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Article

Hen Feather, an Efficient Biosorbent for the Adsorptive Removal of the Dye Chrysoidine R from Its Aqueous Solutions

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Abstract: The paper focuses on the eradication of a hazardous azo dye Chrysoidine R from its aqueous solutions through adsorption over a biosorbent—Hen Feather. Chrysoidine R is a highly toxic dye, which poses severe health complications amongst humans. It can affect respiratory and gastrointestinal systems, may damage organs, produce dermatitis and even cause cancer. Hence, its removal from wastewater is highly desired and essential. Therefore, a bio waste material Hen Feather, which is available in huge quantity, is used as adsorbent to remove this dye from its aqueous solutions. Preliminary adsorption studies have been carried out and it is found that pH 4.0, dye concentration 7.5×10^{-5} M, Hen Feather amount 0.34 g and 30 min contact time result into maximum amount of dye removal. Total five well-known adsorption isotherm models namely, Langmuir, Freundlich, Temkin, Halsey and Jovanovich have been examined for the Chrysoidine R—Hen Feather system and interestingly all models have been found applicable in the present case. On the basis of Langmuir adsorption isotherm constant, various thermodynamic parameters like, change in Gibb's free energy, change in enthalpy and change in entropy, were also evaluated and it is found that ongoing adsorption process is favorable, feasible, spontaneous and endothermic in nature. Thus, these studies indicate that Hen Feather acts as an excellent adsorber for the dye Chrysoidine R.

Keywords: Chrysoidine R; Hen Feather; adsorption; isotherm

1. Introduction

Water contamination is one of the most serious environmental challenges worldwide and has been further intensified by the rapid expansion of industrial and agricultural activities [1,2]. Increasing quantities of untreated or inadequately treated industrial and agricultural effluents are discharged into water bodies, thereby contaminating one of the most essential natural resources for sustaining life. These contaminants include inorganic pollutants, such as heavy metals and radioactive substances, as well as a wide range of organic compounds, including dyes, phenols, pesticides, and polychlorinated biphenyls [3]. Among these pollutants, synthetic organic dyes are of particular concern because of their high chemical stability, resistance to biodegradation, and persistence in aquatic environments. Even at relatively low concentrations, dyes can impart intense coloration to water, reduce light penetration and photosynthetic activity, and adversely affect aquatic ecosystems and their aesthetic quality [4]. Therefore, the effective removal of synthetic dyes from contaminated water is of considerable environmental importance.

Addressing these global challenges requires the development of efficient, sustainable, and economically viable remediation strategies. Although conventional treatment technologies, such as coagulation, ion exchange, and membrane filtration have been successfully employed for wastewater treatment, they often suffer from limitations

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related to high operational costs, energy consumption, sludge generation, and maintenance requirements. Recent advances in materials science, particularly nanotechnology, have provided promising opportunities for the development of advanced water-purification technologies; however, many of these approaches remain relatively expensive, technically demanding, and time-consuming for large-scale application [5]. In this context, adsorption has emerged as an attractive alternative for the removal of a wide range of pollutants from aqueous systems. In particular, low-cost adsorbents derived from agricultural and industrial wastes, including fly ash, rice husk, sawdust, and poultry feathers, have received considerable attention [6]. Adsorption offers several advantages, including operational simplicity, relatively low cost, high efficiency, and versatility toward different classes of pollutants. Consequently, it has remained one of the most widely investigated approaches for wastewater treatment over the past several decades [7,8].

Large quantities of synthetic dyes are released into aquatic environments through industrial activities associated with textile manufacturing, paper production, pharmaceuticals, leather processing, food processing, and other dye-consuming industries [9]. Textile effluents are particularly difficult to treat because they may contain high concentrations of structurally complex dyes that are resistant to conventional biological degradation and may exhibit toxic, mutagenic, or carcinogenic properties [10]. Azo dyes constitute one of the largest classes of synthetic dyes used industrially and account for a substantial proportion of the colorants employed in the textile sector. Their characteristic azo linkage (–N=N–), together with their aromatic structures, contributes to their chemical stability and persistence. Moreover, the degradation of certain azo dyes may generate aromatic amines, some of which possess significant toxic and carcinogenic potential [11]. Therefore, the development of simple, economical, efficient, and environmentally benign methods for the removal of azo dyes from wastewater remains an important research priority.

In this context, Chrysoidine R represents a relevant target pollutant for adsorption-based remediation. Chrysoidine R is a synthetic azo dye characterized by an intensely colored brown-red appearance and contains aromatic rings linked through an azo group. Its chemical structure contributes to its stability and enables interactions with various substrates, including paper, textiles, and leather. The dye is used for coloration purposes in different industrial applications where bright and intense colors are required. The physicochemical characteristics of Chrysoidine R, including its molecular formula, molecular weight, physical state, color, water solubility, melting point, specific gravity, and maximum absorption wavelength, are summarized in Table 1. The molecular structure of Chrysoidine R is presented in Figure 1.

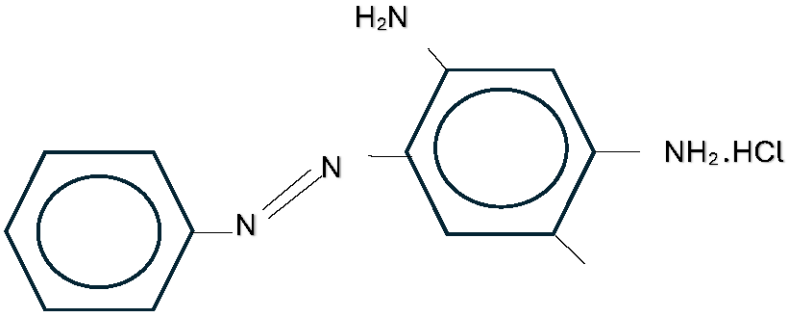

Figure 1. Chemical structure of Chrysoidine R.

Table 1. Physicochemical properties of Chrysoidine R.

Parameters	Property
Class	Mono Azo
Synonyms	Calcozine orange RS
Chemical Formula	$C_{13}H_{15}ClN_4$
IUPAC Name	4-Methyl-6-phenyldiazenylbenzene-1,3-diamine Hydrochloride
Molecular Weight	262.74 g/mol
Physical State	Solid
Colour	Brown Red
Melting Point	125 °C
Odour	Odorless
Solubility in Water	Soluble
Adsorption Maximum (λ_{max})	448 nm
Specific Gravity	1.13

The presence and persistence of Chrysoidine R in aquatic environments may pose significant environmental concerns. Colored effluents can interfere with the penetration of sunlight into water and consequently disturb

photosynthetic processes and the ecological balance of aquatic systems [12]. Persistent dye residues may adversely affect the growth, reproduction, and survival of aquatic organisms, including fish, algae, and invertebrates. Furthermore, the persistence of certain synthetic dyes and their transformation products raise concerns regarding their potential accumulation within aquatic organisms and subsequent transfer through food webs [13]. The reported toxicological effects associated with azo dyes, including potential mutagenic and carcinogenic effects, further emphasize the importance of controlling their release into the environment [14]. Human exposure to hazardous dyes may occur through inhalation, ingestion, or dermal contact, potentially resulting in adverse effects depending on the concentration, duration, and route of exposure [14]. These concerns highlight the need for effective treatment strategies capable of removing Chrysoidine R from contaminated water before its discharge into natural water bodies.

Previous studies have demonstrated that Hen Feathers can serve as an effective and inexpensive biosorbent for the removal of several classes of synthetic dyes from aqueous solutions. Hen Feathers are an abundant poultry-processing waste material and are predominantly composed of keratin, a protein containing various functional groups capable of interacting with dissolved pollutants and it has been demonstrated while characterizing the Hen Feathers by several workers [15–18]. Hen Feathers have also been investigated for the adsorptive removal of several hazardous dyes [19–28]. These studies have generally demonstrated the feasibility of Hen Feathers as low-cost biosorbents and have investigated important parameters such as pH, temperature, adsorbent dosage, contact time, and initial dye concentration. In particular, the successful adsorption of both cationic and anionic dyes indicates the versatility of Hen Feathers as an adsorbent material. More recent research has further confirmed the potential of poultry feathers for dye removal and has explored surface modification and characterization approaches to improve adsorption performance [29]. Collectively, these findings establish Hen Feather as a promising waste-derived material for the treatment of dye-contaminated water.

Despite the considerable body of research on the application of Hen Feathers for the removal of different synthetic dyes, the adsorption behavior of Chrysoidine R onto Hen Feather has not been adequately investigated. A literature survey indicates that previous studies have primarily focused on several dyes, whereas the Chrysoidine R–Hen Feather adsorption system remains unexplored in the available literature identified for this study [20,30–35].

The novelty of the present work therefore lies in the systematic investigation of Hen Feather as a low-cost, waste-derived biosorbent for the removal of Chrysoidine R, an azo dye that has not previously been extensively examined in this adsorption system. The study not only extends the application of Hen Feather to a new target dye but also seeks to establish the relationship between the major operational parameters and adsorption performance. In particular, the effects of pH, adsorbent dosage, contact time, initial dye concentration, and temperature are investigated to determine the conditions favorable for maximum dye removal. Furthermore, equilibrium and thermodynamic behavior are evaluated using appropriate adsorption isotherm models, with particular emphasis on understanding the influence of temperature on the adsorption process. By converting an abundant poultry-processing waste into a functional adsorbent, the study simultaneously addresses two environmental concerns: the management of poultry waste and the removal of hazardous synthetic dyes from wastewater.

In view of the above considerations, the present study aims to develop a simple, economical, and environmentally sustainable adsorption-based approach for the removal of Chrysoidine R from aqueous solutions using Hen Feather as a biosorbent. The investigation is intended to identify the optimum conditions for dye removal, evaluate the adsorption equilibrium and thermodynamic characteristics of the process, and provide insight into the suitability of Hen Feather for the treatment of dye-contaminated wastewater. The findings are expected to contribute to the development of sustainable and affordable wastewater-treatment strategies while demonstrating the potential for beneficial utilization of poultry waste in environmental remediation.

2. Materials and Methods

The dye Chrysoidine R (Ch-R) and other chemicals like HCl, NaOH and H_2O_2 used in this study were procured from M/s Sigma Aldrich, India. Hen Feathers were obtained from local poultry, M/s Ansari, Bhopal, India.

A pH meter (M/s Hanna, Italy) was used to determine the pH of the solutions. The concentration of the solution was measured using double beam UV-Spectrophotometer (M/s Systronics, India). The working solutions were stirred using a mechanical shaker (M/s Remi, India).

To prepare Hen Feathers as an adsorbent, first, blood stains, dirt, and adhered soft tissues were removed by continuously washing the feathers under a stream of tap water. The feathers were then soaked in detergent and washed under running water several times. The Hen Feathers were then kept in double distilled water for 3–4 h. Feathers thus obtained were dipped in H_2O_2 solution for approximately 24 h to eliminate any organic contaminants that might have remained and once more placed in double distilled water overnight. The material was now dried

in a hot air oven at 80 °C. Using sharp scissors, barbs and barbules approximately 1 mm in length were cut off from the shaft of the feathers. The tiny, dry pieces of Hen Feathers thus obtained were stored in a desiccator.

To carry out the adsorption studies, a concentrated (1 M) stock solution of the dye was prepared in double-distilled water, and all working solutions were prepared by diluting the stock solution with double-distilled water. To determine the effects of various parameters and conduct adsorption isotherm studies an appropriate volume of the dye Chrysoidine R of a known initial concentration was transferred to a stoppered conical flask containing a fixed amount of adsorbent. The pH of the solution was adjusted using a buffer solution. Keeping the temperature constant, the flask was stirred for a predetermined period and then filtered using filter paper (Filterking, 1A, 125 mm). The concentration of the filtrate was measured using double beam UV-Spectrophotometer (M/s Systronics, India) at λ_{max} = 448 nm. The difference between the initial and final dye concentrations was used to calculate the amount of dye adsorbed and the percentage dye removal. The adsorption capacity of Hen Feather at the equilibrium is represented by Q_e (mol/g), which was evaluated using the following formula.

$$Q_e = \frac{(C_o - C_e) \times V}{m} \quad (1)$$

where, C_o (mol/L) is the concentration of the dye in bulk phase initially, C_e (mol/L) is the concentration of the dye at equilibrium, V (litre) is the volume of the dye solution and m (gram) is the mass of adsorbent added with the dye solution.

3. Results and Discussions

3.1. Preliminary Investigations

Because the nature of the adsorbent, adsorbate, and adsorption medium strongly affect the adsorption process, preliminary investigations have been conducted to optimize the parameters such as pH, adsorbate concentration, adsorbent dosage, temperature, contact time etc. The following paragraphs describe experimental procedures and results obtained after carrying out these investigations.

3.1.1. Influence of pH

It is well established that the adsorption process depends strongly on the pH of the solution, and the increase or decrease in adsorption capacity is pH-dependent [30]. In the present case a wide range of pH (1 to 10) was used to determine the influence of pH on the adsorption of Chrysoidine R onto Hen Feathers. The percentage of dye removal at each corresponding pH of the dye solution is shown in Figure 2. Figure 2 shows a systematic increase in dye removal from pH 1 to 4 and beyond pH 4, there is a systematic decrease. Thus, it can be safely interpreted that the maximum adsorption of the dye was obtained at pH 4 and this pH was used for all further studies.

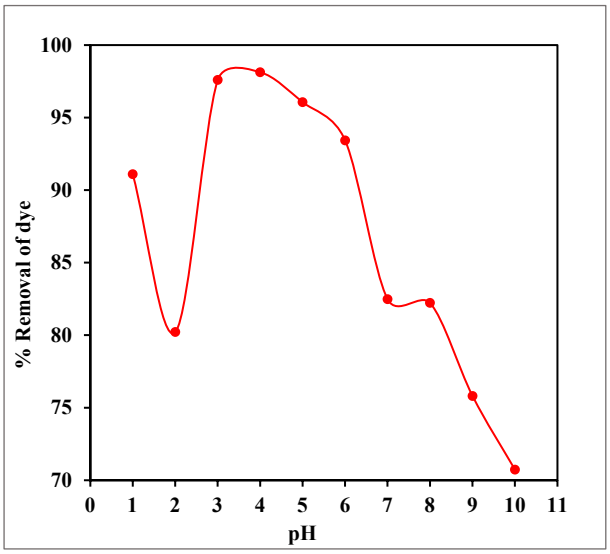

Figure 2. Influence of pH on the adsorptive uptake of dye Chrysoidine R by Hen Feather. (Volume of the solution = 20 mL, initial dye concentration: 7.5×10^{-5}, adsorbent dosage: 0.34 g, contact time: 30 min, temperature: 303 K).

It is well documented that Hen Feathers contain keratin protein and disulphide (–S–S–), amino ($–NH_2$) and carboxylic acid (–COOH) groups on their surfaces [15]. On the other hand, the dye Chrysoidine R has a pK_a of

around 5, hence, under low pH conditions (pH 4) the $–NH_2$ group of the dye may readily form $–NH_3^+$ ions and its interaction with carboxylic acid group (–COO–) of the Hen Feather results in electrostatic attraction and thereby physisorption. Thus, in the acidic medium Chrysoidine R—Hen Feather system exhibits better adsorption capacity [31].

3.1.2. Influence of Initial Dye Concentration

The initial dye concentration has a major impact on the rate and extent of adsorption in any adsorbate-adsorbent system, hence it is essential to understand its role. Because of the concentration gradient between the adsorbent surface and the aqueous phase, the initial concentration of dye in the solution controls the diffusion of dye molecules. The migration of the dye molecules and their fixation to the adsorbent are driven by this gradient [32].

Chrysoidine R solutions with initial concentrations ranging from 5×10^{-5} M to 8.5×10^{-5} M were prepared for this investigation and were placed in eight different stoppered conical flasks. The pH of the solution was kept at 4 and 0.34 g of Hen Feathers was added to each flask. The mixtures were agitated for 30 min at a temperature of 303 K. while maintaining the other parameters at their optimum levels, and the adsorption of Chrysoidine R at these concentrations was examined.

The results presented in Figure 3 show that as the initial dye concentration increases the amount of dye removed from the solution first decreases and then increases up to an optimal concentration of 7.5×10^{-5} M. After this point, a decrease in the dye removal was observed. This decrease can be attributed to the saturation of available binding sites on the Hen Feather. As the concentration increased, the adsorption sites became increasingly occupied, leading to a slight repulsion among the dye molecules, limiting further adsorption. At a concentration of 7.5×10^{-5} M of Chrysoidine R, the dye removal rate stabilized, reflecting the maximum adsorption capacity of the Hen Feather towards the dye.

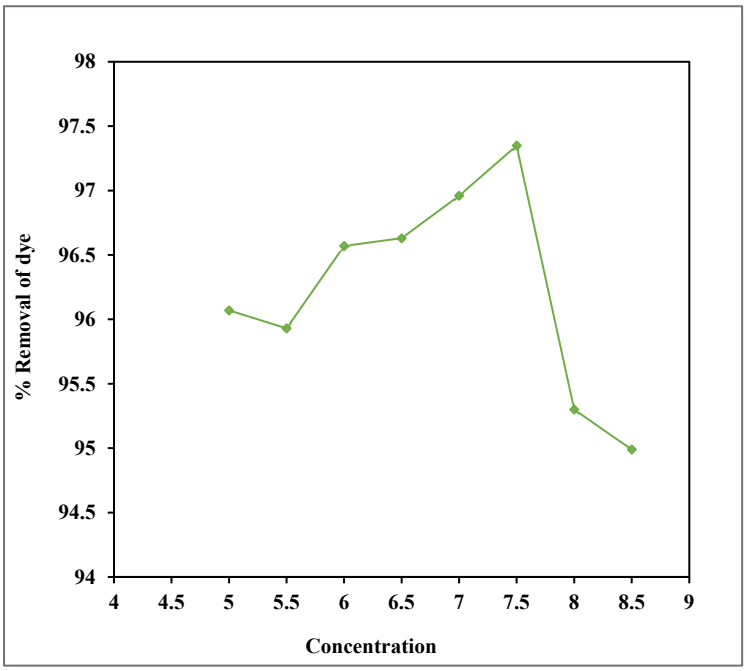

Figure 3. Influence of initial dye concentration on the adsorptive uptake of Chrysoidine R by Hen Feather. (Volume of the solution = 20 mL, pH of solution = 4, adsorbent dosage = 0.34 g, phase contact time = 30 min, temperature = 303 K).

3.1.3. Influence of Adsorbent Dosage

In batch studies, determining the optimal adsorbent dosages is important after establishing the ideal pH of the solution and concentration of the dye for maximum removal efficiency. The number of active sites increase with increasing adsorbent amount, increasing the possibility of adsorption [33]. On the other hand, efficiency may decrease after a certain point. This happens because using too much adsorbent might cause particles to aggregate, making adsorbent sites less accessible to the adsorbate. After reaching its maximum removal effectiveness, the system either stabilizes at saturation or experiences a decline as a result of agglomeration, which restricts the number of new adsorption sites that the dye molecules may occupy.

The adsorption study of Chrysoidine R was conducted by varying the Hen Feather dosage between 0.1 g and 0.42 g in nine separate stoppered conical flasks, each containing 20 mL of a solution with a dye concentration of

7.5×10^{-5} M and pH 4. Each flask was shaken at 303 K for 30 min and the solution was filtered to evaluate dye uptake in each sample.

As shown in Figure 4, dye uptake increased with increasing adsorbent dosage, reaching a maximum removal efficiency of 95.30% with 0.34 g of Hen Feathers. Because there was initially less competition for active sites, dye molecules were able to diffuse and absorb more effectively. However, dye removal effectiveness dropped at 0.34 g most likely as a result of particle aggregation, which decreased the number of available active sites. Therefore, it was determined that the ideal dosage for maximizing Chrysoidine R adsorption is 0.34 g of Hen Feather.

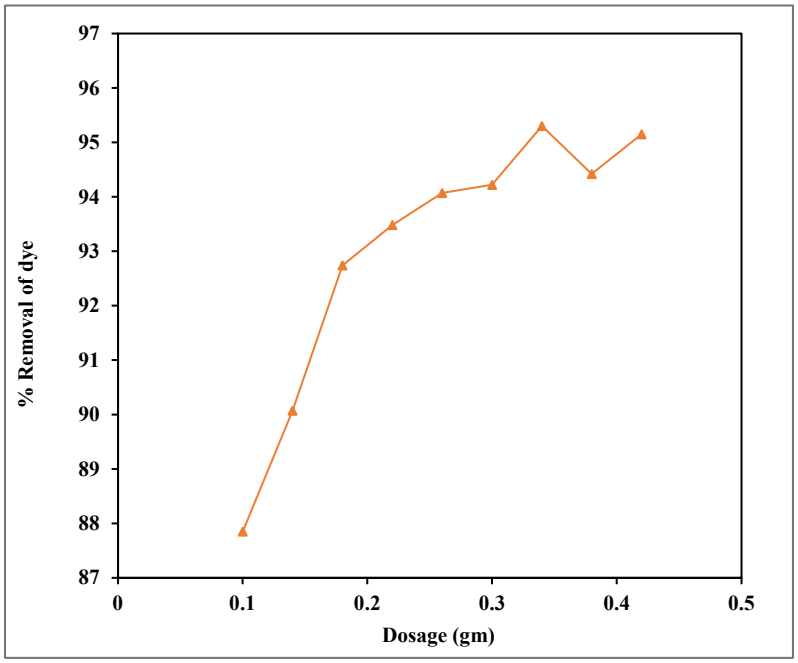

Figure 4. Influence of Hen Feather dosage on the adsorption of Chrysoidine R. (Volume of the solution = 20 mL, initial dye concentration = 7.5×10^{-5} M, pH of solution = 4, phase contact time = 30 min, temperature = 303 K).

3.1.4. Influence of Contact Time

In adsorption investigations tracking the contact time is crucial since it determines the ideal amount of time required to bring the adsorbed and liquid phases into equilibrium [34]. For this experiment, a 20 mL solution was prepared using a 7.5×10^{-5} M Chrysoidine R dye solution with 0.34 g of Hen Feathers and the pH was adjusted to 4. Aliquots were withdrawn after every 15 min starting from the first 15 min and continued for a total of 1 h and 45 min.

The graph presented in Figure 5 exhibits the relationship between contact time and the dye removal efficiency of the adsorbent. As the contact time increased from 15 min to 1 h and 45 min, a maximum dye removal of 96.08% was observed in 30 min. Therefore, 30 min was determined as the optimal contact time for the Chrysoidine R adsorption on Hen Feather.

3.2. Adsorption Isotherms Modelling

The adsorption characteristics obtained in the initial experiments formed the foundation for developing a systematic approach to the adsorptive removal of Chrysoidine R onto Hen Feathers. Using the optimal parameters identified in the preliminary investigations, isotherm studies were conducted for the Chrysoidine R—Hen Feather adsorption system. The equilibrium data obtained were examined for five well-known adsorption isotherm models namely, the Langmuir, Freundlich, Temkin, Halsey and Jovanovich and presented in the following paragraphs.

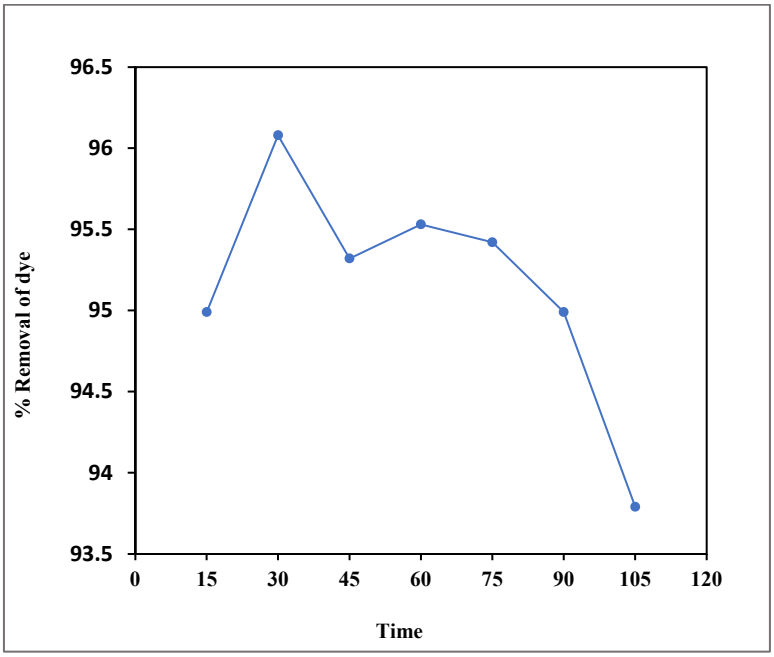

Figure 5. Influence of contact time on the adsorption of Chrysoidine R onto Hen Feather (Volume of the solution = 20 mL, initial dye concentration = 7.5×10^{-5} M, pH of solution = 4, adsorbent dosage = 0.34 g, temperature = 303 K).

3.2.1. Langmuir Adsorption Isotherm Model

This empirical model was proposed by Irving Langmuir in 1916 and was originally for solid–gas equilibria and later it was applied to solid–liquid equilibria as well [29]. The formation of Langmuir adsorption isotherm model is based on various postulates. It is assumed that the adsorption takes place on a homogeneous surface and is monolayer, or one molecule thick. The formation of monolayer is conjectural and appears as a plateau in the isotherms. It eliminates the possibility of lateral interaction between the different adsorbed species that are present at different locations. It is assumed that every adsorption site has the same energy and that every adsorbate moiety can be affected by the same mechanism. The expression for the Langmuir model in its linear form appears as follows:

$$\frac{1}{q_e} = \frac{1}{q_o} + \frac{1}{bq_oC_e} \quad (2)$$

where, q_o (mol/g) is the maximum adsorption capacity and b = Langmuir constant (1/mol). All other constants have the same meanings as described in Equation (2).

Plots of $1/q_e$ versus $1/C_e$ gave straight lines at temperatures of 303, 313, and 323 K, as shown in Figure 6. In each case, regression coefficients (R^2) were close to unity. Thus, it can be concluded that equilibrium in this condition fits well in the Langmuir adsorption isotherm model. The values of b and q_o are calculated on the basis of slope and intercept of the Langmuir adsorption isotherm and presented in Table 2. Table 2 indicates that the adsorption capacity of the Chrysoidine R—Hen feathers system increases with temperature and at 323 K, a maximum adsorption capacity of 4.36×10^{-3} mmol·g^{-1} has been obtained.

Table 2. Values of maximum adsorption capacity and Langmuir isotherm constant for the uptake of Chrysoidine R by Hen Feathers at different temperatures.

Parameters	Temperature		
	303 K	313 K	323 K
$q_0 \times 10^{-3}$ (mmol/g)	1.76	1.83	4.36
$b \times 10^5$ (1/mol)	3.53	3.41	1.34
R^2	0.9916	0.9944	0.9911

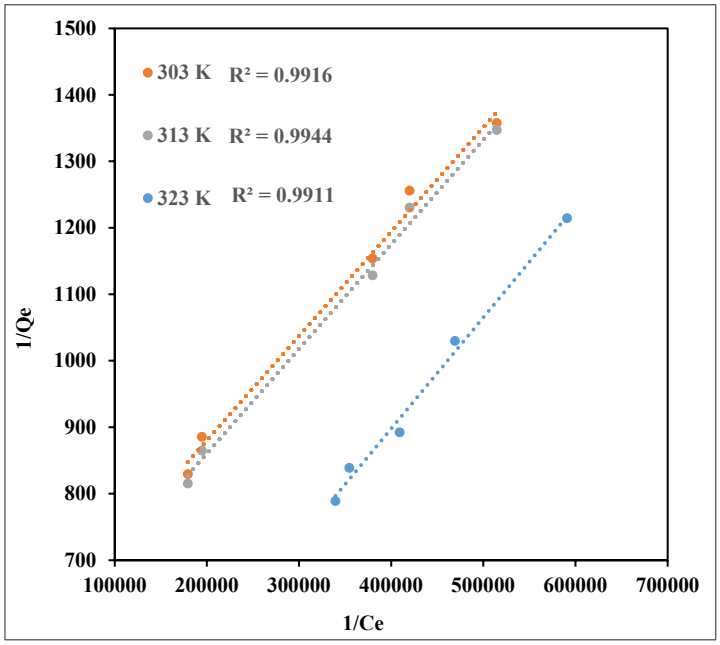

Figure 6. Langmuir adsorption isotherm at different temperatures for the adsorption of Chrysoidine R over Hen Feather at pH 4. (Volume of the solution = 20 mL, initial dye concentration: 7.5×10^{-5}, pH of solution = 4, adsorbent dosage: 0.34 g, contact time: 30 min, temperature: 303 K).

3.2.2. Freundlich Adsorption Isotherm Model

The Freundlich isotherm model is an empirical equation, which is used to describe adsorption processes occurring on heterogeneous surfaces, where the surface contains a variety of different active sites with varying affinities and thermal energies [35]. Unlike the Langmuir isotherm, which assumes a monolayer coverage, the Freundlich model accommodates the possibility of multilayer adsorption. According to this model, sites with higher affinity are occupied first, followed by sites with progressively lower affinities. Additionally, the model accounts for lateral interaction among adsorbed species. Linearized expression of the Freundlich model is as follows:

$$\log q_e = \log K_F + \frac{1}{n} \log C_e \quad (3)$$

where, K_F is the Freundlich constant, indicating adsorption capacity and parameter 'n' is a measure of adsorption intensity or favorability.

The plot of log q_e vs log C_e at three temperatures of 303, 313 and 323 K for the adsorption of Chrysoidine R onto Hen Feathers is represented in Figure 7. These three plots exhibit linear behavior among all the temperatures, with the regression coefficients, which are close to unity. The Freundlich constants obtained by these straight lines are presented in Table 3. Therefore, it can be concluded that the Freundlich isotherm is also applicable in the adsorption of Chrysoidine R over the Hen Feather.

The verification of the Langmuir and Freundlich adsorption isotherms indicate that after the formation of a monolayer due to electrostatic attraction between dye and Hen Feathers, a uniform multiple layer accumulation of Chrysoidine R molecules takes place due to weak van der Waals forces. This also supports the involvement of physisorption in the present case as described earlier under influence of pH studies.

Table 3. Values of various Freundlich adsorption isotherm constants for the uptake of Chrysoidine R by Hen Feathers at different temperatures.

Parameters	**Chrysoidine R**		
Temperture	303 K	313 K	323 K
K_F	0.02	0.32	0.06
n	3.76	2.17	1.35
R^2	0.9673	0.9934	0.9973

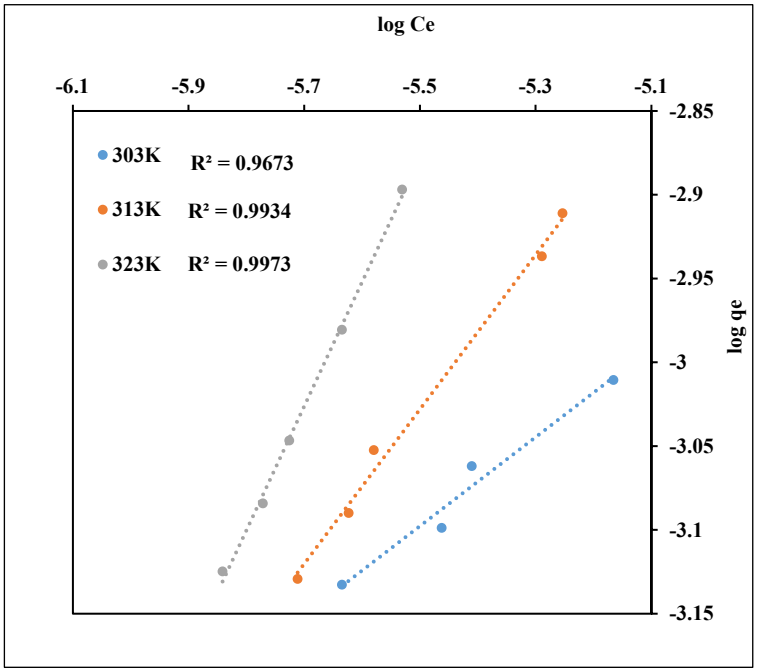

Figure 7. Freundlich adsorption isotherm for the adsorption of Chrysoidine R over Hen Feather at different temperatures. (Volume of the solution = 20 mL, initial dye concentration: 7.5×10^{-5}, pH of solution = 4, adsorbent dosage: 0.34 g, contact time: 30 min, temperature: 303 K).

3.2.3. Temkin Adsorption Isotherm Model

Initially, this model was employed for the adsorption of hydrogen gas onto platinum electrodes submerged in acidic solutions. This model is based on the assumption that the decline in the heat of adsorption with surface coverage caused by interaction between adsorbate and adsorbent molecule in a layer is linear rather than a logarithmic decrease [36]. This model provides insight into the possibility of lateral or indirect adsorbate–adsorbent interactions. The linear form of Temkin isotherm is expressed as follows:

$$q_e = k_1 \ln k_2 + k_1 \ln C_e \quad (4)$$

where, k_1 is the heat of adsorption and it is equal to RT/b (R = 8.314 J/K/mol), k_2 is equilibrium binding constant and T is the temperature in Kelvin.

The derivation of the equation is characterized by an even distribution of binding energies up to a certain maximum binding energy. Therefore, a uniform distribution of the binding energy over the adsorbent surface is indicated if the plot of q_e vs. $\ln C_e$ is a straight line. The values of k_1 and k_2 can be determined by analyzing the slope and intercept of the isotherm plots (Table 4).

Table 4. Values of various Temkin adsorption isotherm constants for the uptake of Chrysoidine R by Hen Feathers at different temperatures.

Parameters	Temperature		
	303 K	313 K	323 K
k_1 (1/mol)	0.0054	0.0066	0.0104
$k_2 \times 10^5$	7.29	146.50	28.33
R^2	0.9741	0.9945	0.9908

Figure 8 shows the Temkin isotherm model for the Chrysoidine R over Hen feathers at different temperatures, straight lines is obtained in the plot of q_e vs. $\ln C_e$ plot and verify the suitability and applicability of the Temkin adsorption isotherm model for this system at all the temperatures. The regression coefficients for all the lines are found to be very close to unity indicating thereby applicability of Temkin isotherm model in the present case (Table 4).

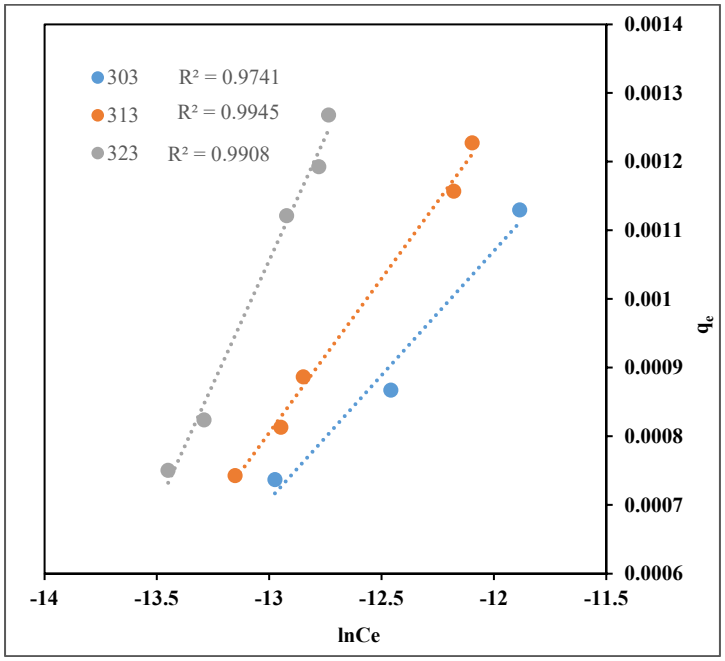

Figure 8. Tempkin adsorption isotherm for the adsorption of Chrysoidine R over Hen Feather at different temperatures. (Volume of the solution = 20 mL, initial dye concentration: 7.5×10^{-5}, pH of solution = 4, adsorbent dosage: 0.34 g, contact time: 30 min, temperature: 303 K).

3.2.4. Halsey Adsorption Isotherm

Halsey adsorption isotherm is designed to analyze multilayer adsorption on surfaces that are not uniform, particularly at higher pressure. This model assumes that as the distance from surface increases, additional layers formed due to weaker interaction with the surface [37]. Similar to the Freundlich isotherm, the Halsey model is also applicable to heterogeneous surface in which the adsorption heat is non—uniformly distributed. At a significantly greater distance from the surface, Halsey proposed an expression for the multilayer condensation. This equation provides the details on the adsorbent's hetero-porosity. The Halsey equation can be expressed as

$$\ln q_e = \left(\frac{1}{n_H}\right) \ln K_H - \left(\frac{1}{n_H}\right) \ln C_e \quad (5)$$

where, K_H = Halsey constant which indicates the adsorption capacity and n_H is Halsey model parameter characterizing the system.

Figure 9 shows a plot of $\ln q_e$ and $\ln C_e$ at different temperatures and dye concentrations; the slope of the curve is used to determine K_H, while the intercept is used to determine the value of n_H. A plot of $\ln q_e$ vs. $\ln C_e$ gives a straight line and the graphs are shown in Figure 10 at different temperature 303 K, 313 K, and 323 K respectively. In this case regression coefficients (R^2) were close to unity (Table 5). From the observation we can conclude that equilibrium in this condition fits well in the Halsey adsorption isotherm.

Table 5. Values of different Halsey adsorption isotherm constants for Chrysoidine R uptake by Hen feathers at different temperatures.

Parameters	Temperatures		
	303 K	**313 K**	**323 K**
n_H	3.16	2.69	1.32
K_H	0.37	0.43	7.14
R^2	1.0000	1.0000	0.9950

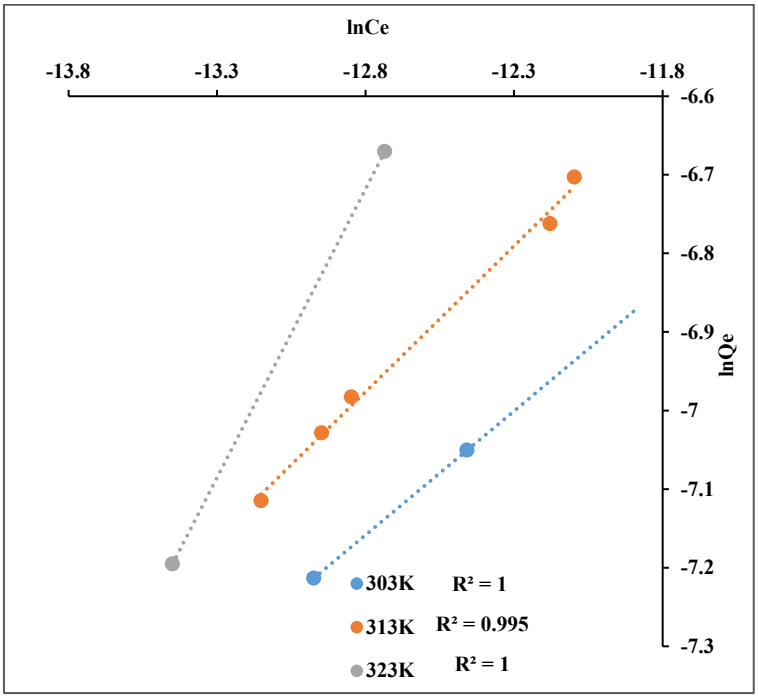

Figure 9. Halsey adsorption isotherm at different temperature for the adsorption of Chrysoidine R over Hen Feather at pH 4. (Volume of the solution = 20 mL, initial dye concentration: 7.5 × 10^{-5}, pH of solution = 4, adsorbent dosage: 0.34 g, contact time: 30 min, temperature: 303 K).

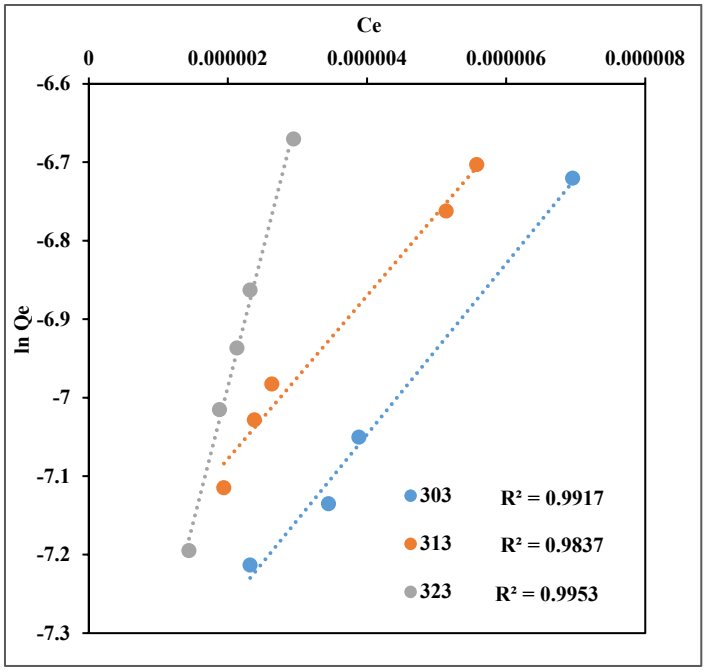

Figure 10. Jovanovich adsorption isotherm at different temperature for the adsorption of Chrysoidine R over Hen Feather. (Volume of the solution = 20 mL, initial dye concentration: 7.5 × 10^{-5}, pH of solution = 4, adsorbent dosage: 0.34 g, contact time: 30 min, temperature: 303 K).

3.2.5. Jovanovic Adsorption Isotherm

The Jovanovic adsorption isotherm [38] is a theoretical model derived to describe the equilibrium relationship between the amount of a substance adsorbed on a solid surface and its concentration in the surrounding fluid at a constant temperature. It works especially well for explaining monolayer adsorption on a homogeneous surface in which there is no interaction between the adsorbed molecules. The Jovanovic adsorption isotherm equation is expressed as:

$$\ln q_e = \ln q_{max} - K_J C_e \quad (6)$$

where, q_{max} is maximum monolayer adsorption capacity and K_J is the Jovanovic constant related to the adsorption energy.

A graph was plotted between the $\ln q_e$ and C_e at different temperatures and dye concentrations (Figure 10) and the value of q_{max} and K_J are determined from the slope and intercept respectively of the isotherm (Table 6). In Jovanovic adsorption isotherm, intercept q_{max} represents the maximum amount of adsorbate that can be adsorbed to form a monolayer. It is the saturation point of the adsorption process where the slope K_J indicates the adsorption affinity between the adsorbate and the adsorbent. The value of the Jovanovic constant (K_J) signifies strong adsorption.

Table 6. Values of maximum monolayer adsorption capacity and Jovanovich adsorption isotherm constant for Chrysoidine R uptake by Hen Feathers at different temperatures.

Parameters	Temperature		
	303 K	313 K	323 K
$q_{max} \times 10^{-4}$	5.63	6.85	4.62
$K_J \times 10^5$	1.09	1.04	3.46
R^2	0.9917	0.9837	0.9953

3.3. Adsorption Thermodynamics

On the basis of Langmuir adsorption constant (b), various thermodynamic parameters have been calculated, offering a detailed understanding of the adsorption system's behavior for the ongoing adsorption. These thermodynamic parameters are changes in Gibbs free energy (ΔG), Enthalpy (ΔH), and Entropy (ΔS) and are determined using the following mathematical expressions [39]:

$$\Delta G^o = -RT \ln b \tag{7}$$

$$\Delta H^o = -R\left(\frac{T_2 T_1}{T_2 - T_1}\right) \times \ln\left(\frac{b_2}{b_1}\right) \tag{8}$$

$$\Delta S^o = \frac{(\Delta H^o - \Delta G^o)}{T} \tag{9}$$

where, b_1 and b_2 are the Langmuir constants at temperature T_1 (K) and T_2 (K), respectively and R is the universal gas constant and its value is 8.314 $JK^{-1} \cdot mol^{-1}$.

The nature of adsorption can be determined by using these thermodynamic quantities calculated from the above relations. A negative value of Gibbs free energy change ΔG indicates a feasible and spontaneous process, whereas a positive value of ΔG indicates a non-feasible process. The insight of heat of absorption by the system is gained by the values of enthalpies. An exergonic process has a negative value of ΔH, which indicates that heat is released during the process. While on the other hand, a positive value of ΔH confirms heat absorption by the system, exhibiting that the nature of the process is endergonic. The third relation ΔS decides the affinity between the adsorbate and the adsorbent. A positive value of ΔS indicates that the affinity of the adsorbate towards the adsorbent is strong and adsorption occurs with increased disorder at the solid solution junction in the adsorption system, while on the other hand a negative value of ΔS indicates a weak affinity between adsorbate and adsorbent. Therefore, interpretation of the thermodynamic data helps to determine the feasibility, spontaneity, heat flow of the adsorption process.

The values of Langmuir constant 'b' derived from the Langmuir adsorption isotherm at different temperatures were substituted into Equations (7)–(9) to calculate the values of ΔG, ΔH and ΔS, respectively (Table 7).

Table 7. Thermodynamic parameters for the uptake of Chrysoidine R by Hen Feathers at different temperatures.

Parameters	Temperature		
	303 K	313 K	323 K
−ΔG (kJ/mol)	32.18	32.09	29.75
ΔH (kJ/mol)	2.85	78.15	39.30
ΔS (J/K/mol)	96.79	147.13	213.77

Feasibility and spontaneity of a reaction are essential considerations. In this case, the values of ΔG are negative at all the temperatures, which indicates that the process is readily achievable and the adsorption of Chrysoidine R on Hen Feather is feasible. Additionally, the enthalpy change (ΔH) reveals the nature of the heat flow involved in the process. The positive values of the ΔH at the temperatures indicate that the adsorption of the dye is endothermic, indicating that heat is required the absorption of heat to proceed effectively. Thus, the adsorption of Chrysoidine R onto Hen Feathers requires heat to enhance the adsorption efficiency.

3.4. Adsorption Favorability

Weber and Chakravorty [40] introduced a practical use of the Langmuir constant for calculating the separation factor (r), a dimensionless parameter that indicates the favorability of a reaction. This factor can be derived from the Langmuir model through the following equation:

$$r = \frac{1}{1 + bC_o} \quad (10)$$

Values below unity are desirable for the favorability of a process, whereas the condition r > 1, an unfavorable process, r = 1 shows linearity and r = 0 shows irreversibility. Therefore, the condition $0 \leq r \leq 1$ refers to the favorable process. In the present case values of the constant 'r' as calculated by values of b at different temperatures are positive and less than unity (Table 8), thereby indicating that the adsorption of Chrysoidine R onto Hen Feathers favorable.

Table 8. Separation factor (r) for the adsorption of Chrysoidine R by Hen Feathers at different temperatures.

Parameters	Temperature		
	303 K	313 K	323 K
r	0.03	0.03	0.08

4. Conclusions

Based on the results presented above it can be safely concluded that the Hen Feathers can be used as an effective adsorbent for the removal of the dye Chrysoidine R from its aqueous solution. Due to the carcinogenic and toxic nature of the azo dye Chrysoidine R, its removal from wastewater becomes very important. Several techniques have been used to remove the azo dye from the wastewater but adsorption is one of the most effective techniques among them. The adsorption of the cationic dye—Chrysoidine R onto Hen Feathers occurs optimally in the acidic medium at pH 4.0. The initial dye solution concentration of 7.5×10^{-5} M for Chrysoidine R has been determined to be optimum for its adsorption onto Hen Feathers. As the amount of Hen Feather adsorbent increases, adsorption of the dye also increases and the maximum adsorption is obtained for a Hen Feather amount of 0.34 g. The adsorption efficiency for Chrysoidine R onto Hen Feathers increases with increasing temperature. At 303 K, maximum 96.08% removal of the azo dye Chrysoidine R is obtained after a 30-min contact period. On the basis of adsorption isotherm models, it can be interpreted that Chrysoidine R forms a homogeneous unimolecular layer over the Hen Feather and the further accumulation of molecules gives rise to multilayer formation. The adsorption isotherm studies further reveal that the adsorption process is favorable, feasible, spontaneous and endothermic in nature. It is also established that Chrysoidine R adsorbs onto Hen Feathers through physisorption. Thus, it can be safely concluded that Hen Feather is an excellent scavenger for removing the azo dye Chrysoidine R from its aqueous solution.

Author Contributions

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Conflicts of Interest

The authors declare no conflict of interest.

Use of AI and AI-Assisted Technologies

No AI tools were utilized for this paper.

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