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The Effect of Acid Mine Drainage (AMD) Treatment Using Clean Electrolysis Technology and Heavy Metal Reduction and Ph Increase: A Peruvian Mine Case Study

Farfán-Chilicaus, Gary Christiamn[1], García-Juárez, Hugo Daniel[1], Cruz-Salinas, Luis Edgardo[1], Licapa–Redolfo, Gladys S.[2], Campos-Fernández, Sarahí Alcira[3], Licapa–Redolfo, Rolando[4], Reyes-Pérez, Moisés David[1], Guerrero-Millones, Ana María[5]

[1]*Universidad César Vallejo - Campus Chepén, Perú*
[2]*Grupo de Investigación en Ecología Evolutiva, Protección de Cultivos, Remediación Ambiental, y Biotecnología (EPROBIO), Universidad Privada del Norte, Trujillo, 13011, Perú*
[3]*Universidad Nacional de Cajamarca, Perú*
[4]*Universidad Nacional de San Cristóbal de Huamanga, Perú*
[5]*Universidad Señor de Sipán, Perú*
Email: gfarfanch@ucvvirtual.edu.pe

The objective of the present research was to determine the concentration of iron and pH, influenced by current density and residence time in the electrolysis treatment of acid mine drainage (AMD) in Hualgayoc, Cajamarca. The scope of the research was experimental, for which 200 mL of AMD solution with average initial pH of 2.62 and iron concentration (Fe) of 52.58 ppm were used. Current densities of 15, 20, 25, and 30 mA/cm2 were employed, as well as different residence times of 35, 40, 45, and 50 minutes. After conducting the experiments, it was found that with 15 mA/cm2 and 35 minutes of treatment, a pH of 6.09 and an iron concentration of 4.32 ppm were achieved. The optimal parameter was found at 50 minutes of treatment and 30 mA/cm2, resulting in a pH of 7.63 and an iron reduction of 97.45%. According to the analysis of variance, the alternative hypothesis was accepted because the F treatment in all cases was greater than the Fα, V1, V2; thus, it is affirmed that current density and residence time significantly influence the concentration of iron and pH.

Keywords: Acid mine drainage, electrolysis, heavy metals, pH.

1. Introduction

The treatment of acid mine drainage (AMD) originating from abandoned mines and ponds in the mining sector presents a significant challenge, mainly due to its acidic nature, low pH levels, and high concentrations of sulfates and heavy metals. These characteristics have the potential to induce adverse toxicological effects. AMD is seen by some as a significant environmental problem globally, while others consider it the second most prominent challenge after climate change. According to Tuffnell (2017), electrochemical treatment has emerged as a promising option to mitigate the adverse impacts associated with ravines' presence. The use of electrochemical methods has been widely employed in the removal of various industrial wastes and contaminated soils, indicating its potential effectiveness (Olías & Nieto, 2018).

The main problem related to mining operations is the production of acid mine drainage resulting from the oxidation process of sulfur-containing minerals included in those residues. Sulfur oxidation is facilitated mainly on the deposit site through microbial activity, specifically due to the presence of Thiobacillus ferrooxidans, as well as the availability of moisture and oxygen (Nwaila et al., 2021). According to a source cited as La Vanguardia (2019), based on the foregoing, there is a need for a scientifically supported study aimed at mitigating or minimizing the adverse effects caused by acid mine drainage on the ecosystem. In light of this, electrolysis is proposed as a potential solution method to address the current problem. This involves the application of a specific intensity electrical current through electrodes within the affected mining area, inducing oxidation-reduction reactions both at the cathode and anode. By using electrical energy as a means of environmental decontamination, the aim is to mitigate the negative impacts associated with acid mine drainage. This leads to the following question: To what extent does current density and time influence the iron concentration and pH in the electrolysis treatment of acid mine drainage from the Hualgayoc, Cajamarca area in 2022?

With this research, it is intended to provide the scientific and technological community with data on current density and residence time that allows the reduction of heavy metals such as iron and the increase of pH in acid mine drainage solutions. This will enable, through electrolysis, to bring them to optimal parameters within environmental quality standards and maximum permissible limits, thus reducing the negative impact generated by these waters on the ecosystem. Electrolysis is an emerging clean technology that still requires much investigation into its processes and mechanisms.

Likewise, the hypotheses that arose from the study problem are: Current density and time do not influence the iron concentration and pH in the electrolysis treatment of acid mine drainage from the Hualgayoc, Cajamarca area, and current density and time influence the iron concentration and pH in the electrolysis treatment of acid mine drainage from the Hualgayoc, Cajamarca area. The specific hypotheses are: Current density does not influence the reduction of iron concentration in the electrolysis treatment of acid mine drainage from the Hualgayoc, Cajamarca area, and current density influences the reduction of iron concentration in the electrolysis treatment of acid mine drainage from the Hualgayoc, Cajamarca area; time does not influence the reduction of iron concentration in the electrolysis treatment of acid mine drainage from the Hualgayoc, Cajamarca area, and time influences the reduction of iron concentration in the electrolysis treatment of acid mine drainage from the Hualgayoc, Cajamarca area; the interaction of current density and time does not influence the reduction of iron concentration in the electrolysis treatment of acid mine drainage from the Hualgayoc, Cajamarca area, and the interaction of current density and time influences the reduction of iron concentration in the electrolysis treatment of acid mine drainage from the Hualgayoc, Cajamarca area, and current density does not influence the increase of pH in the electrolysis treatment of acid mine drainage from the Hualgayoc, Cajamarca area; current density influences the increase of pH in the electrolysis treatment of acid mine drainage from the Hualgayoc, Cajamarca area, and time does not influence the increase of pH in the electrolysis treatment of acid mine drainage from the Hualgayoc, Cajamarca area; time influences the increase of pH in the electrolysis treatment of acid mine drainage from the Hualgayoc, Cajamarca area, and the interaction of current density and time does not influence the increase of pH in the electrolysis treatment of acid mine drainage from the Hualgayoc, Cajamarca area; these hypotheses allow demonstrating the solution to the study problem.

Theoretical Bases. The study by Valles (2021) in the Durango region, Mexico, aimed to determine chemical and electrolytic treatment techniques to effectively remove iron and neutralize acid mine drainage (AMD). Under the following operating conditions: At a time of 60 minutes, with a current density of 19 A/m2, an initial iron (Fe) concentration of 300 ppm, an initial pH of 2.5, and in the absence of agitation at an initial temperature of 25°C, it was demonstrated that with the use of electrolysis treatment, a maximum iron removal rate of around 99.99% was achieved; a final pH of 6.5 was obtained. It was concluded that iron removal exceeded 80% from the 20th minute of the experimental period.

Similarly, Gonzales & Malca (2019) investigated the impact of current density on the efficacy of heavy metal removal during electrocoagulation treatment at Yanacocha S.R.L. The initial pH of the solution ranged between 2.00 and 2.12. The experimentation involved the use of a reactor operating at a current of 10 amperes; two electrodes made of steel and aluminum were used serving as cathode and anode, respectively. The reactor operated for an average duration of 3 hours, with 36 minutes dedicated to achieving a solution with a pH ranging from 5.15 to 6.00. A reduction in heavy metal concentrations of 70% to 100% was achieved.

Continuing with the study, Castañeda & Choton (2019) conducted research on the impact of current density and residence length in the reduction of Fe2+ in acidic solution during the electrocoagulation process. Three different current densities (20, 40, and 80 mA/cm2) and four residence times (10, 20, 40, and 60 minutes) were used. It was evidenced that at a current density of 80 mA/cm2 and a residence duration of 40 minutes, the highest percentage of Fe2+ ion removal achieved was 76.20%. Likewise, a removal percentage of 17.97% was observed when the current density was set at 20 mA/cm2. It was determined that the current density within the pH range of 6-7 contributes to increased flocculation, sludge formation, and generation of metal oxides. This particular current density is responsible for a certain percentage of removal. Based on the ANOVA statistical analysis performed with a 95% confidence level, it has been determined that current density is the variable that exerts the most significant influence on the reduction of Fe(II) ions through the electrocoagulation process.

To reinforce the background of the study, Terán (2019) demonstrated the decrease in lead levels by 48.45% after a duration of 30 minutes and an applied current density of 40 mA/cm2. A removal efficiency of 98.96% was achieved after 60 minutes under the same conditions. The ANOVA analysis indicates that the electrolysis process for lead reduction is influenced by both time and current density. Acid mine drainage (AMD) occurs during the extraction process of certain deposits such as coal, metallic sulfides, iron, uranium, and others, where significant amounts of sulfurous minerals are exposed to weathering, leading to possible acid drainage. For this phenomenon to occur, aerobic circumstances are necessary, involving sufficient quantities of water and oxygen, along with the simultaneous catalytic activity of bacteria (Zamora & Meza, 2022). Additionally, (Kalonji-Kabambi, Demers, & Bussière, (2020), the acceleration of geochemical events leading to the creation of acid waters is mainly due to the oxidation of pyrite, especially in mining regions.

Similarly, Zamora & Meza (2022) state that the hydrolysis of dissolved Fe, Al, and Mn can result in the generation of H+ ions, leading to a high concentration of H+ ions and a subsequent drop in pH. Acid drainage is defined as a condition in which the concentration of acidic minerals exceeds that of alkaline minerals. It includes elevated levels of sulfate (SO4), iron (Fe), manganese (Mn), aluminum (Al), and other ions. However, the mineral dissolution process of carbonate serves to counteract acidity and remove metal ions such as Fe and Al.

When metallic sulfides come into contact with the environment, they oxidize and produce acid mine waters. Iron is essential in this process, both in its divalent and trivalent forms. Below are the pyrite oxidation reactions (Gamonal, 2020):

$$FeS_2 + 7/2\ O_2 + H_2O = 2SO^{2-}_4 + Fe^{2+} + 2H^+ \ \ldots\ldots\ldots\ldots\ldots\ldots \quad (1)$$

$$2Fe^{2+} + 1/2\ O_2 + 2H^+ = 2Fe^{3+} + H_2O \ \ldots\ldots\ldots\ldots\ldots\ldots \quad (2)$$

$$Fe^{3+} + 3H_2O = Fe(OH)_3 + 3H^+ \ \ldots\ldots\ldots\ldots\ldots\ldots \quad (3)$$

In general, the following equation represents the expression for the pyrite oxidation process (Jimbo, 2019):

$FeS_2 + 15/4\ O_2 + 7/2\ H_2O = Fe(OH)_3 + 2H_2SO_4$ ………………………… (4)

The stage of acidic water formation is considered.

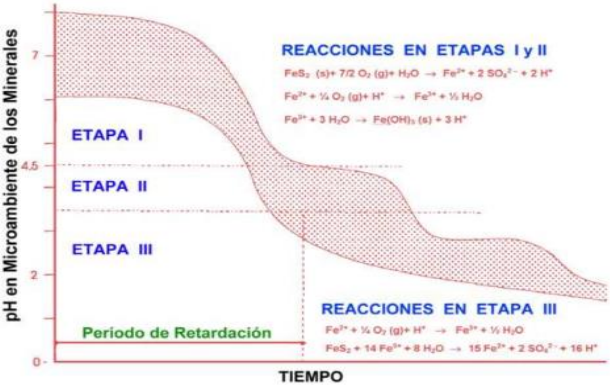

Figure 1. Stages in the formation of acidic waters

Source: Jimbo (2019)

In the initial stage, the oxidation process of sulfur minerals results in the release of iron ions. These iron ions then undergo chemical oxidation in a neutral environment, transforming into Iron hydroxide. Subsequently, the iron hydroxide precipitates and contributes to the acidity of the medium. In this phase of the process, the synthesis of acid water through oxidation, mainly facilitated by air and bacteria (particularly Thiobacillus ferrooxidans), releases moisture at a similar rate. This occurs when the rate of oxidation is low in both direct and indirect mechanisms of acid generation. In general, the gradual development of acidity can be partially countered by the inherent alkalinity of the medium. According to Jimbo (2019), in the second stage, the decrease in the neutralization capacity of the medium is overcome by the accumulated acidity, resulting in a pH drop. Consequently, bacterial activity becomes more common in the oxidation of pyrite. The resulting chemical reaction is the formation of iron sulfate, which is subsequently transformed into ferrous sulfates by oxidation. Upon exposure to water, sulfate undergoes a chemical reaction resulting in the formation of sulfuric acid and iron hydroxide. The latter compound is insoluble in water and gives a yellowish tone to the aqueous solution. Currently, the indirect mechanism demonstrates a higher level of effectiveness than the direct one, specifically in the context of air oxidation. According to Gamonal (2020), in the third stage, it has been observed that bacterial activity can facilitate the leaching of iron sulfide into sulfate when the pH of the environment, particularly in areas around pyrite grains, drops below 3. The iron ion is affected by this phenomenon. The current state of acid production experiences variability as a result of increased iron solubility and decreased iron hydroxide precipitation. In summary, Thiobacillus ferrooxidans generates additional acid through the oxidation of ferric ions to ferrous ions, subsequently facilitating sulfite oxidation. It is imperative to address the following factors, given the substantial acid production currently occurring.

2. Experimental Section

The research was conducted in the El Tingo ravine of the El Tingo population center, Hualgayoc district, Hualgayoc province, Cajamarca department, with WGS 84 UTM coordinates zone 17S E:759125 N:9255332.

Figure 2. Location of the study area.

Source: ArcGis.

The unit of analysis consisted of an acid mine drainage (AMD) from the El Tingo ravine, El Tingo population center, Hualgayoc district, Hualgayoc province, Cajamarca department. The population consisted of 30 liters of acid mine drainage (AMD) from the El Tingo ravine, El Tingo population center, Hualgayoc district, Hualgayoc province, and Cajamarca department. The sample was established by 4 parameters of the VI1 (Current Density) x 4 parameters of the VI2 (Residence Time) x 3 replicates, resulting in 48 samples. Likewise, the standard or initial sample without any treatment was analyzed. Each sample consisted of 200 mL, making a total of 9.8 L of acid mine drainage (AMD) from the study area.

Table 1. Matrix table for the results of the 48 tests for each of the dependent variables

		Residence time (minutes)							
		35		40		45		50	
Current Density (mA/cm^2)	15	R_1 R_2 R_3	Prom	R_1 R_2 R_3	Prom	R_1 R_2 R_3	Prom	R_1 R_2 R_3	Prom
	20	R_1 R_2 R_3	Prom	R_1 R_2 R_3	Prom	R_1 R_2 R_3	Prom	R_1 R_2 R_3	Prom
	25	R_1	Prom	R_1	Prom	R_1	Prom	R_1	Prom

	R_2 R_3		R_2 R_3		R_2 R_3		R_2 R_3	
30	R_1 R_2 R_3	Prom	R_1 R_2 R_3	Prom	R_1 R_2 R_3	Prom	R_1 R_2 R_3	Prom

Being an applied research, with a pure experimental design, consisting of a control group: Comparison groups were formed (with one of them manipulating the variable). Taking into account internal validity: The groups were formed randomly. As can be seen in Table 2 and Table 3. The iron concentration in the AMD solution was determined using the spectrophotometry technique, a quantitative chemical analysis method in the laboratory.

The design evaluated two independent variables and two dependent variables. Likewise, pre-tests and post-tests were used to analyze the evolution of the groups before and after the experimental treatment with electrolysis.

Table 2. Matrix table for Fe concentrations after treatment

		Residence Time (minutes)							
		35		40		45		50	
Current density (mA/cm^2)	15	M-5 M-21 M-37	Prom	M-3 M-19 M-35	Prom	M-9 M-25 M-41	Prom	M-4 M-20 M-36	Prom
	20	M-2 M-18 M-34	Prom	M-7 M-23 M-39	Prom	M-1 M-17 M-33	Prom	M-8 M-24 M-40	Prom
	25	M-6 M-22 M-38	Prom	M-10 M-26 M-42	Prom	M-11 M-27 M-43	Prom	M-12 M-28 M-44	Prom
	30	M-13 M-29 M-45	Prom	M-14 M-30 M-46	Prom	M-15 M-31 M-47	Prom	M-16 M-32 M-48	Prom

Table 3. Matrix table for the pH obtained after treatment

		Residence time (minutes)							
		35		40		45		55	
Current density (mA/cm^2)	15	M-13 M-29 M-45	Prom	M-5 M-21 M-37	Prom	M-2 M-18 M-34	Prom	M-4 M-20 M-36	Prom
	20	M-16 M-32 M-48	Prom	M-6 M-22 M-38	Prom	M-1 M-17 M-33	Prom	M-7 M-23 M-39	Prom
	25	M-3 M-19 M-35	Prom	M-9 M-25 M-41	Prom	M-8 M-24 M-40	Prom	M-15 M-31 M-47	Prom
	30	M-12 M-28	Prom	M-11 M-27	Prom	M-14 M-30	Prom	M-10 M-26	Prom

M-44 M-43 M-46 M-42

Regarding the experimental procedure, the following sequence was followed:

Preparation of steel electrodes: The electrodes used (anode and cathode) were AISI 304 steel plates, with dimensions of 5.5 x 5.5 x 0.2 centimeters. They were carefully polished, then cleaned with soap, rinsed with potable water, degreased with a solvent, and dried with a cloth to remove any impurities (oils, grease, or dust) from their surface.

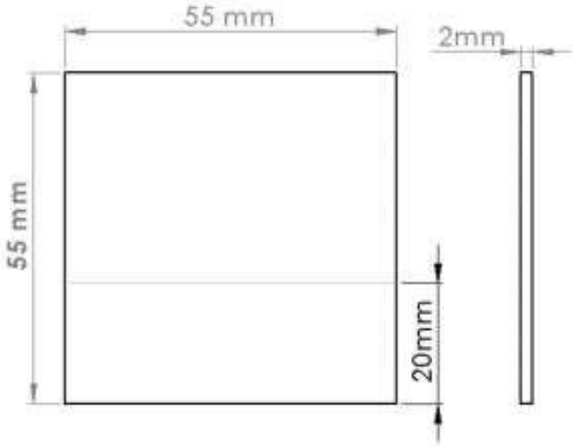

Figure 3. Characteristics of the steel electrodes

Construction of the electrolysis cell: The cell for electrolysis was comprised of a 500 mL precipitation beaker. The scheme of the electrolysis system used in the research is shown in Figure 4.

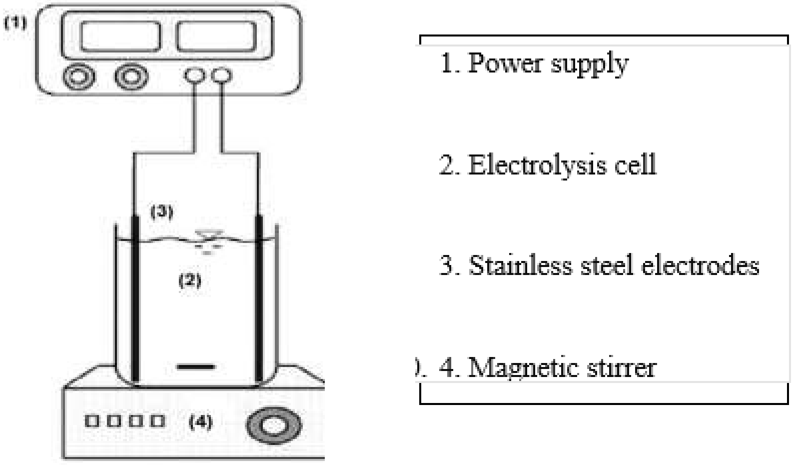

Figure 4. Scheme of the electrolysis cell setup

The effective area used will be 23.9 cm2 per electrode. Table 4 summarizes the conditions used for the electrolysis process carried out in this research.

Table 4. Operating conditions for the electrolysis cell.

Name	Description
Volume per trial	0.20 L
Type of reactor	Batch
Number of electrodes per trial	02
Cell cathode	Stainless Steel AISI 304
Cell anode	Stainless Steel AISI 304
Size of electrodes	5.5 x 5.5 x 0.2 cm.
Trial time	Variable
Current parameters (voltage, amperage)	Variable
Separation between electrodes	2 cm

The samples were coded as follows: After treatment, they were allowed to rest for two hours, and a volume of 0.20 L was extracted. Then, they were coded and randomly selected for subsequent analysis of the different concentrations of iron and pH.

The final characterization of the solution under study was as follows: To verify the reduction of iron concentration through the electrolysis method under the aforementioned conditions and to measure the increase in pH, the tested samples underwent chemical analysis, which allowed for quantitative variations to be evaluated.

Below is the experimental procedure depicted in Figure 5:

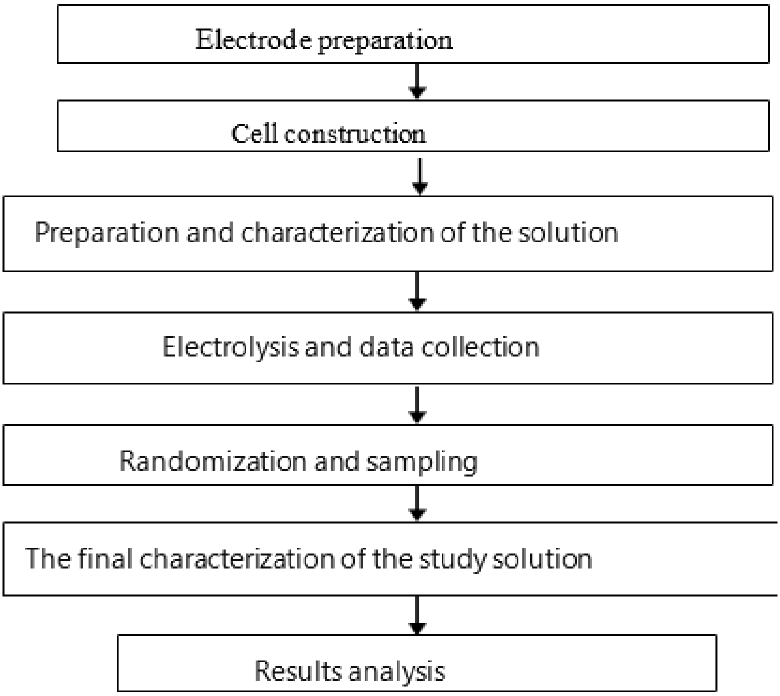

Figure 5. Experimental Procedure

3. Results and Discussion

Iron Removal

Below, Table 5 and Figure 6 show the results of the iron concentration, and Table 6 and Figure 7 display the percentage of iron reduction after conducting the experimental run, considering that the initial iron concentration averaged 52.48 ppm.

Table 5: Average Fe Concentration Report, in ppm, after treatment

		Residence time (minutes)			
		35	40	45	50
Current Density (mA/cm^2)	15	4.320	4.300	4.030	3.970
	20	4.290	3.820	3.700	3.360
	25	3.860	3.330	2.520	1.950
	30	3.020	2.470	1.540	1.340

Table 6: Average Fe Reduction Report, in %, after treatment

		Residence time (minutes)			
		35	40	45	50
Current Density (mA/cm^2)	15	91.768	91.806	92.321	92.435
	20	91.825	92.721	92.950	93.598
	25	92.645	93.655	95.198	96.284
	30	94.245	95.293	97.066	97.447

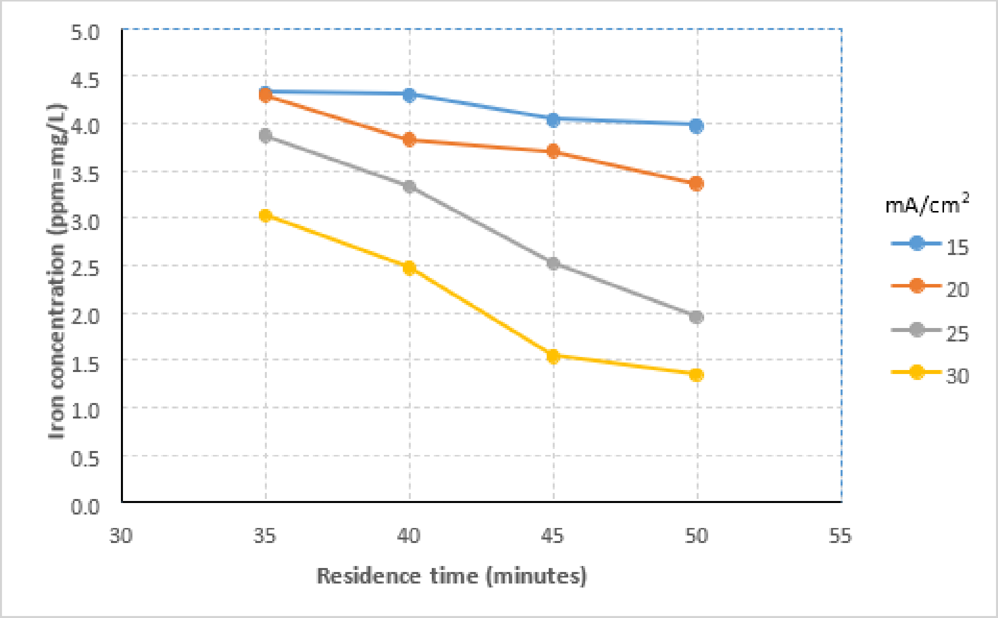

Figure 6. Report of Fe concentrations, in ppm = mg/L, after treatment

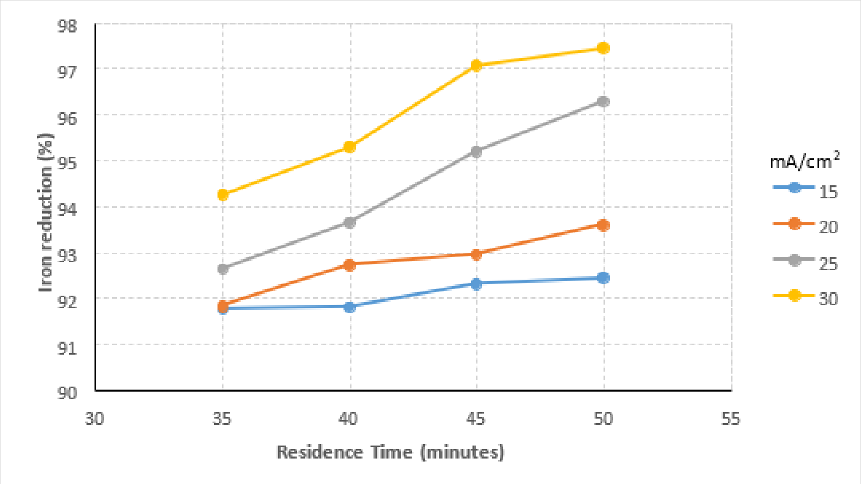

Figure 7. Report of Fe reductions, in %, after treatment

According to the results obtained, it is evident that as the residence time and current density increase, the reduction of Fe in the DAM solution also increases. For instance, within the initial 35 minutes and at a density of 15 mA/cm^2, the iron concentration was reduced from 52.48 ppm to 4.320 ppm, representing a reduction percentage of approximately 91.768%. The optimal parameter was achieved with a 50-minute treatment and 30 mA/cm2, resulting in a reduction of the iron concentration to 1.340 ppm, representing a 97.447% reduction in Fe. This reduction occurred because the DAM solution contained dissolved iron metal ions, and through electrolysis within the cell consisting of two electrodes—one positive (anode) and the other negative (cathode), both made of steel—oxidation occurred at the anode and reduction at the cathode.

When an external current was applied, the release of oxygen (O_2) was observed at the anode and hydrogen (H_2) at the cathode, but only when the potential difference between the electrodes reached a theoretical minimum.

Two mechanisms were generated, both at the anode and cathode: (1) Oxidation at the anode - at the anode, water ions (H_2O) decomposed through the oxidation reaction, generating oxygen (O_2) and protons (H^+). This reaction helped maintain ionic balance in the solution; (2) Reduction at the cathode - at the cathode, dissolved metal ions, such as iron (Fe^{3+}), were reduced to their metallic form, in this case, elemental iron (Fe). This occurred through the transfer of electrons from the cathode to the metal ion, resulting in its deposition or precipitation on the cathode surface. Once the iron has been deposited on the cathode, it can be recovered through different methods, such as scraping or washing of the cathode. The recovered iron can then be used in various applications.

The DAM solution, under atmospheric conditions, 1 atm and 25°C, does not spontaneously decompose to form $H_2(g)$ and $O_2(g)$. However, this reaction can be induced in an electrolytic cell as shown in Figure 9. When the electrodes are submerged in the DAM solution and connected to the power source (battery), there are enough ions to conduct electricity. Gas bubbles of hydrogen and oxygen begin to appear on the two electrodes immediately, without any net consumption of the acidic solution.

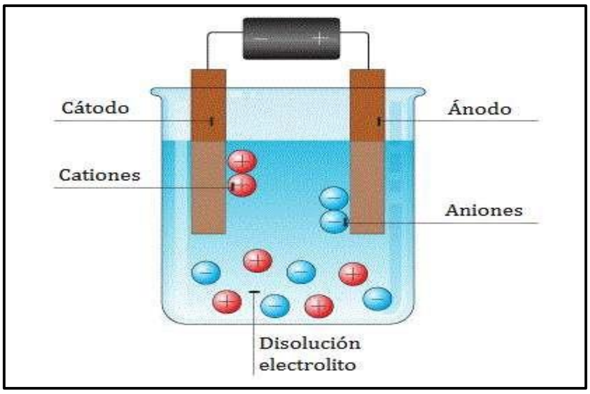

Figure 8. Electrolytic cell

Source: Chemistry (2023)

According to Figure 9, the following reactions are asserted:

Anode: $2\ H_2O(l) \rightarrow O_2(g) + 4\ H^+(aq) + 4\ e-$

Cathode: $2\ [2\ H^+(aq) + 2\ e- \rightarrow H_2(g)]$

$$2\ H_2O(l) \rightarrow 2\ H_2(g) + O_2(g)$$

Additionally, the following mechanism is also generated at the cathode:

Cathode: $Fe^{3+} + 3e- \rightarrow Fe(S)$

The results obtained are supported by various researchers such as Valles (2021), who stated in their research that to effectively remove iron and neutralize DAM, they used a 60-minute treatment and a current density of 19 A/m2, achieving a 99.99% reduction in Fe, which initially had a concentration of 300 ppm, affirming an Fe removal from minute 20 with a reduction percentage of approximately 80%.

Similarly, Gonzales & Malca (2019) investigated the impact of current density on the efficacy of heavy metal removal during electrocoagulation treatment, finding that with the use of 10 amperes for 3 hours and 36 minutes, they achieved a reduction in heavy metal concentrations from 70% to 100%.

In their study, Castañeda & Choton, (2019) conducted research on the impact of current density and residence time on the reduction of Fe2+ in acidic solution, showing that at a current density of 80 mA/cm2 and a residence duration of 40 minutes, the parameters for the highest percentage of Fe2+ ion removal were reached, at 76.20%. Likewise, a removal percentage of 17.97% was observed when the current density was set at 20 mA/cm2. Finally, Terán (2019) investigated the impact of lead removal from the mineral acid drainage of Cerro Corona Hualgayoc - Cajamarca in relation to current density and time; the research demonstrated that there was a decrease in lead levels by 48.45% after a duration of 30 minutes and an applied current density of 40 mA/cm2; furthermore, a removal efficiency of 98.96% was achieved after 60 minutes under the same conditions.

Increase in pH in the DAM solution

Regarding the increase in pH and neutralization of the DAM solution (pH between 6.5 - 8.5), the results obtained after treatment are observed in Table 7 and Figure 9, considering that the initial average pH was 2.62, showing a substantial increase in pH.

Table 7. Report of the average pH values of the DAM solution after treatment

		Residence time (minutes)			
		35	40	45	50
Current density (mA/cm^2)	15	6.090	6.110	6.130	6.170
	20	6.220	6.360	6.440	6.560
	25	6.620	6.940	7.090	7.140
	30	7.250	7.420	7.460	7.630

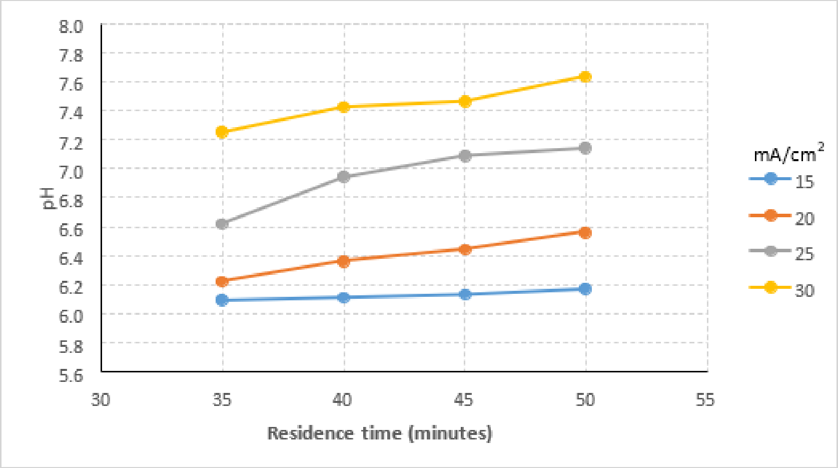

Figure 9. Report of average pH results after treatment

According to the obtained results, it is demonstrated that as the residence time and current density increase, the pH in the DAM Solution increases. For instance, within the initial 35 minutes and at a density of 15 mA/cm2, it was raised from 2.62 to 6.090. The optimum parameter was achieved with a 50-minute treatment and 30 mA/cm2, resulting in a pH of 7.63. This was due to the reduction reaction that occurs during the electrolysis process. In this process, metallic ions such as iron (Fe3+) are reduced to their metallic form at the cathode. This involves the transfer of electrons to the cathode from dissolved metallic ions.

During the reduction of iron at the cathode, protons (H+) present in the solution are consumed. These protons combine with electrons to form gaseous hydrogen molecules (H2). As protons are consumed, the concentration of H+ ions in the solution decreases, leading to an increase in pH. Additionally, oxidation occurring at the anode during the electrolysis process generates oxygen (O2) and protons (H+). However, these protons generated at the anode are not sufficient to counteract the decrease in protons caused by the reduction of iron at the cathode.

As a result, the pH of the solution tends to increase.

The increase in pH in a mine acid drainage solution is beneficial as it helps neutralize the acidity of the solution and stabilize it, reducing its toxicity and facilitating further treatment. However, it is important to monitor and control the pH to ensure it remains within appropriate limits for the treatment process and to avoid additional environmental issues.

The obtained results are supported by Valles (2021), who stated in their research that to effectively remove iron and neutralize the DAM, they used a 60-minute treatment and a current density of 19 A/m2, achieving a pH increase to a value of 6.5 from an initial pH of 2.5. Treatment was conducted without agitation and at a working temperature of 25°C. Similarly, Gonzales & Malca (2019) investigated the impact of current density on the effectiveness of heavy metal removal during electrocoagulation treatment, finding that the pH of the initial solution varied from 2.00 to 2.12, and with the use of 10 amperes for 3 hours and 36 minutes, they managed to increase the pH within a range between 5.15 and 6.00.

In the analysis of variance, it was found that the F-treatment is greater than F-alpha, V1, V2, for each of the treatments, as well as for their interactions, thus accepting the alternative hypothesis stating that each of the independent variables and their interactions significantly influence the dependent variable, as evidenced in Table 8 and Table 9.

Table 8. Variance analysis for the results found of iron concentration affected by current density and pH

Source of variations	Sun of squares	Degrees of freedom	Mean squares	$F_{\text{treatment}}$	F_α, V1, V2
Current density	30.71588333	3	10.23862778	767.5373002	2.901119584
Residence time	10.61833333	3	3.539444444	265.333958	2.901119584
Interaction	3.078816667	9	0.342090741	25.64478456	2.188765768
Within the group	0.426866667	32	0.013339583		
Total	44.8399	47			

In the above table, it is observed that the current density has the greatest influence on the iron concentration, as it has the highest F-treatment value, followed by residence time, and finally by the interaction of both. In other words, the current density, residence time, and the interaction of current density with residence time significantly affect the iron concentration, which is statistically supported by the analysis of variance.

Table 9. Variance analysis for the results found of pH affected by current density and residence time

Source of variations	Sum of squares	Degrees of freedom	Mean squares	Ftratamiento	F_α, V1, V2
Current density	12.36870625	3	4.122902083	711.8679856	2.901119584
Residence time	0.697939583	3	0.232646528	40.16918465	2.901119584
Interaction	0.20871875	9	0.023190972	4.004196643	2.188765768
Within the group	0.185333333	32	0.005791667		
Total	13.46069792	47			

According to table 9, the current density also has the greatest influence on the pH, as it has the highest F-treatment value, followed by residence time, and finally by the interaction of both. In other words, current density, residence time, and the interaction of current density with residence time significantly affect the pH of the DAM solution, which is statistically supported by the analysis of variance.

4. Conclusions

It is concluded that the current density and residence time influence the reduction of iron concentration and pH increase in the electrolysis treatment of acid mine drainage from the Hualgayoc area, Cajamarca, as evidenced by the analysis of variance and the obtained results.

The current density significantly influences the reduction of iron concentration in the electrolysis treatment of acid mine drainage from the Hualgayoc area, Cajamarca. This was evidenced by ANOVA, with F treatment = 767.54 > Fα,V1, V2 = 2.90.

Time significantly influences the reduction of iron concentration in the electrolysis treatment of acid mine drainage from the Hualgayoc area, Cajamarca. This was evidenced by ANOVA, with F treatment = 265.33 > Fα,V1, V2 = 2.90.

The interaction of current density and time significantly influences the reduction of iron concentration in the electrolysis treatment of acid mine drainage from the Hualgayoc area, Cajamarca. This was evidenced by ANOVA, with F treatment = 25.64 > Fα,V1, V2 = 2.19.

Current density significantly influences the pH increase in the electrolysis treatment of acid mine drainage from the Hualgayoc area, Cajamarca. This was evidenced by ANOVA, with F treatment = 711.87 > Fα,V1, V2 = 2.90.

Time significantly influences the pH increase in the electrolysis treatment of acid mine drainage from the Hualgayoc area, Cajamarca. This was evidenced by ANOVA, with F treatment = 40.17 > Fα,V1, V2 = 2.90.

The interaction of current density and time significantly influences the pH increase in the electrolysis treatment of acid mine drainage from the Hualgayoc area, Cajamarca. This was evidenced by ANOVA, with $F_{\text{treatment}}$ = 4.00 > Fα, V1, V2 = 2.19.

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Notes

Conflict of Interest Statement

The authors declare no conflict of interest.

Author Contributions

FC (Professor), the first author and corresponding, designed the framework, constructed the survey, and completed the writing and funding; GJ (Dr.), as corresponding author, organized the research project and the survey; CS (Research Professor): as second author, conducted the analysis; LR (Professor): Critical revision of manuscript; CF (Dr. student): Experimental, data acquisition and curation(Professor); LR (Professor): revision of manuscript; RP (Research Professor): Statistical Analysis; GM (Research Professor): Validation and Writing.

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