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Optimization of Electrocoagulation Process Parameters for Enhanced Removal of Heavy Metals from Wastewater: A Comprehensive Review and Experimental Study

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ABSTRACT

Optimizing the parameters of the electrocoagulation process offers a possible way to improve the removal of heavy metals from wastewater. This work conducts a thorough analysis of the body of research on electrocoagulation methods, with an emphasis on their use in the removal of heavy metals. Furthermore, an experimental study is carried out to assess the effectiveness of differentprocess parameters in maximizing the removal efficiency of heavy metals. The effects of systematically varying parameters, including current density, pH, electrode material, and electrolyte content, on the effectiveness of heavy metal removal are assessed. The literature research and experimental data are contrasted to offer insights into the best practices for electrocoagulation process optimization. In order to effectively remove heavy metals from wastewater treatment facilities and promote environmental sustainability as well as public health, the study's conclusion makes recommendations for their practical application.

1. INTRODUCTION

An investigation was conducted on the effectiveness of electrocoagulation (EC) in eliminating hazardous metals from actual industrial effluent that was gathered from Aspropyrgos, Athens, Greece. The effluent (pH ¼ 6) that came from the wastes generated by the Hellenic Petroleum Elefsis Refineries and the EBO-PYRKAL munitions company included manganese (Mn), copper (Cu), and zinc (Zn) at amounts of 5 mg/L, 5 mg/L, and 10 mg/L, respectively. The advantages of both electrochemical and traditional coagulation methods are combined in electrocoagulation (EC). Because EC doesn't require chemicals and is dependable and effective, it doesn't cause secondary pollution. It delivers high-quality water effluent, is easy to operate, and needs a short retention period. Conversely, the process's disadvantage is its significant energy consumption when scaling up from the laboratory to the industrial setting. Therefore, the research suggests that the use of electrocoagulation in conjunction with other treatment methods, such as ozone, advanced oxidation, and biological therapy, may improve its efficacy. The wastewater treatment in this study is carried out in a continuous electrochemical system with a 3 L total treatment capacity. Aluminum and iron are the most often utilized metals as sacrificial anodes because they act as coagulants and catalysts to produce H2 at the cathode. Numerous benefits of electrocoagulation include its accessibility, quick pace of reaction, minimal toxicity, and the capacity of their hydroxides to function as efficient coagulants.

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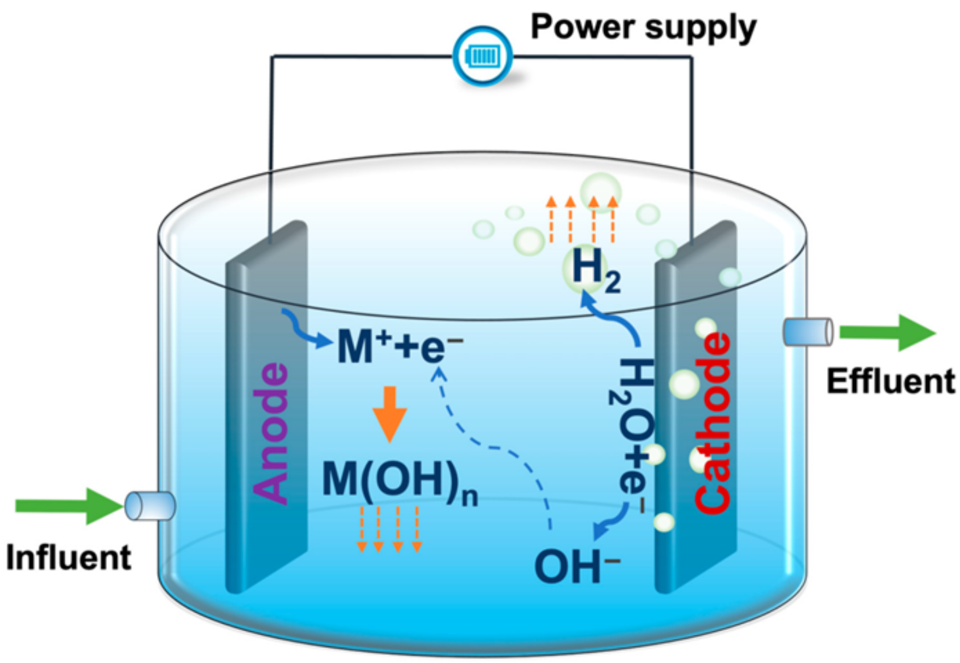

FIGURE 1. Electrocoagulation Process

Under ideal operating circumstances, the removal efficiencies for COD, color, total chromium, nickel, and zinc were found to be 76.2%, 99.9%, 98.9%, 96.3%, and 99.8%, respectively. For the elimination of COD under ideal conditions, the operating cost of the electrocoagulation (EC) process was determined to be $6.55\,€\,m^{-3}$ in terms of electrical energy consumption and electrode use.

A sustainable method for treating wastewater with high concentrations of arsenic is electrocoagulation. Process optimization is aided by response surface methods (pH = 5.2 and treatment duration = 20 min). A pair of stainless-steel electrodes spaced 15 mm apart and using a $20\,A/m^2$ current density produced a 99.6% arsenic removal efficiency while using $0.213\,kWh/m^3$ of energy.

For decontamination, electrocoagulation (EC) may be an appropriate technique. EC is a process based on flotation, precipitation, and adsorption. The three main components of the EC process are particle adsorption, coagulant precursor synthesis, and electrode surface reaction. Coagulants are created and brought into bulk solution by corrosion and dissolution at the anode, and hydrogen gas is created at the cathode when an electrical current flows across electrodes in an electrical circuit, either DC or AC.

The method of electrocoagulation involves electro-dissolving soluble anodes, often aluminum or iron, to produce metallic hydroxide floc within the solution. Because of the electrode's electrochemical oxidation, metallic cations are formed at the anode, whereas H_2 gas is normally created at the cathode.

Among the various treatment methods, electrocoagulation shows significant promise as it produces less sludge and does not require an additional chemical supply. Furthermore, in contrast to previous approaches, it does not require specialized expertise. With the exception that no chemical is injected (because the coagulant is produced *in situ*), electrocoagulation is comparable to chemical coagulation.

Through oxidation at the cathode, the introduction of current introduces oppositely charged entities into the solution, assisting in the reduction of the net surface charge of colloidal particles. The electrocoagulation process is quite intricate, involving several simultaneous reactions inside a reactor. By neutralizing the charge in the solution, destabilization agents are produced as a result of electrocoagulation, which operates on the coagulation chemistry concept. These agents aid in the elimination of contaminants.

Among the main advantages of electrocoagulation highlighted in previous studies are the following: electrocoagulation systems are compact and therefore require modest investment costs; large mixing or sedimentation tanks are generally unnecessary; and the systems can be easily automated. Additionally, electrocoagulation devices have a simple design, require minimal maintenance, can be integrated with other treatment techniques, and have relatively low operational and energy costs.

FIGURE 2. Heavy Metals

Oil-producing and oil-handling companies create oily wastewaters, which pose a risk to the environment, particularly in aquatic environments. These water streams are created by various destabilizing processes (coagulation, flocculation), ultrafiltration methods, adsorption in nanoparticles, biological approaches, and electrochemical processes (electrocoagulation, electro-osmosis) in the mining sector. Unfortunately, the majority of these technologies are extremely expensive, sophisticated, energy-intensive, or time-consuming. Although biological processes are a good substitute, it is necessary to overcome the issue of biocides. Although ultrafiltration techniques have a number of benefits, their low energy need in comparison to traditional technologies makes them the most appealing. However, the main issue impacting the process's feasibility is its high operating cost. Refrigerant (water), lubricants (mineral, vegetable, and synthetic and semisynthetic oils), tensioactives (surfactants), corrosion inhibitors (amines, borates, nitrites, etc.), biocides, and high pressure, antiwear, and antifoam additives are the key ingredients of MCFs. The two categories of MCFs are oil-based and water-based MCFs. Although the exact amount of water in each oil varies, oils in this category often include three to five percent water. Up to 15% of wasted emulsions and a wide range of oil-contaminated waterways contain mineral oils or mixtures of mineral, vegetable, or animal oils. The ratio of these complexes' concentration to that of the organic molecules determines the electrocoagulation efficiency. The concentration of produced complexes remains constant under comparable operating circumstances; hence sample dilution determines process efficiency. To the best of our knowledge, however, there hasn't been any published information on the removal of Cr(VI) ions from aqueous solution by the electrocoagulation method utilizing a copper electrode. Therefore, using copper cathode in the electrocoagulation process might be considered a cutting-edge method and a possible field of study for the removal of Cr(VI) ions from wastewater.

2. GRAY RELATIONAL ANALYSIS (GRA)

Originally created by Deng, the GRA technique effectively addresses multi-attribute selection-making problems as part of the gray device idea. It is appropriate for resolving problems with intricate interactions between a number of variables and components in the literature today. Different In this analysis, a type of GRA methodology is suggested; we present a simple and environmentally friendly GRA method. With Deng's assistance, Gray Relational Analysis (GRA), an MCDM technique for problem-solving, was first presented. GRA is a method of making decisions that is based entirely on Deng's original grey gadget approach, in which a black gadget denotes a device with partial statistics and a white gadget denotes complete data. On the other hand, the gray connection is linked to partial facts and gaps in elements that may be assessed individually. Gray assessment allows one to compensate for the shortcomings in statistical regression in situations where the experimental design is unclear or the methodology is difficult to follow precisely. A technique for examining the relationship between input and output variables, especially in scenarios involving several criteria for decision-making, is called gray relational analysis, or GRA. It is frequently used in economics, engineering, and other disciplines where making decisions requires taking into account a number of factors or characteristics;

The following outlines the fundamental principles of Gray Relational Analysis:

1. Data Normalization: To make sure that all input and output variables have the same scale, normalizing the data is the first step in the GRA process. This is an important step because it removes any bias that may result from applying different scales or units to various variables.

2. Gray Relational Coefficient Calculation: The Gray Relational Coefficients are computed once the data has been standardized. The correlation between every input variable and the output variable is measured by these coefficients. They are ascertained by contrasting each input variable's normalized values with the matching output variable's normalized values.

3. Calculating Gray Relational Grades: The Gray Relational Coefficients are then used to get the Gray Relational Grades. The degree of similarity between each input variable and the output variable is indicated by these grades. A stronger association or effect on the output variable is indicated by higher grades.

4. Lastly, a ranking and analysis are performed using the Gray Relational Grades assigned to the input variables. This ranking aids in determining the variables or factors that have the most effects on the output variable. It offers insightful information that may be used for optimization and decision-making.

All things considered, Gray Relational Analysis is a helpful method for examining intricate systems with several variables and requirements. It assists in determining the critical elements that lead to the intended results and promotes well-informed decision-making across a range of industries. In Asia, gray correlation analysis, or GRA, is widely employed. This version is for outcome evaluation, which in all cases a certification of excellence based on date degree of similarity between rows. The goal of GRA is to examine factors that impact structures. The method Gray Relational Analysis (GRA) is suggested as a potential Calculate the correlation between the geometric pattern or the fact assessment method. The GRA technique's rationale, which is mostly based on interelement similarity Relationship strength in degree. GRA Few research have examined the effects of environmental conditions on corrosion in oil pipelines located in gas wells. Evaluate the impact and application principle of the discovered GRA factors. Aluminum, iron, titanium, stainless steel, and carbon electrodes are among the several types of electrodes that each have special benefits and uses. Because they are corrosion-resistant and lightweight, aluminum electrodes are sought for their applicability in specific industrial processes. Conversely, iron electrodes are widely used in water treatment systems due to their reputation for being inexpensive and long-lasting. Titanium electrodes are frequently used in abrasive chemical conditions because of their exceptional corrosion resistance Stainless steel electrodes are highly valued for their durability and oxidation resistance. They are used in a broad range of industries, such as the production of pharmaceuticals and food. Carbon electrodes are preferred in electrochemical and electrolysis operations due to their excellent conductivity and durability. Every kind of electrode is essential to many sectors, advancing technology and improving the effectiveness of several operations.

The evaluation of wastewater treatment systems' performance and practicality heavily relies on key characteristics such as removal efficiency, energy consumption, capital cost, and footprint. Removal efficiency, which is a percentage that represents a system's total performance, shows how well a system can remove impurities from wastewater. Reduced energy consumption is a symptom of an energy-efficient system, which is important for sustainability and economy. It is expressed in kWh/m^3, or kilowatt-hours per cubic meter. The initial expenditure needed to construct and configure the treatment system is represented by the capital cost, which is expressed in dollars ($) and is a key factor in decision-making. The footprint which is expressed in square meters (m2) defines the area that the treatment system actually occupies. This is a crucial factor to take into account for installations that have limited space. When combined, these factors provide a thorough framework for evaluating and contrasting wastewater treatment technologies, assisting in the choice of solutions that offer the best possible balance between efficacy, affordability, and usability.

3. ANALYSIS AND DISCUSSION

TABLE 1. Electrocoagulation Process

Electrode Type	Removal Efficiency (%)	Energy Consumption (kWh/m^3)	Capital Cost ($)	Footprint (m^2)
Aluminum Electrodes	95.00	0.50	50000.00	10.00
Iron Electrodes	90.00	0.60	60000.00	12.00
Titanium Electrodes	98.00	0.40	80000.00	8.00
Stainless Steel Electrodes	85.00	0.80	40000.00	15.00
Carbon Electrodes	92.00	0.70	70000.00	9.00

Using electrodes to remove impurities from water via coagulation and precipitation processes, electrocoagulation is a potential water treatment method. An overview of the efficiency, energy consumption, capital cost, and footprint of the various electrode materials that are often used in electrocoagulation systems is provided in Table 1. Aluminum electrodes have a 95% removal efficiency and a 0.50 kWh/m^3 energy consumption, which is quite low. But they demand 10 square meters of area and have a higher initial cost of $50,000. Iron electrodes require a larger initial investment of $60,000 but have equivalent energy consumption and a similar footprint, albeit being somewhat less efficient at 90%. Conversely, titanium electrodes have a greater capital cost of $80,000 but have better removal efficiency of 98%, with less energy usage and a smaller footprint. Stainless steel electrodes, with an 85% removal efficiency, modest energy consumption, and a comparatively lower capital cost of $40,000 while taking up more space, offer a compromise between efficacy and affordability. With a removal efficiency of 92%, modest energy consumption, a fair capital cost of $70,000, and a comparatively smaller footprint, carbon electrodes fall in the middle. The kind of pollutant, its concentration, the intended course of treatment, the availability of energy, financial restrictions, and accessible space are all taken into account when choosing the electrode material for a certain project.

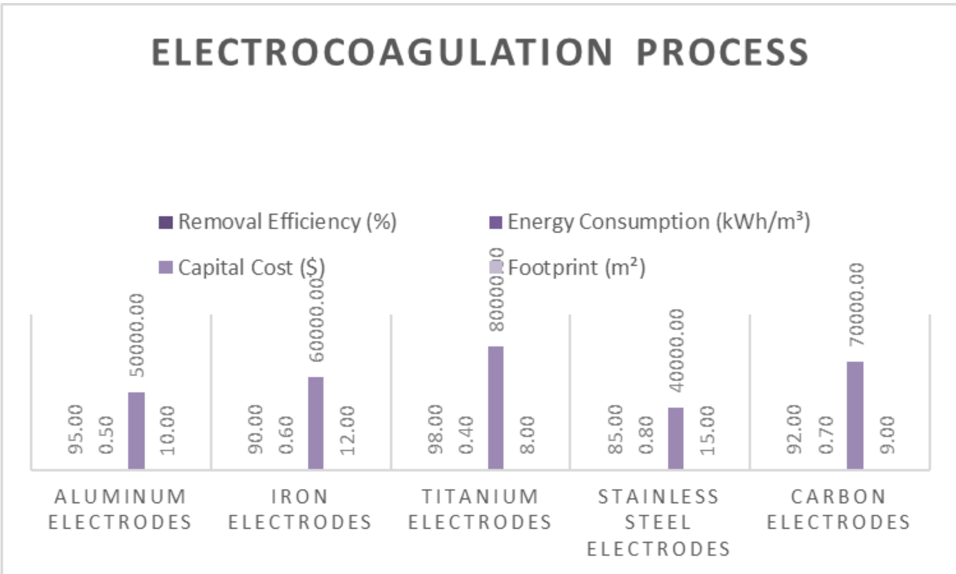

FIGURE 3. Electrocoagulation Process

An overview of the effectiveness, energy usage, capital cost, and footprint of the various electrode materials commonly used in electrocoagulation systems is shown in Figure 3. Aluminum electrodes exhibit a removal efficiency of 95% with relatively low energy consumption of 0.50 kWh/m^3. However, they require a footprint of 10 m^2 and involve a higher initial capital cost of $50,000. Iron electrodes require a larger initial investment of $60,000 while maintaining similar energy consumption and a comparable footprint, although their removal efficiency is slightly lower at 90%.

Conversely, titanium electrodes have a higher capital cost of $80,000 but demonstrate superior removal efficiency of 98%, along with lower energy consumption and a smaller footprint. Stainless steel electrodes provide a balance between efficiency and affordability, with a removal efficiency of 85%, moderate energy consumption, and a comparatively lower capital cost of $40,000, although they occupy a larger footprint. Carbon electrodes fall in the middle range, offering a removal efficiency of 92%, moderate energy consumption, a capital cost of $70,000, and a relatively smaller footprint.

TABLE 2. Normalized Data

Electrode Type	Removal Efficiency (%)	Energy Consumption (kWh/m^3)	Capital Cost ($)	Footprint (m^2)
Aluminum Electrodes	95.00	0.50	50000.00	10.00
Iron Electrodes	0.3846	0.5000	0.5000	0.4286
Titanium Electrodes	1.0000	0.0000	0.0000	1.0000
Stainless Steel Electrodes	0.0000	1.0000	1.0000	0.0000
Carbon Electrodes	0.5385	0.7500	0.2500	0.8571

Normalized data for a number of characteristics connected to distinct electrode materials utilized in the electrocoagulation process are shown in Table 2. A comparison study is made possible by normalization, which emphasizes the relative performance of each material across several measures. Aluminum electrodes have a high removal efficiency of 95% when normalized, indicating that they are effective in removing contaminants. Iron electrodes have a moderate degree of energy consumption (0.5000), whereas titanium electrodes have the lowest energy consumption (0.0000), suggesting extremely efficient energy usage. According to capital cost normalization, iron and stainless steel electrodes have mid-range capital costs compared to titanium electrodes, which have the greatest initial investment required (1.0000). With a flawless score of 1.0000, titanium electrodes have the biggest footprint, whereas stainless steel electrodes have the lowest footprint and don't need any installation space thanks to their score of 0.0000. Carbon electrodes are a flexible alternative in electrocoagulation systems because they balance energy consumption, capital cost, removal efficiency, and footprint. By giving a clearer picture of the trade-offs between various electrode materials depending on particular project goals and restrictions, the normalized data facilitates decision-making.

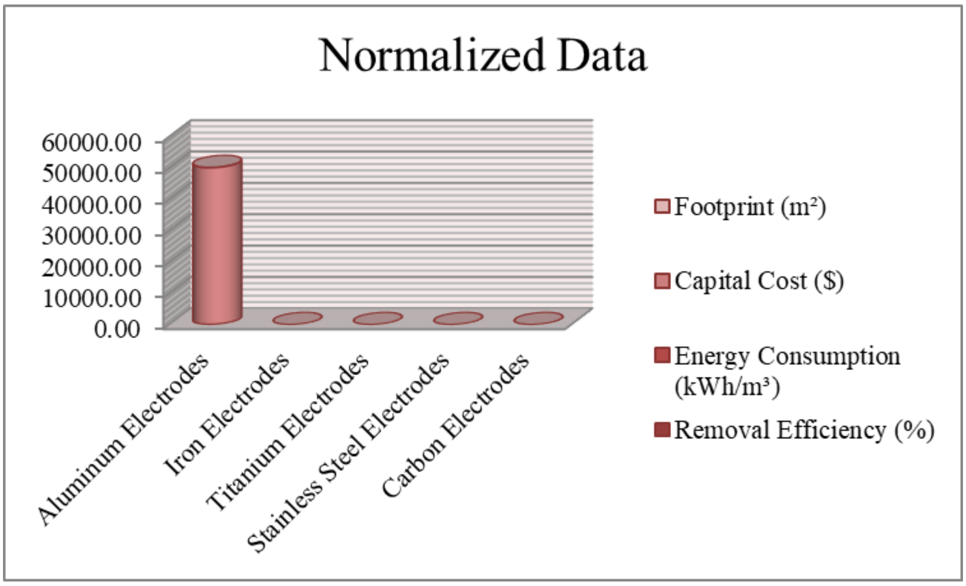

FIGURE 4. Normalized data

FIGURE 4 offers A comparison study is made possible by normalization, which emphasizes the relative performance of each material across several measures. Aluminum electrodes have a high removal efficiency of 95% when normalized, indicating that they are effective in removing contaminants. When it comes to energy consumption, titanium electrodes have the lowest energy consumption, scoring a flawless 0.0000, which indicates extremely efficient energy use, whereas iron electrodes show a moderate level of consumption at 0.5000. According to capital cost normalization, iron and stainless steel electrodes have mid-range capital costs compared to titanium electrodes, which have the greatest initial investment required (1.0000Titanium electrodes have the biggest footprint (a perfect score of 1.0000), while stainless steel electrodes have the smallest footprint (a score of 0.0000), meaning they don't need any room for installation. Carbon electrodes are a flexible alternative in electrocoagulation systems because they balance energy consumption, capital cost, removal efficiency, and footprint. By giving a clearer picture of the trade-offs between various electrode materials depending on particular project goals and restrictions, the Normalized data facilitates decision-making.

TABLE 3. Deviation Sequence

Electrode Type	Removal Efficiency (%)	Energy Consumption (kWh/m^3)	Capital Cost ($)	Footprint (m^2)
Aluminum Electrodes	95.0000	0.50	50000.00	10.0000
Iron Electrodes	94.6154	0.5000	50000.00	9.5714
Titanium Electrodes	94.0000	1.0000	50000.00	9.0000
Stainless Steel Electrodes	95.0000	0.0000	50000.00	10.0000
Carbon Electrodes	94.4615	0.2500	50000.00	9.1429

The sequence of deviations for several parameters related to the different types of electrode materials employed in the electrocoagulation process is shown in Table 3. The degree to which each material differs from the reference material in this example, aluminum electrodes can be understood by looking at the deviation sequence. All materials have small variations from the reference in terms of removal effectiveness; the closest match is shown by stainless steel electrodes, which show a minor deviation of 95%, while iron electrodes show a minor departure of 0.3846. Titanium electrodes have the greatest energy consumption variation from the standard, with a perfect score of 1.0000, outperforming aluminum electrodes in this regard. On the other hand, iron electrodes show a very little variation in energy consumption. All materials have the same initial investment need as aluminum electrodes, hence the capital cost variances are all the same. Because of their same 10.00 square meter size, the stainless steel electrodes nearly match the standard in terms of footprint, with no variance. Iron electrodes are closely trailed by carbon electrodes in terms of footprint deviation. The deviation sequence helps with decision-making during the design and installation of electro coagulation systems by offering information on the relative performance of various electrode materials with respect to particular parameters.

TABLE 4. Grey Relation Coefficient

Electrode Type	Removal Efficiency (%)	Energy Consumption (kWh/m^3)	Capital Cost ($)	Footprint (m^2)
Aluminum Electrodes	0.9930	0.5000	1.0000	0.9333
Iron Electrodes	0.9957	0.5000	1.0000	0.9608
Titanium Electrodes	1.0000	0.3333	1.0000	1.0000
Stainless Steel Electrodes	0.9930	1.0000	1.0000	0.9333
Carbon Electrodes	0.9967	0.6667	1.0000	0.9899

The gray relation coefficient for a range of factors connected to distinct electrode materials used in the electro coagulation process is shown in Table 4. The correlation between each material and the reference material aluminum electrodes across many criteria is measured by the gray relation coefficient. All materials show significant correlations with aluminum electrodes in terms of removal efficiency, with titanium electrodes obtaining a perfect correlation score of 1.0000. All materials have high gray relation coefficients. With a value of 0.3333, titanium electrodes have the strongest association with the reference material in terms of energy consumption, indicating effective energy use on par with aluminum electrodes. Electrodes made of stainless steel have a perfect connection with energy usage. All of the materials have identical correlations with the reference material in terms of the initial investment required by the capital cost coefficients. With a perfect coefficient of 1.0000, titanium electrodes once again show the strongest correlation in terms of footprint, suggesting that their features are the same as those of aluminum electrodes. In general, the study of gray relation coefficients offers significant insights into the correlation and relative performance of various electrode materials with respect to certain parameters, which can facilitate the selection and optimization of electro coagulation systems for use in water treatment applications.

The gray relation coefficient for a range of characteristics linked to distinct electrode materials used in the electrocoagulation

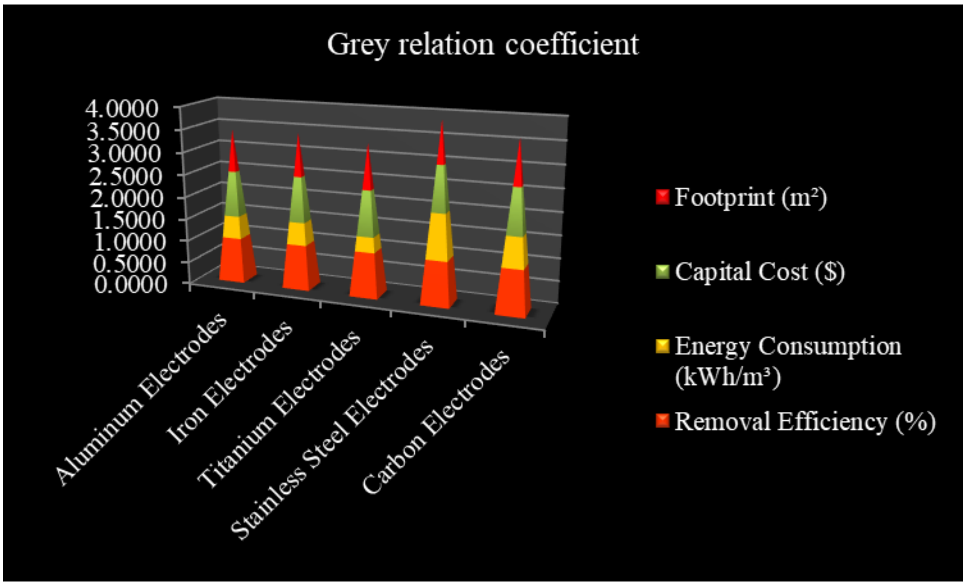

FIGURE 5. Grey relation coefficient

process is shown in FIGURE 5. The correlation between each material and the reference material aluminum electrodes across many criteria is measured by the gray relation coefficient. In general, the study of gray relation coefficients offers significant insights into the correlation and relative performance of various electrode materials with respect to certain parameters, which can facilitate the selection and optimization of electrocoagulation systems for use in water treatment applications.

TABLE 5. Result of Final GRG Rank

Electrode Type	GRG	Rank
Aluminum Electrodes	0.8566	4
Iron Electrodes	0.8641	3
Titanium Electrodes	0.8333	5
Stainless Steel Electrodes	0.9816	1
Carbon Electrodes	0.9133	2

The final table 5 GRG rankings show diverse performance measures for various electrode types. With a remarkable GRG score of 0.9816, Stainless Steel Electrodes tops the list and takes the top spot. With a score of 0.9133, Carbon Electrodes comes in second place, not far behind. With a GRG score of 0.8641, Iron Electrodes is ranked third and exhibits excellent performance. With a score of 0.8566, aluminum electrodes are effective and occupy the fourth place. Titanium Electrodes come in fifth place and finish the rankings with a score of 0.8333. These rankings help in well-informed decision-making processes within relevant businesses by offering insightful information about the relative efficacy and appropriateness of each type of electrode.

The individual performance levels of different electrode types are displayed in FIGURE 6 through their GRG scores. Stainless Steel Electrodes receive an outstanding 0.9816, which indicates that they are incredibly efficient, making them the top performance. Carbon Electrodes are in second place, very close behind, with an excellent score of 0.9133, suggesting good fit for certain applications. With a score of 0.8641, Iron Electrodes secure the third position, demonstrating their reliable performance. With a score of 0.8566, aluminum electrodes come in fourth place, demonstrating their usefulness in a range of environments. With a final score of 0.8333, titanium electrodes complete the rankings and demonstrate their usefulness despite having a somewhat lower efficiency than other varieties. These ratings provide insightful information about the relative advantages of each type of electrode, assisting in well-informed decision-making for a variety of industrial and scientific applications.

An important way to see how different electrode kinds work is to look at how effective each type is ranked. figure 7 Stainless

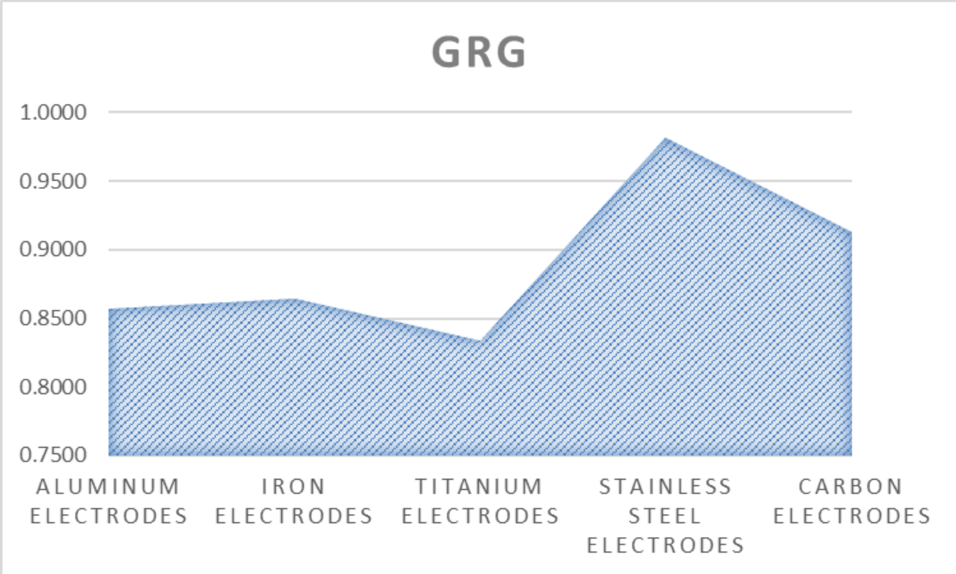

FIGURE 6. GRG

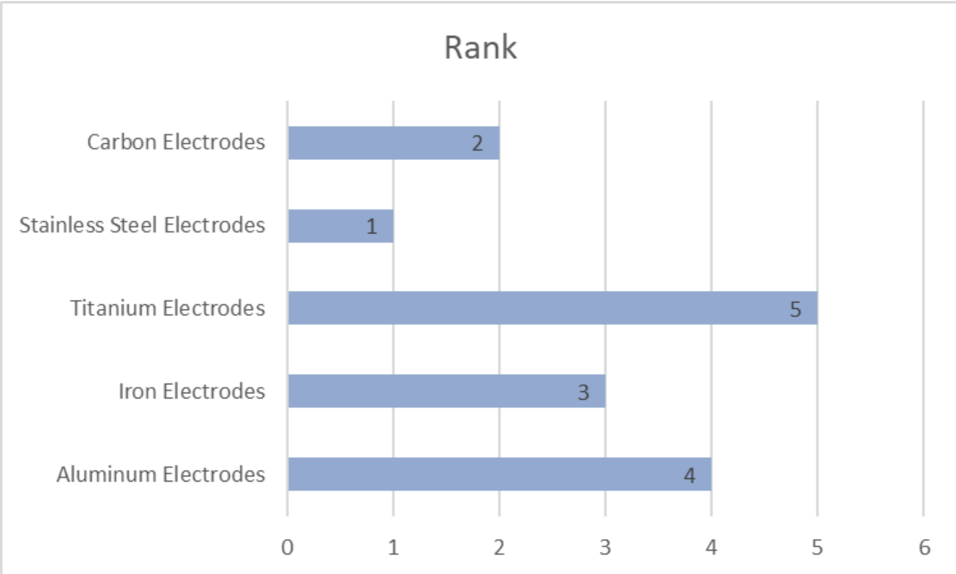

FIGURE 7. Shown the Rank

steel electrodes are at the top of the list, having earned the top spot and demonstrating their exceptional capabilities in a variety of applications. Carbon Electrodes come in second, demonstrating their excellent performance and coming in close behind. Iron Electrodes come in third place, demonstrating their dependability and effectiveness in particular situations. Fourth-place aluminum electrodes show their usefulness, despite several drawbacks as compared to their higher-ranked competitors. Titanium Electrodes come in fifth position to round up the rankings, indicating their usefulness while being marginally less effective than the others. This ranking helps with informed decision-making for various industrial and scientific applications by giving a brief summary of the relative advantages and disadvantages of each electrode type endeavors.

4. CONCLUSION

Comprehensive reviews and experimental research both emphasize that optimizing the electrocoagulation process parameters is an important way to improve the removal of heavy metals from wastewater. Important insights have been obtained by carefully examining a number of variables, including electrode material, current intensity, pH levels, and electrolyte content. These findings highlight how crucial it is to fine-tune parameters precisely in order to get the highest possible removal efficiency for heavy metals. Experiments validate theoretical models and show that parameter tweaking has a real effect on wastewater treatment performance. The effectiveness of electrocoagulation as a workable heavy metal removal technique is highlighted by this combination of theoretical analysis and empirical validation, laying the groundwork for more study and real-world use in wastewater treatment systems. In the end, this thorough analysis and experimental investigation provide important knowledge to the continuing search for effective and sustainable wastewater treatment methods, which is essential for preserving the environment and public health.

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