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COMPARATIVE STUDY OF ELECTROCHEMICAL DEGRADATION OF RHODAMINE B USING GLASSY CARBON, STAINLESS STEEL, AND NICKEL ELECTRODES

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ABSTRACT – Rhodamine B is a synthetic dye commonly used in the textile and printing industries, recognized as a significant water pollutant. It enters aquatic environments primarily through untreated wastewater, posing serious threats to both environmental ecosystems and human health due to its toxic, carcinogenic, and non-biodegradable properties. The dye's persistence in water can result in harmful effects on ecosystems and contamination of vital water sources, underscoring the urgent need for effective removal methods. Electrochemical degradation has emerged as an eco-friendly technology to tackle this issue, breaking down Rhodamine B into less harmful byproducts and providing a sustainable approach for mitigating its environmental impacts. This study investigates the electrochemical degradation of Rhodamine B using glassy carbon (GC), stainless steel (SS), and nickel (Ni) electrodes in an undivided two-electrode system operating under a galvanostatic regime at a current density of 15 mA cm^{-2}. The primary goal was to compare the efficiency and kinetics of degradation across different electrode types. Experimental results demonstrated that GC electrodes, followed by SS, exhibited the highest degradation efficiency, with the process adhering to first-order kinetics. These findings highlight the advantages of GC electrodes in terms of speed and efficiency, offering valuable insights for optimizing treatment processes.

Keywords: Rhodamine B, Electrochemical degradation, Glassy carbon, Stainless steel, Nickel electrodes.

INTRODUCTION

Rhodamine B, also known as [9-(o-carboxyphenyl)-6-(diethylamino)-3H-xanthen-3-ylidene] diethylammonium chloride, is a synthetic dye extensively used in the food, textile, leather, and paper industries [1]. Numerous studies [2] have highlighted its toxic and potentially carcinogenic effects on both humans and animals, making it a significant environmental and public health concern. As a result, there has been a growing scientific focus on developing effective technologies for its degradation and removal [3]. Among the various processes, electrochemical degradation has gained significant attention as a

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highly effective method for the removal of organic pollutants, including Rhodamine B. This technique uses the electrochemical reaction occurring at the electrode surface, where pollutants undergo thought indirect or direct oxidation or reduction, resulting in the transformation of pollutants into safer, less toxic byproducts.

The process is highly adaptable and can be tailored to different contaminants, which makes it a versatile solution for wastewater treatment. One of the major advantages of electrochemical degradation is that it does not require the use of additional chemical reagents, which reduces the overall cost and environmental footprint of the treatment process. Furthermore, this method can be integrated into existing treatment systems, making it an appealing choice for large-scale applications. Another key benefit of electrochemical degradation is its high specificity, which allows for the selective breakdown of targeted pollutants while minimizing the formation of unwanted byproducts.

The degradation rate can be influenced by several factors, such as the applied voltage, electrode material, pH of the solution, and temperature, all of which can be optimized for maximum efficiency. The effectiveness of the electrochemical process is heavily dependent on the choice of electrode material, as different electrodes exhibit varying degrees of catalytic activity, stability, and conductivity. For example, boron-doped diamond (BDD) electrodes are known for their high stability and strong oxidative power, while carbon-based electrodes are often more cost-effective but may offer lower performance [4].

The electrochemical degradation of Rhodamine B is particularly promising because of its effectiveness in degrading organic compounds with high molecular stability. As research continues, efforts are also being made to scale up electrochemical degradation processes for industrial and municipal wastewater treatment, providing a more sustainable and cost-effective alternative to conventional methods. The primary goal of this study was to compare the electrochemical degradation of Rhodamine B using different electrode materials—specifically stainless steel (SS), nickel (Ni), and glassy carbon (GC) electrodes.

Each of these electrode materials offers distinct advantages and challenges that make them suitable for different electrochemical applications. SS electrodes, while cost-effective and widely available, may require surface modifications to enhance their catalytic efficiency and stability. Ni electrodes, known for their corrosion resistance and decent catalytic activity, provide an interesting option for degradation but may suffer from fouling over time. GC electrodes, on the other hand, are widely praised for their high surface area, conductivity, and customizability, making them an attractive choice for efficient pollutant degradation. By comparing these three materials, this study aimed to evaluate their efficiencies in degrading Rhodamine B, considering factors such as efficiency and kinetic rate. Additionally, the comparison provides insights into how electrode surface properties influence the electrochemical process, which is essential for optimizing treatment methods. The findings of this study may contribute to the identification of the most effective electrode material for electrochemical remediation of dye-contaminated wastewater, potentially aiding in the development of more cost-effective and sustainable wastewater treatment solutions.

EXPERIMENTAL

A 1x10^{-5} M solution of Rhodamine B in 0.05 M NaCl was prepared for the experiments. To assess the impact of electrolysis time on the degradation efficiency of Rhodamine B, experiments were conducted in a two-electrode electrolytic cell, with pairs of SS, Ni, and GC electrodes as the working and counter electrodes. Electrolytic degradation was performed at a constant current density of 15 mA cm^{-2} at room temperature using a Gamry Instruments Interface 1000 Potentiostat/Galvanostat (Gamry Instruments, USA). Aliquots of the electrolyte were collected at various time intervals, and absorbance at the peak wavelength of 554.5 nm was measured with a UV/Vis spectrophotometer (Lambda 35, Perkin Elmer, USA).

The concentration of Rhodamine B in the electrolyte was determined using a calibration curve. Removal efficiency was then calculated based on the following equation:

$$Removal\ efficiency\ (\%) = \frac{C_0 - C}{C_0}\ 100 \quad (1)$$

Where c_o is initial concentration Rhodamine B, c is concentration of Rhodamine B in taken aliquot in time, t of electrochemical degradation.

RESULTS AND DISCUSSION

Figure 1a presents the concentration profile of Rhodamine B during its electrochemical degradation on GC, SS, and Ni electrodes under constant current conditions (15 mA cm^{-2}). A decrease in Rhodamine B concentration over time was observed for all three electrodes, indicating improved degradation efficiency. SS and GC showed better performance compared to Ni. The degradation rate was rapid in the first 10 minutes, with Rhodamine B concentration decreasing by up to 50 % and 22 % for SS and GC, respectively, while the Ni electrode exhibited a significantly lower removal efficiency of only 12 % (see Figure 2).

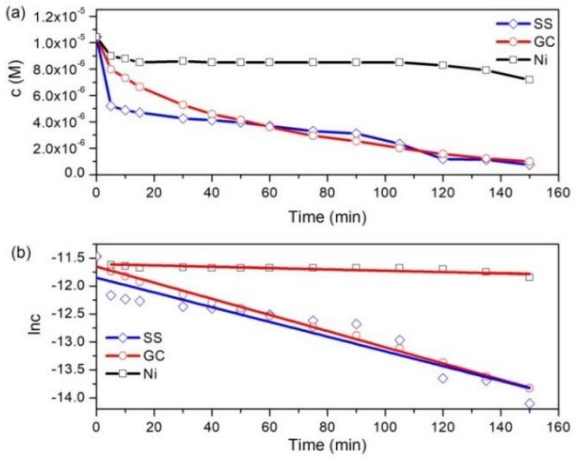

Figure 1 (a) Concentration profiles of Rhodamine B dye (1 x 10^{-5} M) at current density 15 mA cm^{-2} and (b) linear plot of lnc versus t

The concentration of Rhodamine B improved over time for SS and GC, indicating sustained degradation activity. After 150 min of electrolysis Rhodamine B removal efficiency on SS and GC is 92 and 90 %, respectively. In contrast, the Ni electrode displayed a noticeable decrease in concentration after 150 minutes, indicating a slower onset of degradation. The SS and GC electrodes showed a steeper increase in degradation efficiency throughout the experiment, indicating a more effective degradation process. On the other hand, the Ni electrode displayed a slower increase in removal efficiency (only 30 %), highlighting its weaker overall performance under identical conditions.

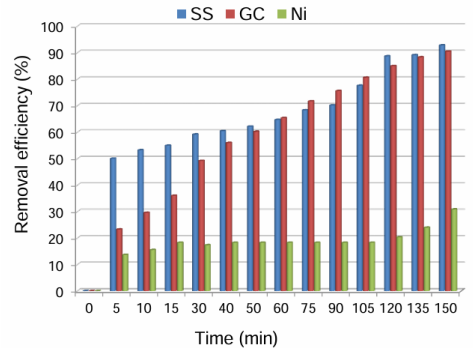

Figure 2 Degradation efficiency of Rhodamine B dye (1 x 10^{-5} M) at current density 15 mA cm^{-2}

A more detailed comparison between the SS and GC electrodes highlighted notable differences in their degradation behaviour. While the GC electrode exhibited a steady and uniform decrease in Rhodamine B concentration, the SS electrode followed a different trend. The most pronounced concentration of Rhodamine B decline for SS occurred within the first 30 minutes, followed by a slower degradation phase until approximately 90 minutes, after which a sudden and significant decrease in concentration was observed.

The observed differences in degradation efficiency can be attributed to the electrochemical properties of the electrodes and their surface interactions with the pollutant. It is well-known from the literature [5] that the GC electrode is stable, chemically inert, and highly electroconductive, which facilitates efficient electron transfer and hydroxyl radical (•OH) generation, ensuring continuous and uniform degradation of Rhodamine B. In contrast, the SS electrode exhibited an initial rapid degradation phase, likely due to its high catalytic activity in the early stages of electrolysis. However, as the reaction progressed, passivation effects became more prominent. The formation of an oxide or hydroxide layer on the SS electrode surface likely inhibits further electron transfer and reduces its catalytic efficiency, leading to a slower electro-degradation of Rhodamine B between 30 and 90 minutes. The final sharp decrease in Rhodamine B concentration observed after 90 minutes may be attributed to partial surface renewal or structural modifications that temporarily restored its activity.

Unlike SS and GC, the Ni electrode demonstrated the least efficient degradation performance. The delayed onset of degradation suggests that surface activation was required before electrochemical degradation could proceed effectively. This behavior may be attributed to the tendency of Ni to form oxide or hydroxide layers that limit electron transfer and reduce the formation of reactive oxidative species [6]. Furthermore, Ni electrodes are known to favor the oxygen evolution reaction (OER) rather than hydroxyl radical production, which could further reduce their efficiency in organic pollutant degradation.

These findings highlight the critical role of electrode material in determining the efficiency of electrochemical degradation. The superior performance of SS and GC electrodes suggests that they are more suitable for practical wastewater treatment applications, particularly in scenarios requiring rapid and sustained degradation of organic pollutants. However, the passivation effects observed for SS indicate the need for further optimization to maintain high degradation rates over extended electrolysis periods.

The rate of Rhodamine B degradation in an electrochemical reactor can be described by first-order kinetics:

$$\ln C = lnC_0 - kt \quad (2)$$

Where C_0 and C are the initial concentration of Rhodamine B and the concentration of Rhodamine B after reaction time t, respectively, and k is the reaction rate constant. The rate constant can be determined from the slope of the linear plot of −lnC versus t (see Figure 1b). The rate constants for the electrochemical degradation of Rhodamine B from wastewater using different electrodes are presented in Table 1. It can be observed that the rate constant is highest for the GC system, followed by SS and Ni.

Table 1 Kinetic rate constant

Electrode	R^2	k min^{-1}
SS	0.87	0.013
GC	0.99	0.014
Ni	0.96	0.001

CONCLUSION

This study compared the electrochemical degradation efficiency of Rhodamine B using SS, GC, and Ni electrodes under identical conditions. Results demonstrated that SS and GC electrodes exhibited significantly higher degradation efficiencies (92 % and 90 % after 150 minutes, respectively) compared to Ni (30 %). GC showed a steady and uniform degradation rate, attributed to its high conductivity and stability, while SS displayed rapid initial degradation followed by passivation effects that slowed the process. Ni electrodes were the least efficient due to slow surface activation and preference for oxygen evolution over hydroxyl radical production. Kinetic analysis revealed the highest reaction rate constant for GC (0.014 min^{-1}), followed by SS (0.013 min^{-1}) and Ni (0.001 min^{-1}). The study highlights the suitability of SS and GC for efficient electrochemical treatment of dye-contaminated wastewater, though SS may require surface modifications for sustained performance.

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