Removal of Artificial Rhodamine B Synthetic Dye Waste Using Magnetic Nanoparticle Adsorbents

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Abstract

The use of synthetic dyes as dyes is increasing so that the waste is polluting the environment. One of the dangerous wastes that damages the environment and causes health problems is rhodamine B dye. The removal of rhodamine B dye is carried out by adsorption using an adsorbent that has been modified to provide magnetic properties. The aim of the research is to synthesize magnetic adsorbent nanoparticles using the co-precipitation method and use them to reduce the concentration of rhodamine B dye in artificial wastewater at various time variations. The study shows that magnetic nanoparticle adsorbents were successfully synthesized using the precipitation method. The adsorbent particles provide a magnetic effect on external magnetic forces, which shows that the adsorbent nanoparticles are magnetic. The application of magnetic adsorbent nanoparticles showed that the longer the adsorption time, the percentage of rhodamine B dye removal increased. The highest removal was obtained at 86% at an adsorption time of 90 minutes and an adsorbent mass of 4 g.

1. Introduction

The increasing industrial activity across various sectors has led to a rise in waste production, including wastewater containing synthetic dyes. Rhodamine B is one such synthetic dye widely used in the textile, cosmetic, and food industries. Despite its widespread application, Rhodamine B is known to pose significant risks to both the environment and human health. It is a carcinogenic and toxic compound that is highly resistant to natural degradation, thereby posing a serious threat to water quality if not properly managed[1, 2].

Rhodamine B is a synthetic dye commonly employed in multiple industries, including textiles, cosmetics, and food processing [3]. However, it is highly toxic and not readily biodegradable by natural microbial activity. Exposure to Rhodamine B can cause skin, eye, and respiratory irritation, as well as chronic health issues such as cancer and liver dysfunction upon ingestion or inhalation. Its environmental impact is also considerable, particularly on aquatic ecosystems, as it is difficult to remove from water and can inhibit photosynthetic processes [4, 5].

Due to the presence of amino groups and a benzene ring, Rhodamine B is resistant to microbial degradation [6]. It is toxic and can cause various health effects such as dermatitis, mucosal skin irritation, nausea, headaches, diarrhea, kidney damage, and anemia. Moreover, Rhodamine B has been linked to cancer and liver failure [7]. The reduction of Rhodamine B concentrations in the environment can be achieved through adsorption processes using suitable adsorbents [8, 9].

In the textile industry, dyes are among the primary raw materials, and once used, they are often discarded, generating dye-laden wastewater. Dye pollutants present a major environmental concern due to their potential to cause irritation and carcinogenic effects [10, 11]. One of the prevalent dye pollutants released from textile industries is Rhodamine B. Owing to its benzene ring and basic amino groups, Rhodamine B is difficult to biodegrade naturally. When discharged into aquatic environments, it can lead to pollution and pose serious health hazards to humans [12].

Effective and efficient treatment methods are required to manage wastewater containing Rhodamine B. Among the various methods explored, adsorption stands out due to its high removal efficiency and adaptability to various pollutants [13-15]. In recent years, the use of magnetic nanoparticle adsorbents has garnered significant attention for their exceptional ability to adsorb synthetic dyes, including Rhodamine B [16, 17].

Magnetic nanoparticle adsorbents offer several advantages over conventional adsorbents. These include a large specific surface area, high porosity, and magnetic properties that enable easy separation from solutions using an external magnetic field [18]. These characteristics make them ideal candidates for removing dyes from industrial wastewater.

Several studies have highlighted activated carbon as a preferred adsorbent due to its large pore surface area. Additionally, clay- and zeolite-based adsorbents have also shown promising potential [19, 20]. However, in practical applications, the separation process between adsorbent and solution often faces challenges due to the mixing of the adsorbent with the surrounding medium, which prolongs the separation time. Therefore, the ease of adsorbent recovery from the solution becomes a crucial consideration in adsorption-based treatment processes.

One alternative for improving adsorbent recovery is to impart magnetic properties to the adsorbent, allowing for rapid separation using an external magnetic force. Accordingly, this study employs the co-precipitation method to synthesize magnetically responsive activated carbon, analyzes its magnetic characteristics, and evaluates its application for synthetic dye removal and the efficiency of its separation from the environment.

The aim of this research is to synthesize magnetically modified activated carbon adsorbents and investigate their application in the removal of the synthetic dye Rhodamine B. The outcomes of this study are expected to contribute significantly to the development of more efficient and environmentally friendly industrial wastewater management strategies.

2. Methods

The study on the removal of synthetic dye waste Rhodamine B using magnetic nanoparticle adsorbents was conducted in several stages, including the preparation stage, synthesis of magnetic nanoparticles, and the application of the synthesized nanoparticles for the removal of Rhodamine B from artificial wastewater, as outlined below:

2.1 Preparation Stage

The initial stage of the study involved the preparation of materials and equipment. The materials used included activated carbon derived from coconut shell charcoal as the adsorbent, ferrous chloride tetrahydrate ($FeCl_2 \cdot 4H_2O$), ferric chloride hexahydrate ($FeCl_3 \cdot 6H_2O$), ammonium hydroxide (NH_4OH), the synthetic dye Rhodamine B, and distilled water. The equipment used comprised beakers, a magnetic stirrer, an analytical balance, thermometer, stopwatch, magnetic bar, burette, retort stand, Gaussmeter, and various characterization and testing instruments.

2.2 Research Procedure

In the synthesis stage of the magnetic adsorbent, 50 mL of ferrous chloride tetrahydrate and 50 mL of ferric chloride hexahydrate solutions were prepared in a 1:2 molar ratio and placed into a 250 mL beaker. The mixture was stirred at 200 rpm and heated to 90 °C. Once the temperature was reached, activated carbon was added to the solution, followed by the slow addition of 100 mL ammonium hydroxide until a black precipitate formed. The synthesis was continued for 120 minutes. After synthesis, the resulting precipitate was washed with water until neutral pH was achieved, separated using a magnetic bar, filtered, and dried in an oven at 105 °C. The magnetic properties of the adsorbent were then characterized.

For the application stage, the best-performing magnetic adsorbent from the synthesis process was selected as the sample for testing the adsorption of Rhodamine B from artificial wastewater. The adsorption tests were conducted by varying both the adsorbent dosage and contact time. The removal efficiency of Rhodamine B was evaluated in terms of percentage removal and adsorption kinetics.

The adsorption capacity was determined by first measuring the maximum absorbance wavelength of a 1 mg/L Rhodamine B solution in the range of 400–700 nm. A calibration curve was prepared using Rhodamine B solutions of 0.5, 1, 2, 3, and 4 mg/L, and their absorbance was measured at the maximum wavelength. Additionally, 0.1 grams of activated coffee-ground charcoal was added to 40 mL of 50 mg/L methylene blue solution, stirred for 50 minutes, filtered, and the absorbance of the filtrate was measured using a visible spectrophotometer at the maximum wavelength of methylene blue.

The data from the concentration variations were fitted to the Langmuir and Freundlich adsorption isotherm models to determine the adsorption behavior. The concentrations of Rhodamine B before and after adsorption were analyzed using a UV-Vis spectrophotometer at its maximum absorbance wavelength of 554.1 nm.

2.3 Characterization

Characterization of the synthesized magnetic adsorbent included magnetic property testing and morphological analysis using Scanning Electron Microscopy (SEM). The application of the magnetic adsorbent was characterized by measuring the absorbance of the samples using UV-Vis spectrophotometry.

3. Results and Discussion

Results of the study on the removal of synthetic dye waste rhodamine B using magnetic nanoparticle adsorbents are described as follows.

3.1 Synthesis of Magnetic Adsorbents

The synthesis of magnetic adsorbents from activated coconut shell charcoal was carried out using the co-precipitation method. The synthesis was conducted at a temperature of 90 °C, which has been reported in several studies as an optimal condition. The results indicate that the resulting adsorbents exhibit magnetic properties, as demonstrated by their attraction to an external magnetic field, as shown in Figure 1.

Figure 1 also compares the behavior of untreated activated carbon and magnetic activated carbon synthesized via the co-precipitation method. It clearly shows that while regular activated carbon is non-magnetic, the activated carbon subjected to magnetic functionalization becomes magnetically responsive. These findings confirm the successful incorporation of magnetic properties into the activated carbon adsorbent.

The image illustrates a comparative visualization between two samples of powdered materials stored in labeled glass vials, with a black magnetic block placed between them. The vial labeled "M" contains magnetic activated carbon, while the vial labeled "C" contains conventional (non-magnetic) activated carbon. The sample in the "M" vial is visibly attracted to the magnetic block, as evidenced by the powder adhering or clustering along the side of the vial nearest the magnet. In contrast, the "C" sample shows no such interaction, with the powder resting undisturbed at the bottom of the vial. This visual evidence supports the conclusion that the co-precipitation synthesis process successfully imparted magnetic properties to the activated carbon in the "M" sample, enabling it to respond to an external magnetic field. The image effectively demonstrates the magnetic responsiveness of the modified adsorbent, confirming the success of the magnetic functionalization process.

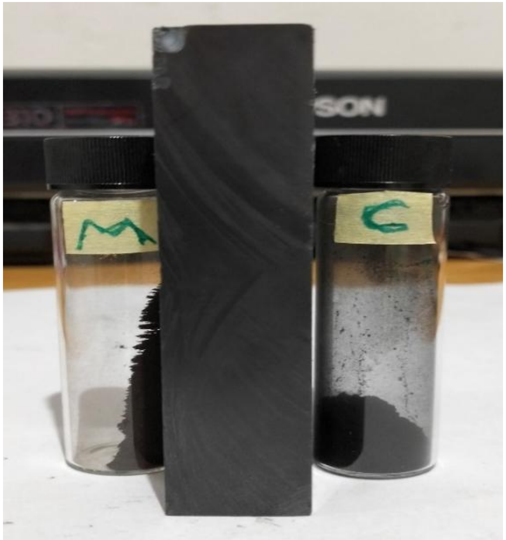
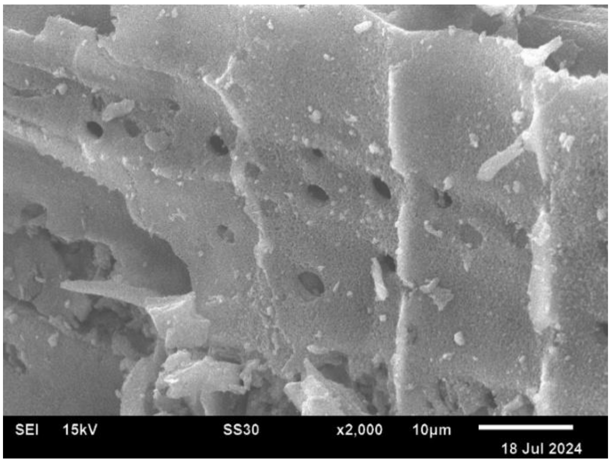


Figure 1. Effect of external magnetic field on magnetic adsorbent (M) and activated carbon (C)

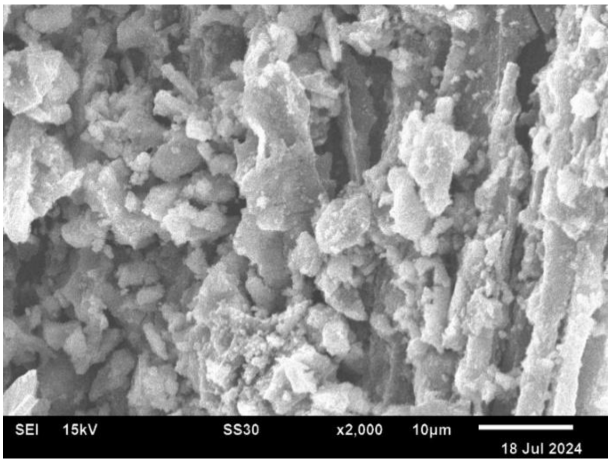
3.2 Characterization of Magnetic Adsorbents

The magnetic adsorbents were characterized morphologically using Scanning Electron Microscopy (SEM). Characterization was performed on both untreated activated carbon and magnetically functionalized activated carbon. The morphological results are presented in Figure 2.

The two SEM (Scanning Electron Microscopy) images as shown in Figure 2 provide a comparative morphological analysis of activated carbon before and after magnetic modification using the co-precipitation method. The first image (Figure A) shows the surface morphology of unmodified activated carbon at 2000× magnification. It exhibits a relatively smooth texture with visible and uniformly distributed pores. These pores are essential for adsorption as they increase the available surface area for interaction with pollutants such as Rhodamine B.



(A)



(B)

Figure 2. Morphology of activated carbon adsorbent (A) and magnetic adsorbent (B)

In contrast, the second image (Figure B) represents the morphology of the magnetic activated carbon. It reveals a rougher surface with the presence of irregularly shaped particles and agglomerates that likely correspond to magnetic nanoparticles, Fe_3O_4 deposited on or embedded into the activated carbon structure. The pore structure appears less defined due to the coverage or partial blockage by these magnetic particles. This observation confirms the successful modification of the carbon surface through co-precipitation, enhancing its magnetic properties, as previously indicated in magnetic response testing. However, this modification might reduce the effective pore accessibility, which could influence adsorption kinetics and capacity. Thus, the morphological differences illustrate the trade-off between adding magnetic functionality and maintaining optimal porous structure for adsorption.

3.3 Application of Magnetic Adsorbents

The application of magnetic adsorbents was tested for the removal of the synthetic dye Rhodamine B from artificial wastewater. The results of Rhodamine B removal over time are shown in Figure 3.

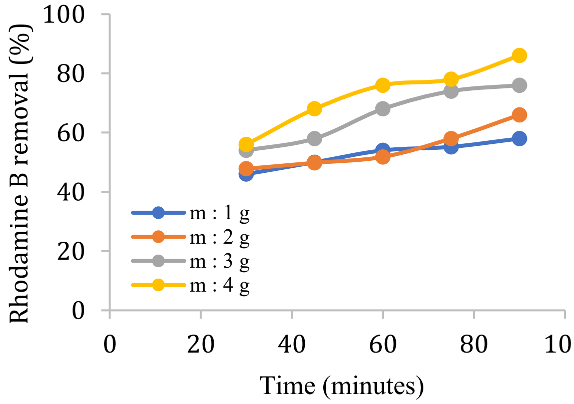


Figure 3. Effect of contact time on the removal percentage of Rhodamine B

The Figure presents a graph illustrating the effect of contact time and adsorbent dosage on the percentage removal of Rhodamine B using magnetic activated carbon. The data clearly demonstrate that both increased contact time and higher adsorbent dosage result in improved dye removal efficiency. For all masses tested, the percentage removal of Rhodamine B increases over time, suggesting that longer interaction periods allow more dye molecules to be adsorbed onto the available surface area of the adsorbent. Among the tested doses, 4 g of adsorbent consistently yields the highest removal efficiency, reaching over 80% after 90 minutes. This indicates that the higher amount of magnetic activated carbon provides a greater number of active adsorption sites. In contrast, the 1 g dosage shows the lowest removal efficiency throughout the duration of the test, peaking below 60%. The trend also shows diminishing returns at higher doses and longer times, indicating a potential saturation point of the adsorbent surface or equilibrium conditions. Overall, the graph confirms that both adsorbent dose and contact time are crucial factors influencing the effectiveness of Rhodamine B removal in wastewater treatment.

As depicted in Figure 3, the percentage removal of Rhodamine B increases with contact time, regardless of the mass of the adsorbent used. This trend is attributed to the extended contact time, which enhances the interaction between the dye molecules and the adsorbent surface, allowing more dye molecules to be adsorbed.

4. Conclusion

Based on the results of the study, the following conclusions can be drawn:

Magnetic activated carbon adsorbents were successfully synthesized using the co-precipitation method.

The magnetic adsorbents were effectively applied for the removal of the synthetic dye Rhodamine B.

The percentage of Rhodamine B removal increased with longer adsorption contact time. The highest removal was obtained at 86% at an adsorption time of 90 minutes and an adsorbent mass of 4 g.

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