

REMEDIATION OF CONGO RED FROM AQUEOUS MEDIA USING A HYBRID HYDROGEL ADSORBENT

Saqib Ahmad¹  0009-0001-0104-1897, Amir Hamza¹  0000-0003-2360-5494,
Azmat Ullah¹  0000-0001-9377-0191, Muhammad Zahoor²  0000-0003-0309-9758,
Riaz Ullah³  0000-0002-2860-467X, Essam A. Ali³  0000-0003-2503-6854,
Muhammad Naveed Umar⁴  0000-0001-5783-6608

¹ Government Degree College, Mingora, Swat, KPK, Pakistan

² University of Malakand, Dir Lower, Pakistan

³ College of Pharmacy, King Saud University, Riyadh, Saudi Arabia

⁴ University of Liverpool, UK

ABSTRACT

Aim of the study

In this paper the research was described, in which a hybrid hydrogel had been prepared, characterized by various instrumental techniques, and used as effective adsorbent for the removal of Congo Red dye (CRd) from an aqueous solution.

Material and methods

The hydrogel was prepared using sodium polyacrylate and clay as raw materials. A batch adsorption approach was employed to evaluate the effects of pH, contact time, initial CRd concentration, adsorbent dosage, and temperature on the adsorption.

Results and conclusions

To gain insight into the adsorption mechanism, kinetic studies were performed. The pseudo second-order model best fit the experimental data, with regression coefficient close to 1. Among the applied isotherm models – Langmuir, Freundlich, and Temkin – the Langmuir isotherm model provided the best fit for the equilibrium data, with the correlation coefficient close to unity (0.989). Thermodynamic analysis, considering enthalpy (ΔH°), Gibbs free energy (ΔG°) and entropy (ΔS°), has indicated that the adsorption process is exothermic, spontaneous, and feasible, with increase in randomness at the solid-solution interface. The adsorbent is effective in removal of selected dye from water and could serve as the best alternative to activated carbon. Further experiments are recommended to validate these results.

Keywords: adsorption, adsorption isotherm, Congo Red, dye removal, feasibility, hybrid hydrogel, spontaneity, thermodynamics, wastewater treatment

✉ e-mail: mohammadzahoorus@yahoo.com

INTRODUCTION

Various chemical industries, such as the leather, textiles, cosmetics, plastics, paper industry, pharmaceuticals, printing, and food sectors, utilizes more than 10,000 distinct dyes and pigments to make attractive products (Thakur et al., 2016). These pigments are used throughout the world, with an estimated annual consumption of approximately 700,000 tons (Dash, 2010). During the dyeing process, less than 100% of the dye adheres to the desired material, and approximately 15% of these dyestuffs end up as contaminants in wastewater (Kayranli, 2011). This leads to serious water pollution issues, which are exacerbated by the addition of other pollutants from domestic and industrial wastewaters, and has even become a critical global problem in the last few decades. Since water is a basic human need, its pollution poses a severe public health concern (Ghaly et al., 2014). There have been several attempts around the world to address water pollution caused by dyestuffs, but none of the reported technologies are 100% efficient.

Organic synthetic dyes are chemicals that have been used extensively in coloring variety of industrial products. They are known to be harmful to aquatic organism due to their interference with aquatic plant photosynthesis, and therefore they lower the oxygen levels in deep waters, with some of them showing carcinogenic effects (Ikram et al., 2021). The primary impacts of industrial dye effluent occur within the receiving water bodies like seas, rivers, lakes, natural ponds, and streams. It can spread over great distance and can negatively affect various types of aquatic life and even whole ecosystems (Donkadokula et al., 2020). The presence of these contaminants in the aquatic ecosystem leads to slowing down photosynthesis rate in the aquatic plants, diminishes the biodegradability power of aerobic microorganisms, and disturbs the food chain (Imran et al., 2015; Sakib et al., 2019). The contamination from dyestuffs can also modify the physical and chemical properties of soil, posing a threat to plant and animal life in a given ecosystem (Manu and Chaudhari, 2003; Hassaan and El Nemr, 2017; Hassaan, et al., 2017). It was noted that the noxious properties of dyes result in the mortality of soil microorganisms, impacting the agricultural yield (Savin and Butnaru, 2008). Human health is severely

affected by dyes. Malachite green, dye used in various industries, affects the reproductive and immune systems of human beings and is highly cytotoxic, genotoxic, carcinogenic, and teratogenic (Srivastava et al., 2004). Rhodamine B is genotoxic, carcinogenic, and neurotoxic, causing subcutaneous tissue-borne sarcoma, and irritation to the eyes, skin, and respiratory tract (Jain et al., 2007; Singh et al., 2017). Crystal violet, used as a biological stain and feed supplement, can cause skin, respiratory, gastrointestinal irritation, and renal failure (Kumar and Ahmad, 2011; Blanco-Flores et al., 2014). Brilliant green is carcinogenic and mutagenic to humans and aquatic life (Kumar et al., 2012). Azo dyes, used in multiple industries, are mutagenic, carcinogenic, and genotoxic, causing bladder cancer, hepatic carcinomas, and chromosomal abnormalities in workers (Puvaneswari et al., 2006; Yadav et al., 2021). Methyl orange is mutagenic, and also harmful to aquatic life (Tan et al., 2016).

Wastewaters contaminated by dyes are usually treated with a variety of chemical and physical methods. These methods include flocculation, electro-flocculation, precipitation, electrokinetic coagulation, ion exchange, membrane processes, irradiation, and ozonation. However, the mentioned methods are too expensive for small-scale industries to treat various types of contamination effectively (Mall et al., 2005). The adsorption method is a compelling alternative solution for treating contaminated water, particularly when the adsorbent material is cost-effective and require no additional methods of pretreatment (Janoš et al., 2003). Adsorption is considered as a superior process because it is an easy to operate and relatively inexpensive process (Eren and Afsin, 2008). Due to high surface area, low-density, three-dimensional structure with multiple functional groups and swelling behavior, hydrogels are more extensively studied adsorbents these days. As with every scientific procedure, research on these hydrogels also suffers from a number of drawbacks. Therefore, such a versatile material is tested in hybrid manner along with adsorbents that are already in use. Following the idea herein, an attempt has been made to produce a hybrid adsorbent with clay, which to our best knowledge has not been used as adsorbent for the selected dye.

In the present study, a hybrid hydrogel adsorbent was prepared and utilized for the elimination of CRD

from aqueous solutions. For the optimization of the adsorption process various parameters were thoroughly examined, such as the initial CRd concentration, the contact time, and pH of the solution. Kinetics, isotherms, and thermodynamics of the process of adsorption was also been studied to understand the mechanism of the adsorption of CRd onto hybrid hydrogel.

MATERIAL AND METHOD

Reagents

All chemicals used were of analytical grade. Sigma-Aldrich provided hydrochloric acid (HCl), sodium hydroxide (NaOH), and Congo Red dye (CRd) while sodium polyacrylate was purchased locally from the market in Mingora, Swat and clay was collected from Gujranwala, Pakistan.

Preparation of adsorbent

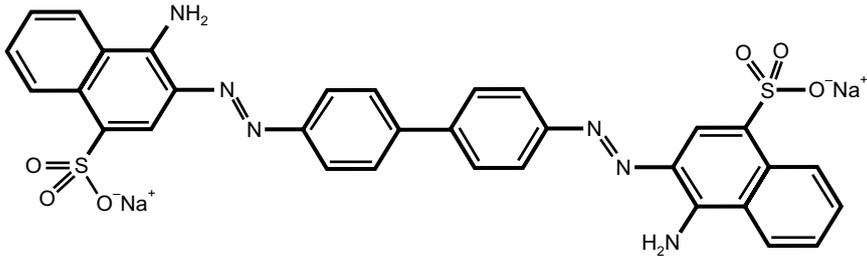
The required amount of clay was collected from Gujranwala, and it was ensured that it was free from impurities, any debris or organic matter. The clay was grounded using a mortar and pestle to form a fine powder and then passed through a mesh so that larger sized particles get separated. Sodium hydroxide solu-

tion was prepared by dissolving a specific mass of NaOH in distilled water. Sodium hydroxide solution was then added slowly from the burette to the clay. The mixture was continuously stirred in order to neutralize the acidic components in the clay. After mixing the clay and NaOH solution, the mixture obtained was subjected to filtration and washed thoroughly with distilled water. The washing was done several times until a neutral pH was reached. After neutralization, the clay was oven-dried for 12 h at a temperature of 80–100°C till complete dryness, then cooled to room temperature and kept in sealed bottle. About 5 g (each) of the sodium polyacrylate and clay composite were mixed together with distilled water and the mixture was stirred until it became homogeneous. The homogenous mixture was then oven dried at 80°C for 12 h. The dried sample was then cooled and stored in an air tight glass vessel.

Preparation of Congo Red dye stock solution

About 500 mg/L stock solution of Congo Red was prepared by dissolving 0.05 g of the dye in distilled water. Working solutions were then prepared from this stock solution applying dilution formula. The physicochemical properties of selected dye are listed in Table 1.

Table 1. Properties of Congo Red dye (source: Authors' own elaboration)

Chemical structure	
Molecular formula	$C_{32}H_{22}N_6Na_2O_6S_2$
Molar mass	696.66 g/mol
Water solubility	soluble
Odor	odorless
λ_{max}	497 nm
pKa	4.1 (at 25°C)
pH	6.7 (at 20°C)

Estimation of surface area

A specified amount of fabricated hydrogel (1.35 g) was added with 30 mL of distilled water, then acidified with HCl until pH 3 was reached, with final volume adjusted to 135 mL. Now 30 g of NaCl was added and stirred vigorously until the complete dissolution of salt. The pH was then brought to 4. From 4 the pH was then raised to 9 by adding NaOH solution, and from the added NaOH the volume (V) surface area was estimated using following relation. The estimated surface area was 21.45 m²/g.

$$A = 32V - 25 \quad (1)$$

Batch adsorption experiments

In batch experimental studies, 0.5 g of hybrid hydrogel was added to the known concentration of CRd, i.e. from 10 to 80 mg/L at room temperature in a glass reagent bottle. For the optimization of pH, an initial concentration of CRd 50 mg/L was added to the 0.5 g of the hybrid hydrogel in a glass reagent bottles, and pH was adjusted from pH 2 to 10. The mixture was stirred for 30 min using a magnetic stirrer. The mixture was then filtered using Whatman filter paper. The residual concentration of the CRd was measured using a double beam UV spectrophotometer at 497 nm. The following equations were used to calculate the percent removal (% R) of CRd and the adsorption capacity of hybrid hydrogel:

$$\% R = \frac{C_i - C_f}{C_i} \times 100 \quad (2)$$

$$q_e = \frac{(C_o - C_e)V}{W} \quad (3)$$

$$q_t = \frac{(C_o - C_t)V}{W} \quad (4)$$

Where C_i (mg/L) represents the initial concentration of CRd, and C_f (mg/L) indicates its final concentration, C_o , C_e and C_t in mg/L refer to the initial CRd concentration, equilibrium concentration and concentration of the CRd at time t , respectively. Then, q_e and q_t are the amount of CRd adsorbed at optimum time and time t . V (L) is the volume of the CRd solution, whereas W (g) is the mass of an adsorbent.

Isotherm studies

For isotherm studies, 0.5 g of the adsorbent was added into a glass reagent bottles containing initial concentrations of CRd 10 to 80 mg/L. The mixture was stirred using a magnetic stirrer and filtered. Various isotherm models i.e. Langmuir, Freundlich, and Temkin were applied to the sorption isotherm data to estimate different adsorption parameters including adsorption capacity.

Kinetic studies

Adsorption kinetics were studied over a time interval of 10–60 min. For each experiment, 0.5 g of adsorbent was added to a glass reagent bottle containing 100 mg/L of CRd solution. The mixture was stirred using a magnetic stirrer. Various kinetic models were applied to the adsorption kinetic data in order to know the nature of the adsorption process.

Thermodynamic studies

For the thermodynamic evaluation, 0.5 g of the hybrid hydrogel was added as an adsorbent to glass reagent bottles containing an initial CRd concentration of 100 mg/L. The thermodynamic studies were carried out at 20, 40, and 60°C. The mixture was stirred for a period of 30 min, with further details as mentioned.

RESULTS AND DISCUSSION

Effect of initial CRd concentration

The impact of the initial CRd concentration on the process of adsorption was studied with CRd concentrations ranging from 10 to 80 mg/L at room temperature, as shown in Figure 1. With an increase in the initial CRd concentration (C_o), there is a gradual increase in the rate of adsorption (q), while the maximal efficacy was observed at around 50 mg/L. Beyond this point, the rate of adsorption (q) begins to slow down, which indicates that surface saturation is reached at 50–60 mg/L. This trend indicates that as the initial concentration of CRd increases, the active sites on the adsorbent become saturated, bringing the adsorbent closer to its maximum capacity, where it can no longer effectively adsorb additional CRd molecules. Initially, higher rate of adsorption is caused by more active sites on the surface of hybrid hydro-

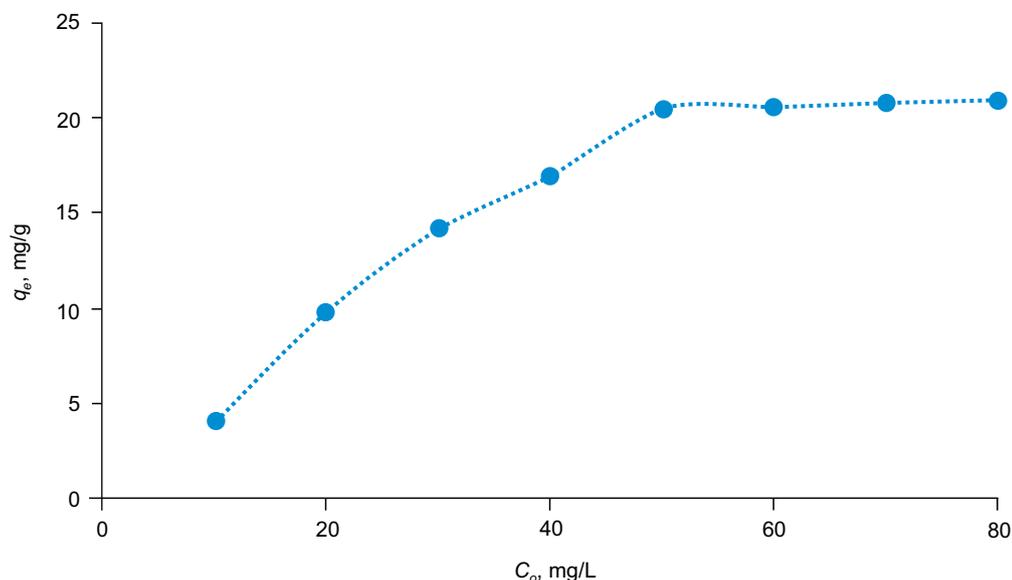


Fig. 1. Effect of initial CRd concentration (source: Authors' own elaboration)

gel. Once the available sites are fully occupied, the rate of adsorption stabilizes and assumes a plateau shape indicating that the adsorbent has reached its full capacity.

The data obtained on the effect of concentration after the removal of CRd were thoroughly analyzed using the Langmuir, Freundlich, and Temkin isotherms models.

The Langmuir isotherm model is applicable in the case of adsorption in a monolayer on an adsorbent surface containing uniform sites in a limited number. Its linear form is expressed as follows (Crini, 2008):

$$\frac{C_e}{q_e} = \frac{C_e}{C_m} + \frac{1}{K_L C_m} \quad (5)$$

Where C_e (mg/L) denotes the concentration of dye at equilibrium, while q_e (mg/g) is the amount of CRd adsorbed onto hydrogel at equilibrium. The constant C_m (mg/g) indicates the adsorption capacity in this equation and K_L is associated with the binding sites affinity for the adsorbate. To calculate the values of K_L and C_m , C_e/q_e was against versus C_e , and the values of these constants were obtained from the slope and intercept of the resulting plot (Fig. 2).

The Freundlich isotherm model is based on an empirical equation, usually used for and effective in

describing adsorption on heterogeneous surfaces and is widely used for analyzing the adsorption processes. Considering its linear equation form, it can be given as (Unuabonah et al., 2008):

$$\ln q_e = \ln K_F + \frac{1}{n} \ln C_e \quad (6)$$

Where C_e (mg/L) represents the CRd concentration of solution at equilibrium, $1/n$ represents the heterogeneity factor, and K_F denoted the Freundlich constant, indicating the adsorption capacity. To determine values of n and K_F , it would be necessary to examine intercept and slope of $\ln C_e$ against $\ln q_e$ plot as shown in Figure 3.

Temkin and Pyzhev (Crini and Peindy, 2006) have studied the impact of indirect interactions between the molecules of adsorbate that influences the adsorption processes, suggesting that as coverage increases, the adsorption heat tends to decrease in a linear manner. The isotherm equation for the Temkin model can be given as:

$$q_e = B \ln K_T + B \ln C_e \quad (7)$$

Where $B = \frac{RT}{b}$ the constant B is associated with the adsorption heat, while K_T (L/mg) is the constant

for the equilibrium which indicates the maximum binding energy, and C_e (mg/L) stands for the concentration at equilibrium of the CRd solution. The constants K_T and B were determined utilizing a linear plot of q_e against $\ln C_e$ as shown in Figure 4.

The different isotherm values in Table 2 make it clear that the Langmuir adsorption isotherm model is best fitting the isotherm data in comparison to the Freundlich and Tempkin isotherm models. The R^2 value for Langmuir isotherm model approximates unity (0.989).

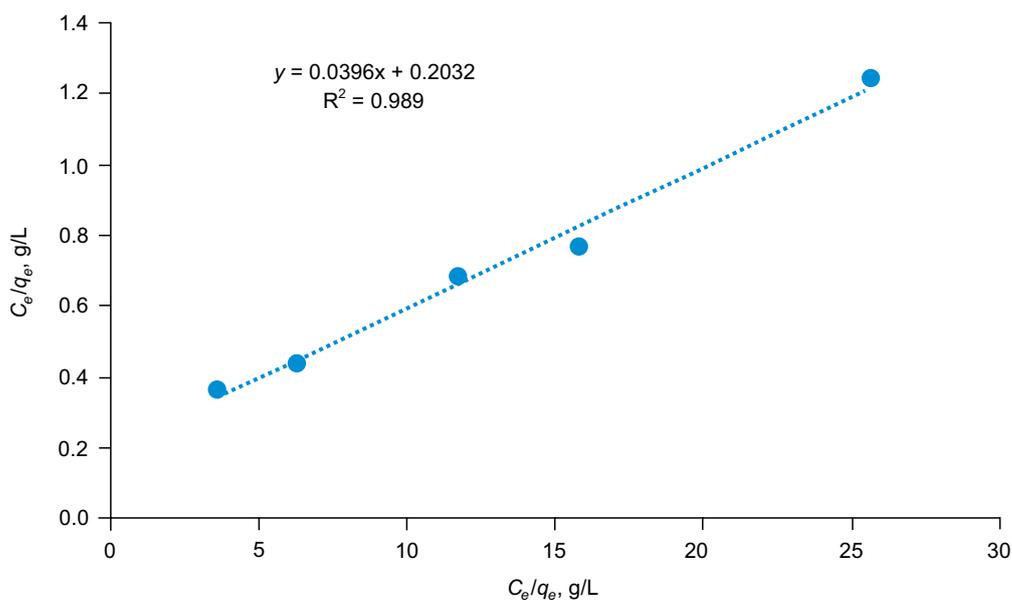


Fig. 2. Langmuir isotherm model plot for CRd on hybrid hydrogel (source: Authors' own elaboration)

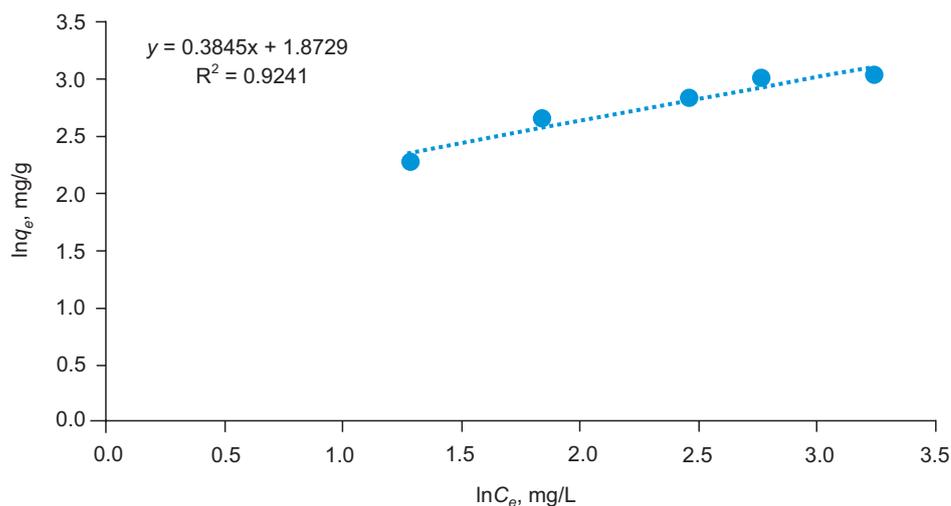


Fig. 3. Freundlich isotherm model plot for the adsorption of CRd (source: Authors' own elaboration)

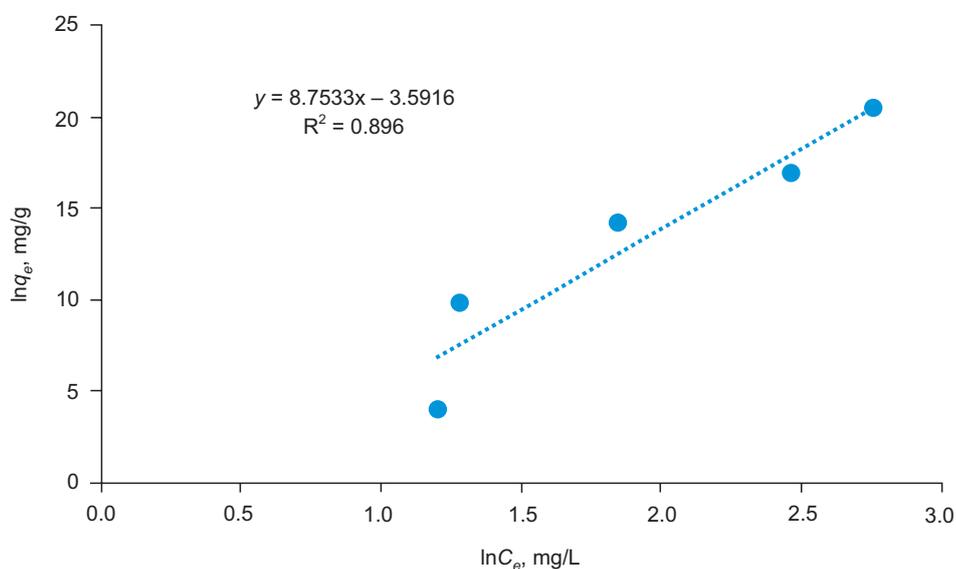


Fig. 4. Temkin isotherm model plot for the adsorption of CRd on prepared adsorbent (source: Authors' own elaboration)

Table 2. Isotherm models parameters for the adsorption of CRd on hybrid hydrogel (source: Authors' own elaboration)

Isotherm model	Parameter	R ²
Langmuir	K_L [L/mg] = 1	0.989
	q_m [mg/g] = 25.25	
Freundlich	K_F [L/mg] = 6.5	0.9241
	$1/n$ = 0.0385	
Tempkin	K_T [L/mg] = 1.51	0.896
	B = 8.75	

Effect of contact time

The effect of contact time was studied at different time intervals up to 60-minute timeframe. Figure 5 shows the effect of contact time on the removal of CRd at the surface of hybrid hydrogel. The plot shows that initially the rate of adsorption is fast in the 20 to 25 minute interval. After this period the rate of adsorption slows down. Around one hour complete surface saturation of hybrid hydrogel with dye has taken place. So, 20-minute timeframe was selected as the optimum for all experimental studies. Beyond this point, no significant changes in adsorption were observed. The rapidity in the initial rate of adsorption can be explained by the

abundant availability of adsorptive sites, which became gradually occupied by CRd molecules as time passes. Once these sites became saturated, the adsorption of CRd remained constant.

Various kinetic models were applied to the adsorption kinetic data. The pseudo first order (PFO) kinetic model can be represented mathematically by the following equation (Yavuz et al., 2003).

$$\ln(q_e - q_t) = \ln q_e - K_1 t \quad (8)$$

In this equation, q_t and q_e (mg/g) are used to represent the amount of CRd adsorbed on the hydrogel at a given time t and the adsorbed amount when equi-

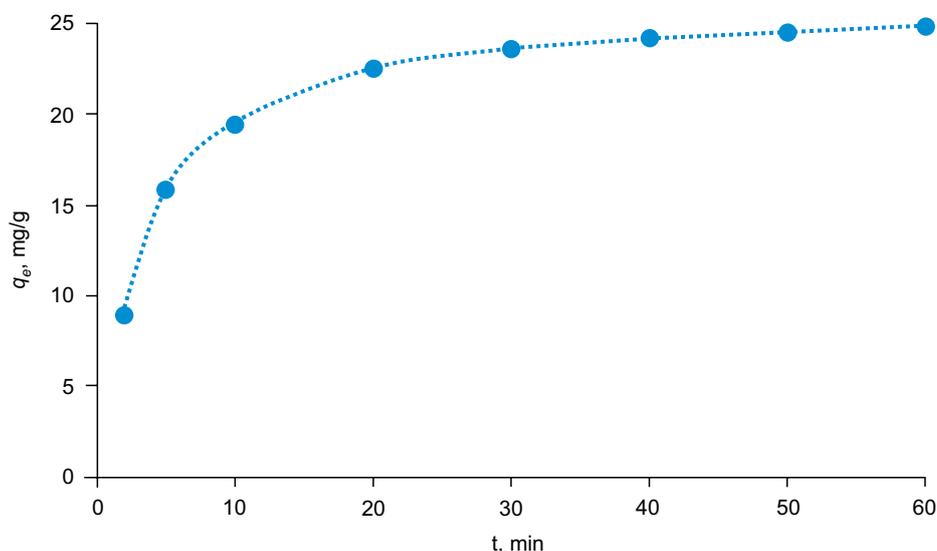


Fig. 5. Effect of contact time on the adsorption of CRd on hybrid hydrogel (source: Authors' own elaboration)

librium is reached, respectively. K_1 (1/min) stands for the rate constant of the model, and t (min.) is the contact time between the adsorbent and CRd. A plot of $\ln(q_e - q_t)$ against t (Fig. 6) was used to estimate the values of constant and regression coefficient.

The linear form of the pseudo-second-order kinetic model can be expressed by the given mathematical equation (Ho and McKay, 2000) as:

$$\frac{t}{q_t} = \frac{1}{K_2 q_e^2} + \frac{t}{q_e} \quad (9)$$

In this equation, K_2 (g/mg.min) represents the rate constant for the pseudo-second-order kinetic model. To obtain the values of both K_2 and q_e , t/q_t was plotted against t , the values of the slope and intercept of the plot (Fig. 7).

The intra-particle diffusion model (Selen et al., 2016) may be represented in a linear fashion as:

$$q_t = K_{id} t^{1/2} + C \quad (10)$$

Here, K_{id} (mg/g min^{1/2}) represents the intra-particle diffusion rate constant, while constant C is indicating the thickness of the boundary layer. The value of K_{id}

and C can be obtained when $t^{1/2}$ is plotted against q_t (Fig. 8), the slope and the intercept of plot are used to calculate these parameters.

The kinetic parameters calculated from various models are presented in Table 3. From the Figures 6, 7 and 8, it is clear that the pseudo-second-order kinetic model fits the experimental data better than the pseudo-first-order kinetic model because the R^2 is higher in the case of pseudo=second-order kinetic model. The intraparticle diffusion kinetic model was used to understand the mechanism of adsorption. From the shape of the curve, more specifically the multilinearity of the curve it can be inferred that two or more than two steps are involved in the adsorption. Film diffusion and intraparticle diffusion are the predominant steps which is also evident from the trend line, which does not pass through the origin indicating that that intraparticle diffusion is not the only rate-limiting step.

Similarly, the calculated value of q_e with the help of the pseudo-second-order kinetic model was found to be very close to the experimental value of q_e . It means that this model fits more accurately the data of the adsorption of CRd on the hybrid hydrogel.

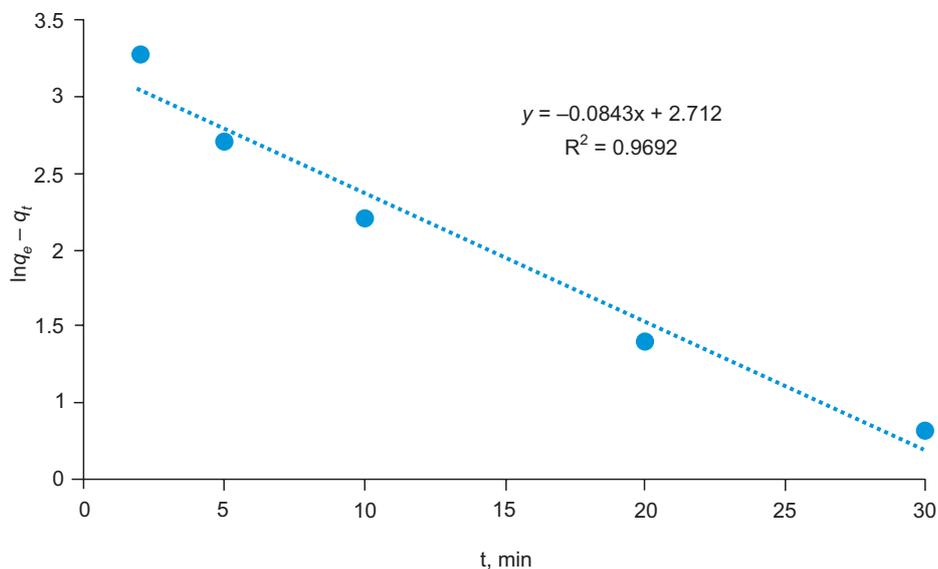


Fig. 6. Pseudo-first-order kinetic model plot for adsorption of CRd on hybrid hydrogel (source: Authors' own elaboration)

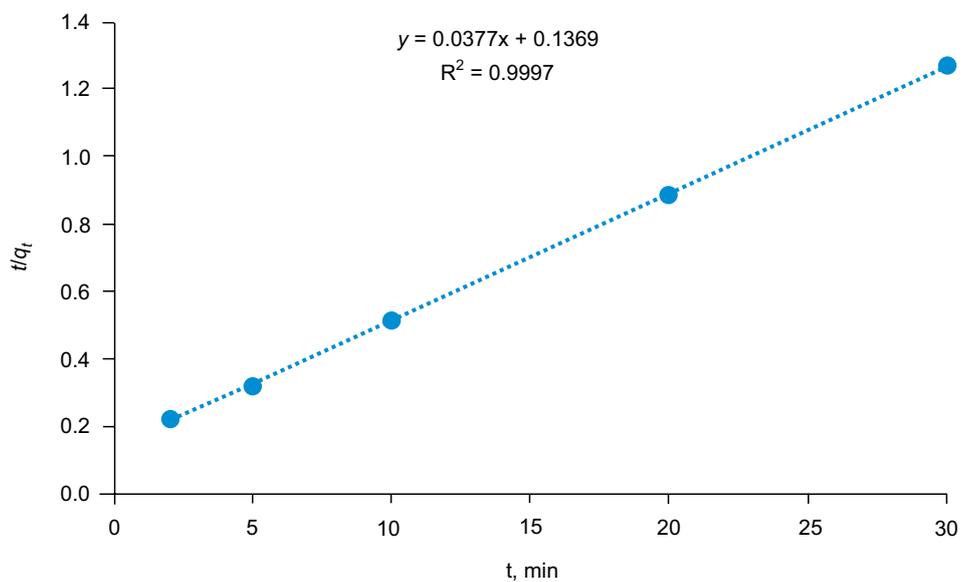


Fig. 7. Pseudo-second-order kinetic model plot for adsorption of CRd on hybrid hydrogel (source: Authors' own elaboration)

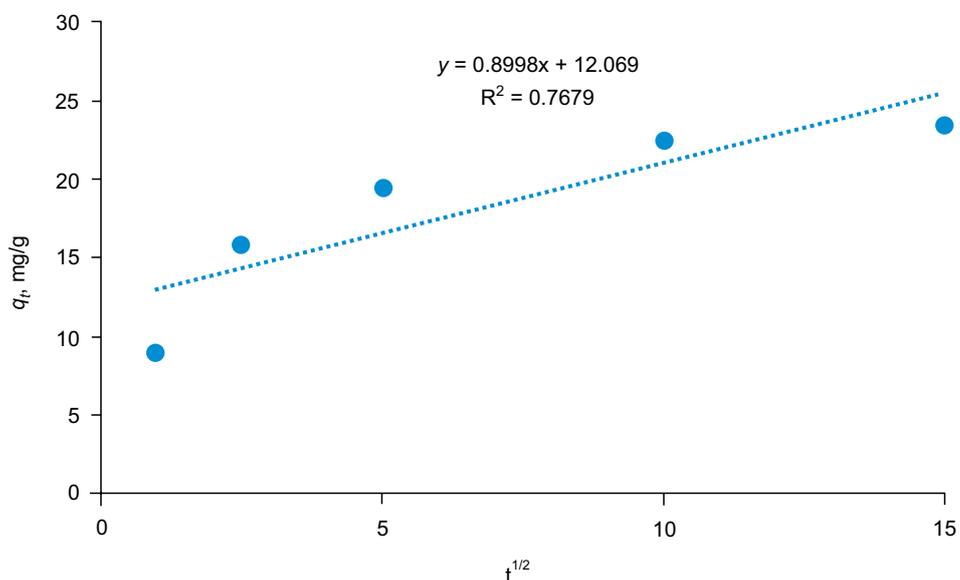


Fig. 8. Plot of the intra-particle diffusion model for adsorption of CRd on hybrid hydrogel (source: Authors' own elaboration)

Table 3. Parameters of kinetic models for the adsorption of CRd on hybrid hydrogel (source: Authors' own elaboration)

Kinetic model	Parameters	CRd	R^2
Pseudo-first-order	K_1 [1/min]	0.0843	0.9692
	q_e [mg/g]	15.06	
Pseudo-second-order	K_2 [g/mg min]	5139.4	0.9997
	q_e [mg/g]	26.53	
Intra particle diffusion	K_{id} [mg/g min ^{1/2}]	0.8998	0.7679
	C	12.07	

Effect of pH

Figure 9 shows the effect of pH on the removal of CRd by the prepared hydrogel. The effect of pH on the removal of CRd by the hybrid hydrogel was studied in the range of pH 2 to 10. The pH of the solution was adjusted using 1.0 N HCl and 1.0 N NaOH. The plot makes it clear that as pH increases from 2 to 6, the rate of adsorption increases too. Above this threshold of pH, the rate of adsorption of CRd decreases to pH 10. Therefore, pH 6 was taken as optimum pH for all experimental studies.

Between pH 2–5 CRd exists as the cation CRd^+ , when pH increases, the cationic form of CRd decreases

and CRd converts to CRd^{z-} (zwitter ion) in solution. When the pH of the solution becomes alkaline, or near alkaline, there is a steady decrease in CRd removal, as the anionic form of CRd (CRd^-) dominates. The factor for highest removal of CRd at highly acidic pH may be due to cationic exchange.

Thermodynamic studies

Thermodynamic study was conducted to clarify the energy changes during the adsorption process in order to define feasibility and characteristics of the adsorption process. To assess the thermodynamic parameters for CRd adsorption, a series of batch experi-

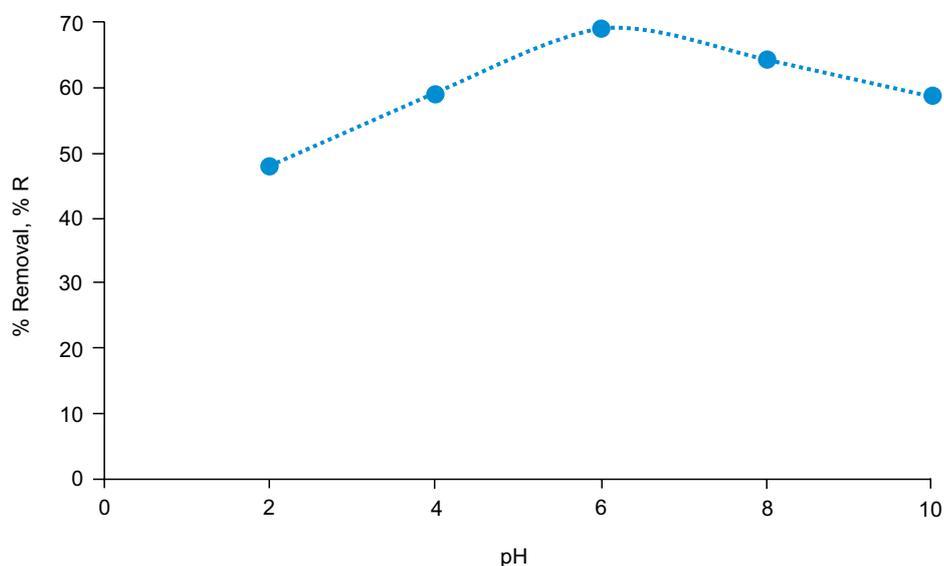


Fig. 9. Effect of pH on the sorption of CRd on hybrid hydrogel (source: Authors' own elaboration)

ments were performed at three different temperatures. These adsorption isotherm data at various temperature were used for the determination of fundamental thermodynamic parameters, like ΔG° , ΔH° , and ΔS° , using the following equations (Purkait et al., 2005; Srihari and Das, 2008; Venkatesha et al., 2012):

$$\ln KL = \frac{\Delta S^\circ}{R} - \frac{\Delta H^\circ}{RT} \quad (11)$$

$$\Delta G^\circ = -RT \ln KL \quad (12)$$

$$\Delta S^\circ = \Delta H - \frac{\Delta G^\circ}{T} \quad (13)$$

Where R represent the universal gas constant, which has a value of $8.314 \text{ J/mol} \cdot \text{K}$. K_L refers to the equilibrium constant (ratio of adsorbent amount to solution amount), and $T (K)$ denotes the temperature.

The $\ln K_L$ against $1/T$ plot is linear – this enables the determination of enthalpy change (ΔH°) and en-

tropy change (ΔS°) using intercept and the slope of the plot (Figure 10), respectively. These values are listed in Table 4. The thermodynamic analysis of adsorption of CRd on the hybrid hydrogel reveals that the process is spontaneous because the values of Gibbs free energy (ΔG°) are negative (Ullah et al., 2024). Generally, the Gibbs free energy for the process of physisorption lies within the range of 0 to -20 kJ/mol , while for chemisorption, the change in Gibbs free energy is much higher, falling usually between -80 and -400 kJ/mol (Li et al., 2010). The values of ΔG° presented in Table 4, ranging from 0 to -20 kJ/mol , suggest that the primary mechanism involved in CRd removal is physisorption. Based on the values of ΔH° , which are found negative, the process is exothermic (Iqbal and Ashiq, 2007). The positive entropy (ΔS°) values indicate an increased affinity with a higher degree of freedom and hence increasing in randomness at the sorbent-sorbate interface during the process of adsorption (Doğan et al., 2004).

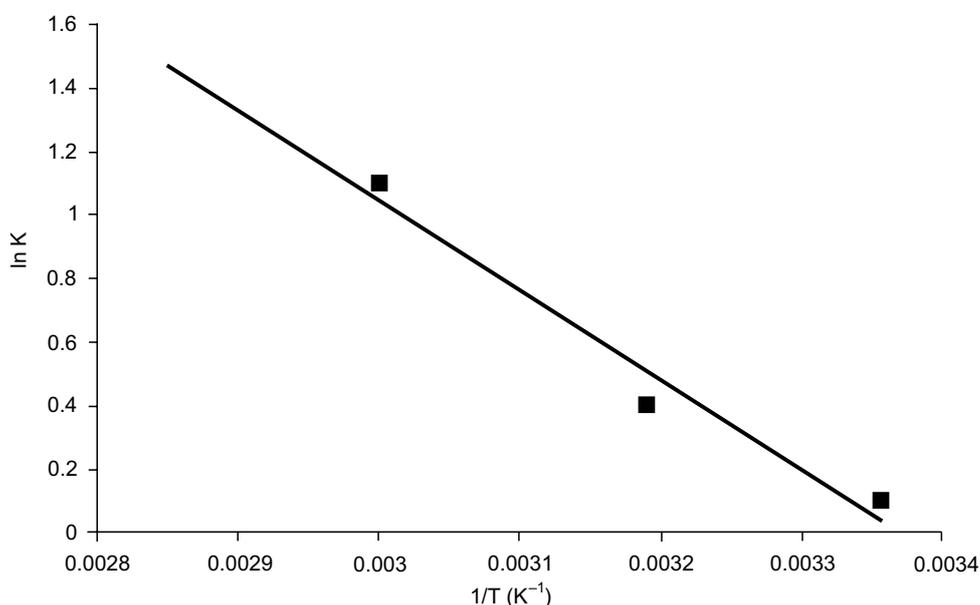


Fig. 10. Vant Hoff plot (source: Authors' own elaboration)

Table 4. Thermodynamic parameters of CRd adsorption on hybrid hydrogel (source: Authors' own elaboration)

Thermodynamic parameters	Temperature [K]		
	293	313	333
ΔG° [kJ/mol]	-3.17	-3.00	-2.77
ΔH° [kJ/mol]	-5.26	-	-
ΔS° [JK ⁻¹ ·mol ⁻¹]	15.73	-	-

CONCLUSION

In this study, a hybrid hydrogel was prepared from clay and sodium polyacrylate. The sorption capacity of the hybrid hydrogel was investigated for the removal of CRd dye from aquatic media. Various kinetic models were employed in linear forms to get the best fit of the data. The kinetic data were well fitted to the linear form of the pseudo-second-order kinetic model. Various isotherm models were also employed to estimate the isotherm parameters. The adsorption isotherm data fitted better to the Langmuir isotherm model than to the Tempkin and Freundlich models. The optimum pH was 6, while the optimum dye con-

centration was 50 mg/L. The thermodynamic studies were carried out at 293, 313 and 333 K, and the results indicate that the adsorption of CRd is feasible and spontaneous due to the negative values of Gibbs free energy (ΔG°). The ΔG° values, ranging from 0 to -20 kJ/mol, indicated that the dominant mechanism behind adsorption was physisorption. ΔH° had a negative value, which confirmed that the process was exothermic, while positive values for the entropy (ΔS°) show increased affinity and increased randomness at the interface between adsorbent and adsorbate. The prepared hybrid hydrogel can be used as alternative to activated carbon and other sorbents.

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USUWANIE CZERWIENI KONGO Z MEDIÓW WODNYCH PRZY UŻYCIU HYBRYDOWEGO ADSORBENTU HYDROŻELOWEGO

ABSTRAKT

Cel pracy

W niniejszej pracy opisano badanie, podczas którego przygotowano hybrydowy hydrożel, a następnie scharakteryzowano go za pomocą różnych technik instrumentalnych i wykorzystano jako skuteczny adsorbent do usuwania czerwonego barwnika Congo (CRd) z roztworu wodnego.

Materiał i metody

Hydrożel został przygotowany przy użyciu poliakrylanu sodu i gliny jako surowców. Zastosowano metodę adsorpcji wsadowej w celu oceny wpływu pH, czasu kontaktu, początkowego stężenia CRd, dawki adsorbentu i temperatury adsorpcji.

Wyniki i wnioski

Aby uzyskać wgląd w mechanizm adsorpcji, przeprowadzono badania kinetyczne. Model pseudodrugiego rzędu jest najlepiej dopasowany do danych eksperymentalnych, ze współczynnikiem regresji bliskim 1. Spośród zastosowanych modeli izoterm – Langmuira, Freundlicha i Temkina – to model izotermi Langmuira zapewnił najlepsze dopasowanie do danych równowagowych, ze współczynnikiem korelacji bliskim jedności (0,989). Analiza termodynamiczna, uwzględniająca entalpię (ΔH°), energię swobodną Gibbsa (ΔG°) i entropię (ΔS°), wykazała, że proces adsorpcji jest egzotermiczny, spontaniczny i możliwy do przeprowadzenia, ze wzrostem losowości na granicy faz ciało stałe–roztwór. Adsorbent jest skuteczny w usuwaniu wybranych barwników z wody i może służyć jako najlepsza alternatywa dla węgla aktywnego. Zaleca się wykonanie dalszych eksperymentów w celu potwierdzenia tych wyników.

Słowa kluczowe: adsorpcja, izoterma adsorpcji, czerwień Kongo, usuwanie barwnika, wykonalność, hydrożel hybrydowy, spontaniczność, termodynamika, oczyszczanie ścieków