Industrial Engineering Journal
ISSN: 0970-2555
Volume : 53, Issue 4, April : 2024

A REVIEW ON ELECTROCOAGULATION TREATMENT OF RHODAMINE 6G FROM AQUA SOLUTION

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Abstract

This review paper provides a comprehensive analysis of the recent advancements in electrocoagulation techniques for the efficient removal of Rhodamine 6G dye from water. Rhodamine 6G is a widely used dye in various industries, posing environmental concerns due to its persistence and potential health hazards. Electrocoagulation, as an electrochemical water treatment method, has gained significant attention for its effectiveness in removing various pollutants, including dyes such as Rhodamine 6g. This comprehensive review paper aims to provide researchers, scientists, and environmental professionals with valuable insights into the current state of electrocoagulation techniques for the removal of Rhodamine 6G dye from water, fostering further advancements in this critical field of environmental research.

Keywords: Rhodamine 6g, dye removal from wastewater, Electrocoagulation, Sustainable chemistry, Environmental Impact, Water pollution.

I. INTRODUCTION

The ever-growing global population and the increase in the industrial requirement had put a pressure on available water source. There is an acute need of sustainable and efficient water treatment technology. The present water treatment technology has limitation with respect to cost, feasibility, limitation to certain emerging contaminants, ease or operation and big infrastructure requirement. There is a demand for simple, sustainable, cost effective and efficient water treatment technology. Recent development in electrochemistry and development of electrical infrastructure, electrochemistry is seen as a promising alternative for water treatment and waste water treatment due to availability of cheap electricity. As there is advancement in producing electricity through renewable sources, the electrochemistry will in term emerge as a green technology for waste water treatment. This futuristic technology becomes attractive due to its ability and capability to deal with the emerging contaminants, easy to operate, low in cost and sustainable in the nature. Textile industry is a big consumer of fresh water and a major source of the wastewater generation. The waste water generated from Textile industry is huge in the volume [31] and contains dyes which is harmful to the nature and human due to its constituent e.g. high colour content, salt concentration, acidic or alkaline contaminants and which exhibits high BOD/COD values [3]. These effluent from dye industry may contain constituent which is toxic, carcinogenic and hazardous to humans and animals. [5]. Various type of chemical dyes based on their chemical nature and application, are used in the textile industry [4]. They differ from their chemical content, pH value, nature of colour, nature of application and type of effluent generation. Due to the visible colour in effluent, the concern with effluent with colour is surfaced and demand for treatment and colour removal is obvious due to its aesthetic issue [4]. Waste water with dye content can reduce the light penetration within the water body e.g. river, pond etc., may result in the hampered aquatic life due to restriction on photosynthesis process in the absence of sufficient light [5].

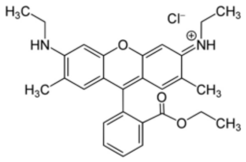
In this review paper, removal of Rhodamine 6G from water using electrocoagulation technique is studied. Rhodamine 6G is a fluorescent dye belonging to the xanthene class, known for its vivid pink to red color. It is commonly used in various industrial applications, such as textiles, cosmetics, and microscopy, due to its high visibility and photostability. Despite its widespread use, the environmental impact of Rhodamine 6G raises concerns, as its release into water bodies can lead to adverse effects on ecosystems and human health. Efforts to develop effective removal techniques, such as electrocoagulation, are essential to mitigate the impact of Rhodamine 6G on water ecosystems and safeguard both environmental and human well-being.

II. RHODAMINE 6G DYE CHARACTERISTICS

2.1.Chemical Characteristics

The chemical structure of Rhodamine 6G consists of a xanthene core with substituted amine groups, contributing to its vibrant color and fluorescence. This structure also imparts stability, making it a preferred choice in applications where long-lasting coloration is desired. Rhodamine 6G is non volatile, water soluble dye which makes it difficult to remove from the waste water [6]. Water with Rhodamine 6G dye may cause irritation of skin, eyes and respiratory system of human beings. It is also identified that the contaminated water is highly carcinogenic and posisonous to animals and aquatic life [6-7].

TABLE I. MOLECULAR CHARACTERISTICS OF RHODAMINE 6G

Name	**Molecular Structure**	**Wavelength λ** (nm)	**Appearance**	**Molecular Weight** (g/mole)
Rhodamine 6G		497	Dark Reddish Purple	479.02

2.2.Environmental Impact

Persistence: Rhodamine 6G exhibits persistence in water, resisting degradation through natural processes. This persistence can lead to the accumulation of dye in aquatic environments, posing a long-term threat to ecosystems. [7]

Toxicity: While studies on Rhodamine 6G's toxicity are still ongoing, there is studies suggesting potential adverse effects on aquatic organisms. The dye's impact on fish, invertebrates, and algae has raised concerns about its ecological consequences [6-8] [10] [13].

Health Concerns: The release of Rhodamine 6G into water sources may pose risks to human health. Although the concentrations typically found in the environment are lower than those used in laboratory studies, continuous exposure could lead to health issues, making it important to mitigate its presence in water [7-13].

Regulatory Aspects: Regulatory bodies, recognizing the potential environmental and health risks associated with Rhodamine 6G, have set guidelines and limits for its discharge into water bodies. Compliance with these regulations is crucial to minimize the impact on ecosystems and human health [32].

III. ELECTROCOAGULATION TECHNIQUE

Electrocoagulation is an electrochemical water treatment process that involves the application of an electric current to metal electrodes submerged in water. This method is particularly effective for the removal of various contaminants, including dyes like Rhodamine 6G. The principles of electrocoagulation revolve around the generation of coagulating agents through electrochemical reactions, leading to the formation of flocs that facilitate the removal of contaminants [11-13].

3.1.Key Components

Following are the key componenets involved in the Electrocoagulation process.

Electrodes: Electrocoagulation systems typically use metal electrodes, commonly aluminum or iron. These electrodes play a crucial role in the generation of coagulating species.

Electrolyte Solution: The water being treated acts as an electrolyte, facilitating the flow of electric current between the electrodes. Additionally, electrolytes may be added to enhance conductivity and improve the efficiency of the electrocoagulation process.

3.2.Electrochemical Reactions in Electrocoagulation process

3.2.1. Anode Reactions

At the anode (positive electrode), oxidation reactions take place. In the case of aluminium electrodes, common reactions include: [11][14-15][17-18]

$$2Al \rightarrow 2Al^{+3} + 6^{e^-} \quad (1)$$

$$2H_2O \rightarrow O_2 + 4H^{++4e^-} \quad (2)$$

The generated aluminium ions and oxygen contribute to the coagulation process.

3.2.2. Cathode Reactions

At the cathode (negative electrode), reduction reactions occur. For aluminium electrodes: [11][14-15][17-18].

$$6H2O + 6^{e^-} \rightarrow 3H_2 + 6OH^- \quad (3)$$

Hydrogen gas and hydroxide ions are produced, contributing to pH increase and aiding in the coagulation process.

3.3. Formation of Coagulating Agents

3.3.1. Metal Hydroxide Precipitates

The hydroxide ions generated at the cathode react with metal ions in the water, forming metal hydroxide precipitates. In the case of aluminum: [14-15] [17-18]

$$Al^{+3} + 3OH^- \rightarrow Al(OH)_3 \quad (4)$$

These metal hydroxide flocs have coagulating properties.

3.3.2. pH Adjustment

Electrocoagulation often results in pH changes in the treated water. The increase in pH contributes to the destabilization of charged particles, promoting coagulation [14][17].

3.4. Floc Formation and Contaminant Removal

3.4.1. Attachment and Aggregation

The coagulating agents, especially metal hydroxide flocs, attach to charged contaminants in the water, destabilizing them. [19]

3.4.2. Floc Formation

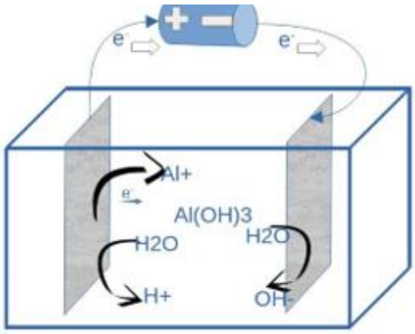
The destabilized contaminants aggregate with the coagulating agents to form larger flocs. [19][21]

3.4.3. Settling or Filtration

The formed flocs settle down due to their increased size and weight, facilitating their removal through sedimentation or filtration processes.

The principles of electrocoagulation involve the electrochemical generation of coagulating agents, primarily metal hydroxide flocs, which aid in the removal of contaminants like Rhodamine 6G through the formation of larger, easily removable particles. Understanding the electrochemical reactions and mechanisms is essential for optimizing the electrocoagulation process for efficient water treatment.

Figure 1 Typical Electrocoagulation mechanism.



3.5.**Floc Formation Dynamics**

3.5.1. Adsorption onto Floc:

Metal hydroxide species adsorb onto the surface of charged particles, including Rhodamine 6G dye molecules [19].

3.5.2. Neutralization and Coagulation:

Adsorbed metal hydroxides neutralize the charges on the dye particles, promoting coagulation. Electrostatic attraction between metal hydroxides and dye molecules facilitates the formation of larger, aggregated flocs [19].

3.5.3. Floc Growth and Maturity:

Aggregated flocs continue to grow in size as more dye particles adhere to the coagulated mass [19]. Mature flocs exhibit enhanced settling properties, facilitating their separation from the treated water.

3.5.4. Settling and Separation:

The formed flocs, laden with coagulated contaminants, settle due to increased size and weight. Enhanced settling allows for efficient separation of flocs from the treated water.

3.6. Electrocoagulation Mechanisms

Understanding the mechanisms behind Rhodamine 6G dye removal through electrocoagulation involves a multidimensional exploration of electrochemical, physical, and chemical processes. The interplay of factors such as pH, electrode materials, and electrochemical reactions contributes to the effective coagulation and removal of Rhodamine 6G dye from water, making electrocoagulation a promising method for water treatment. Following are the various aspects of the electrocoagulation mechanism involved in the removal of Rhodamine 6g dye from water.

3.6.1. Initial Adsorption and Precipitation:

Upon the application of an electric current, metal electrodes (commonly aluminum or iron) undergo oxidation reactions, releasing metal cations into the water. Rhodamine 6G dye molecules, being charged, are attracted to the oppositely charged metal ions, initiating the initial adsorption onto the electrode surfaces. Adsorbed dye molecules undergo complexation reactions with metal ions, leading to the formation of metal-dye complexes [24].

3.6.2. Generation of Coagulating Agents:

Electrolysis at the electrodes results in the production of coagulating agents, primarily metal hydroxide species, which are crucial for the subsequent coagulation process. The metal hydroxide species, such as aluminum hydroxide ($Al(OH)_3$) or iron hydroxide ($Fe(OH)_3$), act as effective coagulants for the dye molecules. [17][19][21]

3.6.3. Coagulation and Flocculation:

Metal hydroxide species adsorb onto the surface of Rhodamine 6G dye molecules, destabilizing the charged particles [24].The destabilized dye particles aggregate to form larger flocs through the process of flocculation, facilitated by the electrostatic attraction and neutralization of charges [19].

3.6.4. Enhanced Settling and Separation:

The formed flocs, comprising metal hydroxides and adsorbed dye particles, settle due to increased size and weight.

Enhanced settling enables effective separation of the coagulated dye flocs from the treated water [19].

3.6.5. Influence of pH:

pH plays a critical role in the electrocoagulation process. At higher pH values, metal hydroxide species are more favorably formed, promoting effective coagulation of Rhodamine 6G dye [22-24]. The electrocoagulation process also induces changes in the pH of the treated water, which in turn influences the efficiency of dye removal [24] [28].

3.6.6. Electrochemical Reactions at the Anode and Cathode:

At the anode, metal oxidation reactions contribute to the release of metal cations (Al^{3+} or Fe^{3+}) into the water, while at the cathode, reduction reactions lead to the production of hydroxide ions (OH^-) and hydrogen gas (H_2) [24]. These electrochemical reactions are integral to the generation of coagulating agents and pH changes essential for effective Rhodamine 6G dye removal.

3.6.7. Surface Charge and Interaction:

The surface charge of the electrodes influences the adsorption and interaction with Rhodamine 6G dye molecules. Controlling the surface charge through pH adjustment and optimizing electrode materials is crucial for maximizing adsorption and coagulation efficiency [24].

3.6.8. Kinetics and Reaction Rates:

Investigating the kinetics of Rhodamine 6G dye removal through electrocoagulation provides insights into the reaction rates and the time required for effective coagulation. Kinetic studies aid in understanding the optimal conditions for enhanced performance [25].

3.6.9. Redox Potential and Oxidation-Reduction Reactions:

Redox potential changes during the electrocoagulation process influence the oxidation and reduction reactions [26]. The redox potential is directly linked to the electrocoagulation efficiency, and a comprehensive exploration is essential for a detailed understanding of the mechanisms.

3.6.10. Effect of Contaminant Concentration:

The initial concentration of Rhodamine 6G dye impacts the saturation of available coagulating agents and, consequently, the removal efficiency. Investigating the impact of varying dye concentrations provides insights into the system's capacity under different contamination scenarios [23-25]. The electrode reactions and floc formation dynamics in the electrocoagulation technique are intricately linked, involving complex electrochemical and physical processes. Understanding these mechanisms is crucial for optimizing electrocoagulation processes to achieve efficient removal of contaminants, particularly dyes like Rhodamine 6G, from water.

IV. FACTORS AFFECTING RHODAMINE 6G REMOVAL.

Following are the factors which affects removal of Rhodamine 6G dye from water using electrocoagulation techniques.

4.1. pH Influence

4.1.1. Effect on Coagulation Efficiency:

pH plays a critical role in electrocoagulation as it directly influences the surface charge of the electrodes and the contaminants. The optimum pH range varies for different dyes. It is noted that 7 pH or neutral pH is found most optimum pH for maximum removal of dye from water [23-25] [29].

4.1.2. Alkaline Conditions for Metal Hydroxide Precipitation:

Higher pH values promote the formation of metal hydroxide flocs, enhancing the coagulation process [23- 25]. The relationship between pH and the removal efficiency should be systematically studied to identify the optimal pH conditions.

4.1.3. pH Adjustment Strategies:

pH adjustments can be achieved through the addition of alkaline substances, such as sodium hydroxide or lime. Continuous monitoring and control of pH during electrocoagulation are essential for maintaining optimal conditions.

4.2. Current Density Influence:

4.2.1. Relationship with Electrocoagulation Efficiency:

Current density determines the rate of electrode reactions, affecting the production of coagulating agents and subsequently, the removal efficiency of dyes [21-25]. An optimal current density must be identified to achieve the highest coagulation performance without compromising energy efficiency.

4.2.2. Balancing Electrode Wear and Coagulation:

Higher current densities often result in faster electrode wear [28], necessitating a trade-off between efficient coagulation and electrode maintenance. Research should focus on understanding the dynamic relationship between current density and electrode performance.

4.2.3. Scaling-Up Considerations:

The influence of current density on dye removal efficiency must be studied across different scales to ensure scalability and practical application in larger water treatment systems [28].

4.3. Initial Dye Concentration Influence:

4.3.1. Saturation and Removal Efficiency:

The initial dye concentration significantly impacts the saturation of available coagulating agents and, consequently, the removal efficiency [31]. Studies should explore the saturation point beyond which additional dye concentration yields diminishing returns in terms of removal efficiency.

4.3.2. Mass Transfer Limitations:

Higher initial dye concentrations may lead to mass transfer limitations, affecting the contact between the contaminants and coagulating agents [23-25] [30]. The interplay between mass transfer limitations and removal efficiency should be thoroughly investigated.

4.3.3. Optimization for Variable Conditions:

Understanding the relationship between initial dye concentration and removal efficiency is crucial for optimizing electrocoagulation processes under varying contamination scenarios [31]. The influence of pH, current density, and initial dye concentration on the efficiency of dye removal using the electrocoagulation technique is multifaceted. A systematic and comprehensive understanding of these factors is essential for designing and optimizing electrocoagulation systems for effective water treatment, particularly in the context of removing dyes such as Rhodamine 6G.

Following are the factors and consideration enhancing the performance of the electrocoagulation process.

1. Electrode Material Selection:
2. pH Control and Adjustment:
3. Current Density Optimization:
4. Electrode Configuration and Arrangement [31]
5. Reactor Design and Flow Rate [31]
6. Electrolyte Concentration [31]
7. Automation of Monitoring and Control Systems
8. Coagulant Dosage Optimization:
9. Reaction Time and Residence Time [29-31]
10. Energy consumption and Efficiency Considerations
11. Advanced Electrode and Reactor design

12. Renewable energy for sustainable process [30-31]

V. CHALLENGES AND FUTURE PERSPECTIVES

There is a lot of scope in the advancement of Electrocoagulation technology for dye removal and extensive research work is required to overcome these challenges as listed below.

It is not always possible that the waste water is polluted with one contaminant only and it is obvious that many type of dyes and other contaminants available to be treated in the wastewater Selecting and fitting technology e.g. Electrocoagulation to treat all types of contaminants is a real challenge. In the Electrocoagulation for dye removal, the electricity cost is the major part of the operating cost. High consumption of electricity may make the technology impractical. Keeping the electricity consumption at low in the large-scale operation is a challenge to be addressed for effective use of Electrocoagulation for dye wastewater. Aluminum/Iron hydroxide is generated during the Electrocoagulation process which shall result in the sludge to be managed. There is a requirement of practical and cost effective solution for sludge management and for disposal or recycling of sludge. Passivation of Electrode is also a major challenge associated with the Electrocoagulation process for wastewater treatment. A passive film layer is generated over the electrode surface causing the electrocoagulation process slower and less effective. A reliable technology for removal of this passive layer is important for the success of the electrocoagulation process for wastewater treatment [30]. With the change in the water characteristics and contaminant concentration, the operating parameters for dye removal e.g. pH, current density, Electrode type and material needs to be established and managed. Achieving proper and effective treatment parameters and conditions is an inherent challenge associated with Electrocoagulation technology for dye wastewater treatment.

Electrode design and Electrode material of construction plays a vital role in the effective removal of rhodamine 6g and similar dye removal from wastewater. Selecting the most effective and cost effective electrode for rhodamine 6g dye removal requires enough study and research. In the real life industrial scenario, large quantities of wastewater with varied contaminants are treated. There is not enough data available to check suitability of electrocoagulation processes in the large scale industries and continuous waste water treatment. Scalability is a big challenge to overcome practical application of Electrocoagulation process for rhodamine 6g removal from wastewater [29] [30].

As a future technology for removal of rhodamine 6g dye from wastewater, Electrocoagulation process needs to be evaluated and tested through practical application to prove itself a cost effective solution. Following are some of the areas where enhanced research and development is necessary for innovative and cost effective alternative solutions in the context of Electrocoagulation treatment for dye removal from wastewater

Development and selection of advanced electrode material & design: Selection of electrode material, electrode design and electrode configuration can impact the technology significantly to improve the effectiveness and applicability. Some of the latest and emerging materials e.g Combination of various metals, Graphene based materials, Organometallic based material, Nano material based electrode and similar other combinations of material to be tested for Dye removal from wastewater by electrocoagulation process. Due to complexity of waste water constitutes and variety of contaminants, it may be necessary to combine the electrocoagulation process with other technologies e.g photocatalytic reaction, Electrosorption, other coagulation & adsorption technology to develop effective and practical approach for treatment of waste water with rhodamine 6g dye. Enhanced and detailed research is required for development of these types of hybrid designs and technologies for synergetic advantages during wastewater treatment. Developing an advanced reactor design may result in the significant reduction of size and time of the wastewater treatment. Many innovative approaches like batch, semi batch and continuous reactor design, different shapes and arrangement of the electrodes. combination of various electrodes, application of electrodes of various materials of construction in the same reactor, Micro reactors, 3D printed electrodes and reactors etc. can be considered for development of novel and innovative electrocoagulation technology applications. Green technology for generation of electricity and electrocoagulation process will directly benefit the application of electrocoagulation technology and may enhance the feasibility and practicability of the technology. Technology like solar powered cell or environmentally friendly alternative electric sources shall be used to reduce the impact on the environment and reduce the carbon footprint via eco friendly waste water treatment. With the help of advancement and research to address these challenges and embracing future perspectives, the field of electrocoagulation for Rhodamine 6G removal can advance towards more efficient, sustainable, and widely applicable water treatment solutions.

VI. CONCLUSION

Based on recent study, it is evident that there is a huge potential in the Electrocoagulation technology as a practical solution for Rhodamine 6G dye removal from water. Several studies have shown the removal of Rhodamine 6G dye with removal efficiency more than 80%. Due to its high efficiency and simplicity in the design and application, Electrocoagulation technology is seen as a future alternative for wastewater treatment and specifically for toxic, hazardous and difficult to remove contaminants such as Rhodamine 6g dye in the waste water. Recent advancement in the area of electrochemistry, ease of availability of electricity and future perspective of green electricity, sustainable energy resources makes it suitable to develop such technologies for wastewater treatment to avoid large capital requirement, space requirement and operating cost for present technology in the wastewater treatment. There are several areas where further research and development is necessary to make the technologies practical and suitable as per industrial applications, such as developing novel electrodes and reactors to reduce electricity consumption and treatment time. development of continuous process and micro scale reactors, developing alternative electrolytes and coagulants to reduce overall cost of electrodes and electricity, combining it with other advanced processes to treat the wastewater with a variety of contaminants etc. Though there is not enough data available for actual industrial application and large scale wastewater treatment via electrocoagulation, it seems that there is huge potential to apply this process in the real life industrial application to treat wastewater with a very less space and operating cost, however it can only be done with extensive research and development of various experimental parameters, conditions and designs to find out the most suitable, practical and low cost design for application of Electrocoagulation process for the treatment of rhodamine 6g contaminated waste water.

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