rates. This indicates that the resin's adsorption capacity increases with increasing flow rate, possibly due to changes in the distribution of Cu²⁺ between the liquid and solid phases under different hydrodynamic conditions. However, the K_L values decreased from 28.4169 L/mg at 30 ml/min to 2.4388 L/mg at 80 ml/min, suggesting that the binding affinity between Cu²⁺ ions and the resin surface decreases at higher flow rates. This pattern is consistent with the explanation provided by Ismadji et al., where q_{\max} and K_L represent two different aspects of the adsorption process, namely total capacity and interaction strength, so an increase in one does not always correspond to an increase in the other [12]. For Pb²⁺, the q_{\max} values were considerably lower than those of Cu²⁺, ranging from 0.0478 to 0.0586 mg/g, which is expected given the much lower initial Pb²⁺ concentration in the wastewater compared to Cu²⁺.

The K_L values for Pb²⁺ also decreased with increasing flow rate, following a similar trend to that observed for Cu²⁺. The R^2 values for Cu²⁺ ranged from 0.7017 to 0.9763, with the highest value obtained at the lowest flow rate of 30 ml/min, while R^2 values for Pb²⁺ ranged from 0.7472 to 0.9456. According to Olusegun and Olabisi, R^2 values between 0 and 1 indicate favorable adsorption isotherms, while an R^2 value of exactly 1 represents a perfectly linear isotherm [17]. The fluctuation in R^2 values in this study is likely due to the relatively narrow range of equilibrium concentrations (C_e) obtained during the column experiment, as well as the possibility that the resin had not yet reached full saturation, resulting in only a partial isotherm. This is supported by Li et al., who stated that Langmuir q_{\max} values are highly sensitive to the concentration range used and may not accurately reflect the true maximum adsorption capacity when the system has not reached saturation [18]. Overall, the Langmuir model still provided a reasonable fit to the experimental data, suggesting that the adsorption of Cu²⁺ and Pb²⁺ onto Dowex Amberlite IRC120 Na resin generally follows a monolayer adsorption mechanism on energetically uniform exchange sites, which is in line with the characteristics of strong acid cation exchange resins.

4. Conclusion

This study demonstrated that a continuous ion-exchange column packed with Dowex Amberlite IRC120 Na resin effectively reduced Cu²⁺ and Pb²⁺ concentrations in actual electroplating wastewater, with initial concentrations of 37.8 mg/L and 3.33 mg/L, respectively, well above regulatory discharge limits. Both resin bed height and flow rate significantly influenced removal performance, with greater resin height increasing the number of active exchange sites and lower flow rates extending the contact time between metal ions and the resin surface. The optimal condition was achieved at a resin height of 20 cm and a flow rate of 80 ml/min, yielding removal efficiencies of 99.96% for Cu²⁺ and 99.61% for Pb²⁺, with all tested conditions producing final effluent concentrations compliant with East Java Governor Regulation No. 52 of 2014. The Langmuir isotherm model provided a reasonable description of the adsorption equilibrium behavior, with R^2 values ranging from 0.70 to 0.98, supporting the conclusion that adsorption follows a

monolayer mechanism on energetically uniform exchange sites. For future research, it is recommended to compare the performance of fresh and regenerated resins and to scale up the column system to industrial dimensions for more practical implementation.

5. Recommendation

For future research, the authors recommend comparing adsorption performance between fresh and regenerated resins to evaluate reusability, and conducting experiments using a column setup that approaches industrial scale to obtain more representative results for practical application.

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