

Research Article

Remediation of Groundwater Containing Gentian Violet Dye Using Hydrogel

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Abstract

The contamination of groundwater by synthetic dyes, particularly Gentian Violet, poses significant environmental and health risks. This study explores the efficacy of hydrogel-based adsorbents for the removal of Gentian Violet dye from aqueous solutions. The adsorption process was meticulously evaluated under varying parameters including pH, contact time, initial dye concentration, and temperature. Kinetic and isothermal models were employed to analyze the adsorption behavior. Results demonstrated that the hydrogels effectively removed up to 94% of Gentian Violet dye within optimal conditions, exhibiting a rapid uptake in the initial stages of adsorption. The adsorption data aligned well with the Langmuir isotherm model with value of (0.9777) indicating monolayer adsorption on a surface with a finite number of identical sites. Kinetic studies followed a pseudo-second-order model with values of (2.891 to 6.876) in removal concentration at equilibrium and relative coefficient (9.660), suggesting that the adsorption process is largely chemisorption. This study highlights the potential of hydrogel materials as a sustainable solution for the remediation of dye-contaminated groundwater, contributing to the development of environmentally friendly technologies for water treatment. Further research is suggested to explore scalability and long-term effectiveness in field conditions.

Keywords

Gentian Violet Dye, Hydrogel, Adsorption

1. Introduction

1.1. Study Background

Water pollution is a pressing environmental concern worldwide, requiring urgent attention. Many human activities, including industrial and domestic processes, discharge waste into aquatic ecosystems, resulting in

pollution that threatens both environmental integrity and human health [1]. Pollutants in water come from diverse sources and exist in various forms, such as suspended particles, dissolved minerals, organic compounds, gases, and microorganisms [2]. While conventional water treatment techniques remove a significant portion of these

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contaminants, toxic residues often remain at levels that exceed safe limits [3]. One major contributor is the textile industry, whose synthetic dyes not only discolor water but also introduce toxicity, unpleasant odors, and adverse effects on aquatic ecosystems. Addressing these issues demands effective treatment of dyed wastewater before it is released into the environment [4].

The global dye industry produces approximately 700,000 tons of dyes annually, with around 20% entering the environment as untreated waste. This has raised environmental concerns due to the harmful components of synthetic dyes, such as sulfur, nitrates, and heavy metals like copper, arsenic, and lead [5].

Water covers more than 70% of the Earth's surface, making it one of the planet's most critical resources. Beyond sustaining life, it is indispensable for food production, hygiene, and livelihoods, shaping human settlement and development patterns [6]. However, only 2.5% of the Earth's water is freshwater, with just a small fraction—0.4% in surface water and 30.1% in groundwater—readily accessible for use [7]. Most freshwater is locked in polar ice caps, leaving humanity dependent on a limited supply. Population growth, which is projected to rise from 7.6 billion in 2013 to 9 billion by 2045, continues to intensify the demand for this precious resource [8].

Groundwater is the primary source of freshwater for many communities, providing water for drinking, agriculture, and industry. Around one-third of the global population relies on groundwater for their daily needs [9]. Numerous megacities, particularly in developing regions, depend heavily on this resource, and in China, 400 out of 657 cities rely primarily on groundwater [10, 11]. However, urbanization, industrialization, agricultural expansion, and climate change pose serious threats to its sustainability. Contaminants such as heavy metals, hydrocarbons, organic pollutants, and pesticides not only degrade water quality but also harm ecosystems and human health [12].

The chemical contamination of groundwater has become a focal point for researchers and policymakers, highlighting both the challenges and opportunities for improving aquifer management [13]. Agricultural practices, particularly the overuse of fertilizers and pesticides, often result in these chemicals leaching into groundwater supplies. Testing is essential to ensure groundwater is safe for drinking, irrigation, and industrial use, especially when considering the risks posed by inorganic contaminants to health and food systems [14].

Groundwater is a cornerstone of the global water system, supporting ecosystems and human activities at multiple scales. Yet, pollution—defined as the introduction of harmful substances or elevated levels of natural components into the environment—poses a significant threat to its quality and availability. This disruption can lead to health issues and ecological imbalance, underscoring the need for sustainable water management practices [15].

1.2. Statement of the Problem

The pollution of groundwater with Gentian violet dye presents a serious environmental concern. Commonly used in various sectors like textiles and paper printing, Gentian violet is a toxic and long-lasting pollutant that can adversely affect human health and aquatic life. Thus, it is vital to discover effective methods for cleaning up groundwater contaminated with this dye.

1.3. Aims and Objectives of the Study

This research aims to explore the feasibility of using hydrogel as a method for remediating groundwater tainted by Gentian violet dye. The specific objectives include:

Evaluating the hydrogel's capacity to adsorb Gentian violet dye in a controlled laboratory environment.

Identifying the optimal conditions (including hydrogel concentration and contact time) for the removal of the dye through hydrogel.

1.4. Significance of the Study

Groundwater is a crucial source of drinking water for many communities, and the presence of harmful dye pollutants poses public health risks. Hydrogel is a flexible material that has demonstrated encouraging results in various environmental applications. If this research is successful, it could pave the way for more effective and sustainable remediation technologies. The study also seeks to provide insights into the potential environmental effects of hydrogel remediation, ensuring that any negative impacts are recognized and addressed.

1.5. Scope and Limitation

The focus of this study will be on assessing the efficacy of hydrogel in eliminating Gentian violet dye from groundwater. Laboratory experiments will be carried out under controlled conditions, while a pilot-scale study will take place at a designated contaminated groundwater location. The research may encounter certain limitations, such as securing adequate funding and resources for the pilot-scale phase, as well as potential difficulties in accurately measuring the long-term effectiveness and You're correct; the numbered citations should match the corresponding references based on their sequence in the list provided. Let me rework the paragraph to ensure each number matches its appropriate reference from your saved list.

2. Literature Review

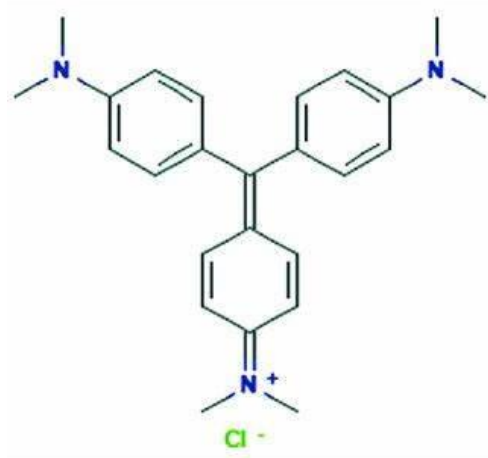
2.1. Gentian Violet

Gentian violet, also called Basic Violet 3 or methyl violet

10B, is a synthetic cationic dye belonging to the triarylmethane group. It is extensively used in the textile industry for dyeing materials such as cotton, wool, silk, and nylon. It also has applications in the manufacture of printing inks, biological stains, and as a dermatological agent in veterinary medicine [16]. Despite its widespread use, gentian violet is highly toxic and can be absorbed through the skin, causing irritation. Inhalation or ingestion can result in severe health issues such as kidney failure, eye irritation that may lead to permanent blindness, and in some cases, cancer [17]. This makes its removal from wastewater an urgent environmental concern.

Numerous techniques are available for removing dyes like gentian violet from water, including membrane separation, microbial degradation under aerobic and anaerobic conditions, chemical oxidation, coagulation and flocculation, reverse osmosis, and fungal decolorization [18]. However, these methods often face limitations, such as excessive chemical usage, difficulty in disposing of concentrated sludge, and inadequate color removal [19]. Among these, adsorption stands out as one of the most effective and practical approaches for advanced wastewater treatment. This method is valued for its low cost, operational simplicity, and efficiency in eliminating hazardous pollutants from industrial effluents [20].

Gentian violet has a symmetric structure with six methyl groups. Its chemical formula is [4-[bis[4-(dimethylamino)phenyl]methylidene]cyclohexa-2,5-dien-1-ylidene]-dimethylazanium chloride [21]. Commercially, it is available as a 0.5% or 1% aqueous or alcohol solution for topical application. Antibacterial dressings containing gentian violet and methylene blue in polyvinyl alcohol and polyurethane foam formulations are also common. While a 0.5% aqueous solution is licensed for use on unbroken skin, it is not recommended for application on mucous membranes or open wounds due to associated health risks [22].



Molar mass 407.99 g/mol

Figure 1. Structure of Gentian Violet.

2.2. Gentian Violet Dye and Its Environmental Impact

Water is a critical resource for life, but its availability has been severely impacted by population growth and harmful human activities over the last century [30]. One of the major contributors to water pollution is the presence of dyes in wastewater from textile manufacturing, posing significant health and environmental risks [31]. Among various treatment methods, adsorption has been identified as one of the most effective approaches for dye removal [32]. Recent studies have explored innovative adsorbents, including unmodified synthesized hydroxyapatite (HAp), for their potential to remove gentian violet (GV) dye from water. This research area remains underexplored, particularly regarding HAp synthesized using advanced techniques.

Unmodified HAp was synthesized using a combined precipitation microwave method and characterized through advanced techniques, including scanning electron microscopy (SEM), energy dispersive X-ray (EDX), X-ray diffraction (XRD), Fourier transform infrared (FTIR) spectroscopy, and zeta potential analyses [33]. Kinetic studies revealed that the pseudo-second-order (PSO) model best fit the experimental data, while the Halsey isotherm provided the best description of adsorption isotherms, with a maximum adsorption capacity of 1.035 mg/g. Experimental conditions for optimal GV dye removal (99.32%) included 90 minutes of contact time, pH 12, an initial dye concentration of 3 mg/L, and an adsorbent dose of 1 g/L. The adsorption mechanism was attributed to electrostatic interactions between the negatively charged HAp surface and the positively charged GV dye. Thermodynamic analyses confirmed the process as endothermic and spontaneous, supported by positive ΔH and ΔS values and a negative ΔG [34].

Similarly, researchers have demonstrated the efficacy of cubic Ia3d aluminosilica (CAS) adsorbents synthesized via a simple one-pot technique for removing cationic dyes like GV from water. The CAS adsorbent displayed a BET surface area of 573 m²/g and showed strong dye adsorption capabilities. Adsorption studies confirmed that GV removal followed the Langmuir isotherm, with a maximum adsorption capacity of 1.36 mmol/g (or 554.85 mg/g). Key adsorption mechanisms included electrostatic attraction, hydrogen bonding, ion exchange, and pore filling. Thermodynamic evaluations confirmed the process as endothermic and spontaneous. Additionally, the CAS adsorbent demonstrated excellent recyclability, maintaining effectiveness over five adsorption-desorption cycles, making it highly suitable for wastewater purification [34].

Another study focused on the removal of gentian violet (also known as crystal violet) using commercial activated carbon with a high specific surface area of 1250 m²/g. Researchers optimized parameters such as stirring speed, adsorbent dose, solution pH, and dye concentration to

achieve effective adsorption. Kinetic analyses confirmed pseudo-second-order behavior, while equilibrium data were best described by the Langmuir isotherm, highlighting the high adsorption capacities recorded at various temperatures. Thermodynamic analyses further confirmed that the adsorption process was both spontaneous and endothermic [23].

Hydrogels, characterized by their highly interconnected and porous 3D polymer network, are another promising material for environmental applications. Despite being insoluble in water, they possess remarkable absorptive capabilities, making them ideal for capturing or releasing various molecules [24]. Hydrogels can be classified based on their production methods, properties, and cross-linking characteristics. Synthetic hydrogels often incorporate nanomaterials to enhance their properties, whereas natural hydrogels, while less mechanically robust, offer advantages such as non-toxicity and biocompatibility [25]. Recent research has highlighted the potential of hydrogels in biomedical applications, including antimicrobial uses and cartilage repair, with ongoing efforts to improve their elasticity for functional integration into human body parts [26].

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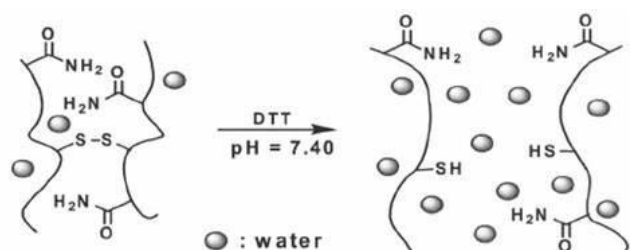


Figure 2. Structure of Hydrogel.

2.3. Review of Groundwater Remediation

Groundwater Pollution and Remediation Strategies

Groundwater pollution is a growing concern in many developing nations due to escalating human activities and, in some cases, natural pollutants. This issue, as discussed by [27], arises from various sources categorized as point source pollution and non-point source pollution. Point source pollution originates from specific, identifiable locations, such as industrial facilities or municipal sewage plants, and is relatively easier to monitor and manage. In contrast, non-point source pollution stems from diffuse sources like agricultural runoff and atmospheric deposition, making it harder to trace and control.

The mechanisms by which contaminants are transported include filtration, chemical reactions, and microbiological

processes, all of which contribute to ecological imbalances and health risks. Prevention of groundwater contamination is critical and involves strategies such as proper waste disposal, hazardous material monitoring, and public health education. For cases where pollution has occurred, remediation techniques like chemical oxidation, bioremediation, and thermal treatments are employed to restore groundwater quality [33].

Groundwater Circulation Wells (GCWs) provide an overview of groundwater circulation wells (GCWs), an innovative technology for groundwater remediation. GCWs not only aid in contamination clean-up but also in the hydraulic characterization of aquifers. These systems offer advantages like targeted flushing of contaminants, reduced remediation time, and lower water consumption compared to traditional methods like pump-and-treat systems. Despite their potential, the research on GCWs is fragmented, necessitating further exploration to fully harness their benefits.

Advances in Hydrogel Applications

Hydrogels have garnered significant attention as versatile materials for environmental remediation due to their unique three-dimensional polymer networks, as highlighted by [15]. These structures allow for effective adsorption of pollutants, including heavy metals and dyes, from contaminated water. In particular, nanocomposite hydrogels—explored by [4]—exhibit properties such as high swelling capacity, chemical stability, and biodegradability. These features make them suitable for diverse applications, ranging from water treatment to biomedical engineering.

Hydrogels can be tailored for specific uses, such as incorporating natural polymers like gelatin or cellulose to enhance adsorption efficiency. Their role in environmental protection includes ion exchange, soil conditioning, and photocatalysis. Furthermore, as reviewed by [3], composite hydrogels containing inorganic fillers like clay minerals or metallic particles have shown promise in dye remediation, with significant advancements in adsorption techniques and material formulations.

Permeable Reactive Barriers (PRBs)

As an alternative to traditional pump-and-treat methods, [12] emphasize the effectiveness of permeable reactive barriers (PRBs) for groundwater remediation. PRBs utilize reactive materials to treat contaminants like heavy metals and pesticides directly within the aquifer. This approach is cost-effective and sustainable, addressing both organic and inorganic pollutants. The authors also discuss the mechanisms of contaminant uptake, including sorption kinetics and breakthrough curves, which are critical for designing efficient PRB systems.

Emerging Trends and Challenges

Chitosan-based hydrogels, as explored by [28], represent another innovative solution for environmental remediation. These materials offer multifunctional properties, including biosorption of dyes and metals, oil-water separation, and

applications in microbial fuel cells. However, further research is needed to unlock their full potential in electrochemical sensing and agriculture.

Hydrogel technologies continue to evolve, with researchers [29] emphasizing their role in addressing nitrate contamination from agricultural runoff. Such advancements underscore the critical need for sustainable and efficient strategies to safeguard groundwater resources against increasing anthropogenic pressures.

3. Method and Procedure

3.1. Adsorption Studies

A total of 0.5 g of adsorbent was measured and introduced into 100 ml of a dye solution with a concentration of 60 mg/L inside a 250 ml conical flask. The mixture was stirred at a speed of 150 rpm for 24 hours. After agitation, the solution was allowed to settle for 20 minutes, and then 15 ml was extracted and placed in a container labeled for identification. This process was repeated at every 20 minutes, continuously until a total of 120 minutes was accomplished while a pH of 7 was maintained. Ultimately, five samples were collected for AAS analysis. The equilibrium amount of gentian violet dye absorbed and the removal efficiency of gentian violet dye (GVD) were calculated using the following equations:

$$q_e = (c_i - c_e) \frac{V}{w}$$

$$\% \text{ Removal} = \left(\frac{c_i - c_e}{c_i} \right) \times 100$$

C_i : initial gentian violet dye concentration (mgL^{-1})

C_f : final gentian violet dye concentration (mgL^{-1})

V : volume gentian violet dye (L)

w : mass of hydrogel (g)

3.2. Adsorbate Preparation

To prepare a stock solution of gentian violet dye at 500 mg/L, 0.5 g of the dye was dissolved in 1 liter of deionized water. From this stock, different diluted solutions were prepared by taking specific volumes (2, 4, 6, 8, 10, and 30 mL) and adding each to 100 mL of distilled water in separate containers. This resulted in dye concentrations ranging from 20 mg/L to 300 mg/L. The absorbance of each solution was then measured, and a calibration curve, as shown in Figure 3, was plotted to establish the relationship between absorbance and concentration. This curve was later used to determine the concentration of unknown dye samples.

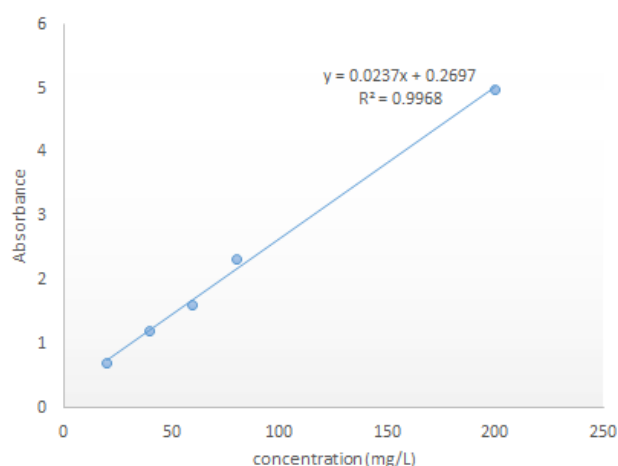


Figure 3. Calibration curve.

4. Results and Discussions

4.1. Effects of Different Experimental Conditions on Gentian Violet

4.1.1. Effect of Concentration

To assess dye removal, 1.0 g of hydrogel was added to dye solutions of varying concentrations (20, 40, 60, 80, and 100 mg/L). Results showed that as the dye concentration increased, the dye removal efficiency decreased. The table below highlights this trend, with the highest removal rate observed at 77.4% when the initial dye concentration was 20 mg/L.

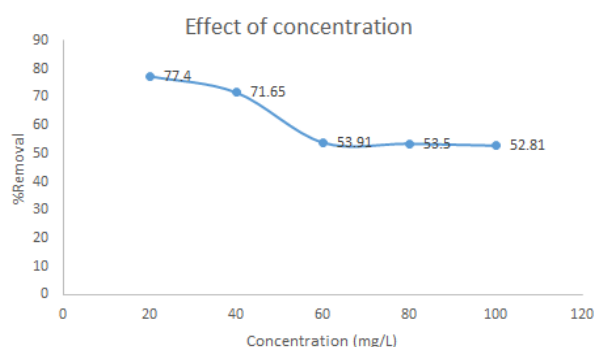


Figure 4. Effect of concentration.

4.1.2. Effect of Time

The adsorption study was conducted by varying the contact time from 20 to 100 minutes to examine the adsorbent's capacity. As shown in the figure below, the removal of red gentian violet dye by the hydrogel increased over time, starting from 20 minutes and continuing until 100 minutes. This indicates that longer contact time led to greater adsorption.

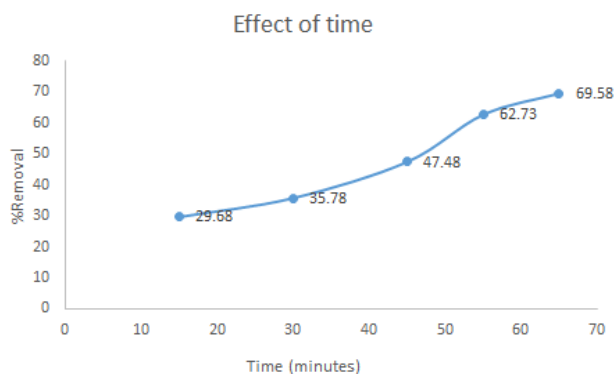


Figure 5. Effect of contact time.

4.1.3. Effect of Dosage

Different amounts of adsorbent, ranging from 0.5 to 2.0 g, were measured and added to three containers, each containing 100 mL of a 60 mg/L dye solution. The mixture was then stirred at 150 rpm for 3 hours using a magnetic stirrer. As shown in the figure below, dye removal was most effective with a 5 g dosage of hydrogel, indicating that gentian violet dye removal improved as the adsorbent dosage increased.

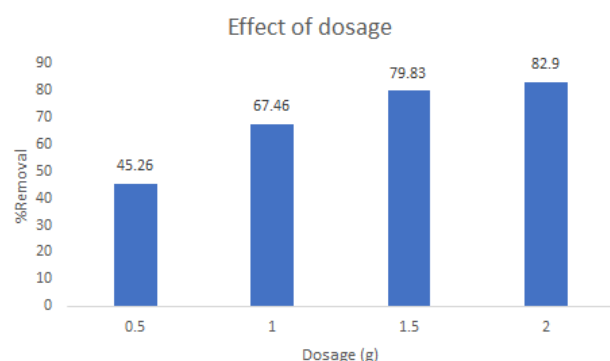


Figure 6. Effect of dosage.

4.1.4. Effect of Temperature

From the figures below, it is seen that the removal of Gentian Violet dye increases with increase in temperature. It goes on to show that the efficiency in the removal of GV dye using hydrogel is optimum at high temperature and moderate at low temperatures.

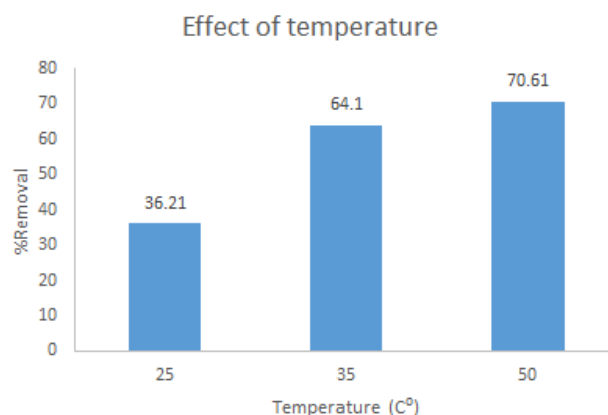


Figure 7. Effect of temperature.

4.2. Adsorption Isotherm Models

From the table below, the R^2 value obtained from the Langmuir was higher by comparison with that of the Freundlich model hence, our adsorption process obeys Langmuir isotherm model which shows monolayer adsorption. In addition, the values of R_L ranging from 0.015-0.061 and $1/n$ of 0.222 obtained from the two isotherms displayed the favorable adsorption of gentian violet.

Table 1. Adsorption isotherms parameters.

Isotherm		parameter			
Langmuir	T(K)	q_m (mgg ⁻¹)	KL (Lmg ⁻¹)	R_L	R^2
	298	6.83	0.610	0.015-0.061	0.9777
Freundlich	T(K)	K_f (mg/l)(L/mg ^{1/n})		$1/n$	R^2
	298	2.6		0.222	0.9116

Adsorption kinetic models

The kinetic models that were put in place on this work are pseudo first and pseudo second order and from the result obtained display the mechanism of the adsorption, highest

level of adsorption and adsorption efficiency of gentian violet dye obeyed pseudo second order due to highest value of correlative coefficient R^2 which was 0.9660. Also adsorption capacity of the dye at equilibrium q_e was high

with the value of 2.891 to 6.876 in pseudo second order compared to pseudo first order with 5.868.

Table 2. Adsorption kinetics parameters.

model	parameter				
Pseudo first order	T(K)	q _{e,cal} (mg/g)	q _{e,exp} (mg/g)	K ₁ (1/min)	R ²
	298	0.0211	5.868	0.033	0.9267
Pseudo second order	T(K)	q _{e,cal} (mg/g)	q _{e,exp} (mg/g)	1/n	R ²
	298	2.891	6.876	0.022	0.9660

5. Conclusion

In conclusion, the project on the remediation of groundwater contaminated with Gentian Violet dye using hydrogel presents a promising approach to address critical environmental issue. The innovative use of hydrogels not only offers high adsorption capacity and selectivity for removing the dye but also aligns with sustainable practices through the use of biodegradable material. By effectively capturing Gentian Violet molecules, this method demonstrates the potential to restore water quality and mitigate the ecological risks associated with dye pollution.

Moreover, this insights gained from this research could pave the way for further advancement in water treatment technologies, enhancing our ability to tackle similar contaminant in the future. Ultimately, this project represents a significant towards achieving cleaner groundwater and promoting environmental health.

6. Summary

The experiment for the removal of Gentian violet dye from groundwater using hydrogel was achieved at optimum removal because adsorption process is a suitable method for removal of dyes due to its initial cost, simplicity of design, ease of operation, and insensitivity to toxic substances. And also, hydrogel is a good adsorbent due its good absorbing properties such as high porosity of particles, large size and attractive surface.

In this work, an experimental study on the utilization of hydrogel for the removal of GV from groundwater was investigated. The potential of this adsorbent was studied for decolonization of GV. Influence of different parameters such as initial pH, initial GV concentration, contact time, adsorbent dosage, and temperature on GV adsorption was examined. The adsorption capacity of Gentian Violet increased with raising the initial dye concentration, time, and

pH; the optimized pH for adsorption was 11. The kinetics of GV removal indicated an optimum contact time of 120 min. via two stage process of the adsorption kinetic profile (initial fast and subsequent slow equilibrium).

7. Recommendation

Using hydrogel for the removal of gentian violet dye is a promising approach due to its unique properties such as high adsorption capacity, biodegradability, easy synthesis and sorption.

Conflicts of Interest

The authors declare no conflicts of interest.

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