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Poly(Acrylic Acid-Co-Acrylamide) Hydrogel-Enabled Removal of Crystal Violet from Water: Adsorption Isotherms, Interaction Mechanisms, and Process Optimization

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ABSTRACT

The present study investigated the adsorption behavior of crystal violet (CV) from aqueous solution using poly(acrylic acid-co-acrylamide) [P(AAc-co-AAm)] hydrogel as an adsorbent. Batch adsorption experiments were conducted at 30°C using different initial CV concentrations to evaluate adsorption kinetics and equilibrium behavior. The hydrogel exhibited rapid CV uptake during the initial contact period, followed by a gradual increase in adsorption until equilibrium was approached, indicating progressive occupation of available adsorption sites. Kinetic analysis was performed using first- and second-order models, while equilibrium data were evaluated using Langmuir, Freundlich, and Temkin isotherms. Among the equilibrium models, the Freundlich isotherm provided the best fit to the experimental data ($R^2 = 0.9631$), followed by the Temkin ($R^2 = 0.9313$) and Langmuir ($R^2 = 0.8988$) models. The Freundlich constant ($K_F = 26.26 \text{ L g}^{-1}$) and adsorption intensity parameter ($n = 1.844$) indicated favorable adsorption of CV onto the hydrogel. The Langmuir model estimated a maximum adsorption capacity of 172.41 mg g^{-1} . Overall, the results demonstrated that P(AAc-co-AAm) hydrogel possesses appreciable adsorption capacity for CV and that its adsorption behavior is predominantly associated with heterogeneous surface sites and variable adsorbate-adsorbent interactions. The findings highlight the potential of P(AAc-co-AAm) hydrogel as an effective polymeric adsorbent for the treatment of dye-contaminated aqueous systems.

Introduction

Water is an indispensable natural resource that sustains human life, agricultural production, industrial development, and ecosystem functioning. However, rapid industrialization, urbanization, and population growth have led to the continuous discharge of contaminants into aquatic environments, resulting in severe deterioration of water quality worldwide. Among various pollutants, synthetic dyes, heavy metals, pharmaceuticals, pesticides, and personal care products are of particular concern due to their persistence, toxicity, and resistance to natural degradation processes (Sharma et al., 2018; Crini & Lichtfouse, 2019).

The textile, paper, leather, printing, cosmetic, and pharmaceutical industries collectively generate large volumes of dye-containing wastewater. It is estimated that approximately 10–15% of synthetic dyes used during manufacturing processes are discharged into aquatic systems, causing aesthetic pollution, reduced light penetration, decreased photosynthetic activity, and adverse effects on aquatic organisms (Yagub et al., 2014). Crystal Violet (CV), a triphenylmethane cationic dye, is extensively used in textile dyeing, biological staining, printing inks, and medical applications. Despite its industrial importance, crystal violet is recognized as a hazardous pollutant because of its mutagenic, carcinogenic, and cytotoxic effects on living organisms. Even at low concentrations, its presence in water can adversely affect aquatic ecosystems and pose potential risks to human health (Salleh et al., 2011; Gupta et al., 2022).

Several physicochemical and biological techniques, including coagulation-flocculation, membrane filtration, advanced oxidation processes, ion exchange, biodegradation, and chemical precipitation, have been employed for dye removal from wastewater. However, these methods often suffer from limitations such as high operational costs, sludge generation, membrane fouling, incomplete pollutant removal, and complex operational requirements (Crini & Lichtfouse, 2019; Ali et al., 2012). Among available treatment technologies, adsorption has emerged as one of the most efficient, economical, and environmentally friendly approaches owing to its simplicity, high removal efficiency, operational flexibility, and potential for adsorbent regeneration (Foo & Hameed, 2010).

In recent years, hydrogels have attracted considerable attention as advanced adsorbent materials for water purification applications. Hydrogels are three-dimensional crosslinked polymeric networks capable of absorbing and retaining substantial quantities of water while maintaining their structural integrity. Their unique characteristics, including high porosity, tunable surface chemistry, large swelling capacity, and abundance of functional groups, make them highly effective for the adsorption of a wide range of contaminants from aqueous media (Ahmed, 2015). The adsorption performance of hydrogels can be further enhanced through the incorporation of functional groups such as carboxyl ($-\text{COOH}$), amino ($-\text{NH}_2$), hydroxyl ($-\text{OH}$), and sulfonic ($-\text{SO}_3\text{H}$) groups, which facilitate pollutant binding through electrostatic attraction, hydrogen bonding, ion exchange, and complexation mechanisms (Chirani et al., 2015).

Both natural and synthetic hydrogels have been extensively investigated for wastewater treatment applications. Natural hydrogels derived from biopolymers such as chitosan, alginate, cellulose, and collagen offer excellent biodegradability and environmental compatibility. However, their practical application is often limited by poor mechanical stability and relatively low chemical resistance. In contrast, synthetic hydrogels based on polyacrylamide, poly(vinyl alcohol), and poly(acrylic acid) exhibit superior mechanical strength, chemical stability, controllable network architecture, and ease of functionalization, making them attractive candidates for large-scale water treatment systems (Ahmed, 2015; Chirani et al., 2015).

Among synthetic hydrogel systems, poly(acrylic acid-co-acrylamide) [P(AAc-co-AAm)] hydrogels have gained increasing interest due to the synergistic contribution of carboxyl and amide functional groups. The carboxylic groups provide negatively charged adsorption sites for cationic pollutants, whereas amide groups enhance hydrophilicity and facilitate hydrogen-bonding interactions. Consequently, these copolymeric hydrogels exhibit excellent swelling characteristics, high adsorption capacities, and favorable reusability for dye remediation applications (Li et al., 2020; Wang et al., 2021).

Although numerous studies have reported the use of hydrogel-based adsorbents for dye removal, many investigations have primarily focused on natural biopolymer hydrogels or single-polymer synthetic systems. Comprehensive studies evaluating the adsorption behavior of crystal violet onto poly(acrylic acid-co-acrylamide) hydrogels remain relatively limited. Furthermore, the influence of hydrogel swelling characteristics on adsorption performance and the applicability of different adsorption isotherm models for describing crystal violet uptake by P(AAc-co-AAm) hydrogels have not been thoroughly investigated. Therefore, there is a need to develop efficient, low-cost, and environmentally sustainable hydrogel adsorbents with high swelling capacity and enhanced affinity toward cationic dyes while elucidating the underlying adsorption mechanisms.

In view of the above considerations, the present study aimed to synthesize an anionic poly(acrylic acid-co-acrylamide) hydrogel through free-radical copolymerization using acrylic acid and acrylamide as monomers, N,N' -methylenebisacrylamide (MBA) as a crosslinking agent, and ammonium persulfate (APS) as an initiator. The synthesized hydrogel was evaluated in terms of its

swelling behavior and adsorption performance for the removal of crystal violet from aqueous solutions. Batch adsorption experiments were conducted at different initial dye concentrations, and the equilibrium data were analyzed using Langmuir, Freundlich, and Temkin adsorption isotherm models to elucidate the adsorption mechanism. The study seeks to provide insights into the potential application of P(AAc-co-AAm) hydrogels as cost-effective, reusable, and environmentally sustainable adsorbents for wastewater treatment.

Materials and Methods

Chemicals and Reagents

Acrylic acid (AAc) and acrylamide (AAm) were used as the primary monomers for hydrogel synthesis. N,N'-Methylenebisacrylamide (MBA) served as the crosslinking agent, while ammonium persulfate (APS) and N,N,N',N'-tetramethylethylenediamine (TEMED) were employed as the free-radical initiator and accelerator, respectively. Crystal Violet (CV) dye was used as the model cationic pollutant in adsorption experiments. All chemicals were of analytical grade and used without further purification. Distilled water was utilized throughout the study for hydrogel synthesis, washing, swelling measurements, and adsorption experiments.

Synthesis of Poly(acrylic acid-co-acrylamide) Hydrogel

Poly(acrylic acid-co-acrylamide) [P(AAc-co-AAm)] hydrogel was synthesized via free-radical copolymerization following the method described by Ahmed (2015) with minor modifications. Briefly, predetermined amounts of acrylic acid (AAc), acrylamide (AAm), and N,N'-methylenebisacrylamide (MBA) were dissolved separately in distilled water until clear homogeneous solutions were obtained. The monomer and crosslinker solutions were subsequently mixed under continuous stirring, followed by the addition of TEMED as an accelerator.

A freshly prepared aqueous solution of ammonium persulfate (APS) was then added to initiate free-radical polymerization. The reaction mixture was thoroughly homogenized and transferred into plastic molds (straws) and allowed to polymerize at ambient temperature (25 ± 2 °C) for 24 h. Following gel formation, the hydrogel cylinders were removed from the molds and cut into small pieces.

To eliminate residual monomers, initiator fragments, and other soluble impurities, the hydrogel samples were washed repeatedly with distilled water for three days, replacing the washing medium every 12 h. The purified hydrogels were then dried in a hot-air oven at 60 °C until constant weight was achieved. The dried samples were stored in airtight containers for subsequent swelling and adsorption studies.

Swelling Study of [p(AAc-co-AAm)] hydrogel

The swelling behavior of the synthesized hydrogel was determined using the gravimetric method (Chirani et al., 2015). A known weight of oven-dried hydrogel (W_d) was immersed in distilled water at room temperature until swelling equilibrium was attained. The swollen hydrogel was removed periodically, surface water was gently blotted using filter paper, and the swollen weight (W_s) was recorded.

Percentage (%) Swelling

We examined how poly(acrylic acid-co-acrylamide) hydrogel swells to understand its ability to absorb distilled water. For this purpose, we first dried the hydrogel samples and then soaked them in distilled water, allowing them to swell up through water absorption. We calculated how much water they took in by weighing the dried and swollen samples at specific time intervals. The percentage of swelling was calculated using this formula:

$$\%SR = \frac{W_s - W_d}{W_d} \times 100$$

Where w_s and w_d is the swollen and dried weights of hydrogel, respectively.

Diffusion of water into hydrogel

The diffusion model used to determine swelling that how much the hydrogel structure expands as water molecules diffuses into hydrogel network, effectively measuring the increase in size. For studying the diffusion of water into hydrogel following model was used;

$$F = S/S_e = k \cdot t^n$$

Where F is the swelling fraction, S is swelling at time t and S_e is swelling at equilibrium. K is constant and depends on the polymeric structure of hydrogel, t is time and n is diffusion exponent of swelling

Kinetics of hydrogel Swelling

To determine whether the swelling behavior of the p(AAc-co-AAm) hydrogel follows first-order or second-order kinetics, swelling kinetic models were applied to the experimental data. First order and second order swelling kinetics were implemented to the swelling data of [p(AAc-co-AAm)] hydrogel. The equation for first order kinetics is as follows;

$$\ln(S_e - S) = -K_1 t + \ln S_e$$

Where s is swelling at time t , S_e is swelling at equilibrium and k is proportionality constant expressed in units of per minute (min^{-1}).

The equation for second order kinetics is as follows;

$$dS/dt = K_2(S_e - S)^2$$

Adsorption study

For the adsorption study an experiment was conducted in which Crystal Violet, a cationic dye was adsorbed onto [p(AAc-co-AAm)] hydrogel. Adsorption experiments were conducted in batch mode to evaluate the removal efficiency of crystal violet from aqueous solutions. A fixed amount of hydrogel (0.09 g) was added to dye solutions of varying initial concentrations (80, 100, 120, 140, and 160 mg L^{-1}) prepared in distilled water.

The mixtures were agitated at room temperature until adsorption equilibrium was reached. After equilibration, the hydrogel was separated from the solution, and the residual dye concentration was determined spectrophotometrically using a UV-Visible spectrophotometer at the maximum absorption wavelength ($\lambda_{\text{max}} = 590 \text{ nm}$) of crystal violet (Yagub et al., 2014).

Adsorption isotherms

To understand this mechanism various adsorption, isotherms like Langmuir, Freundlich, and Temkin isotherms were used.

Langmuir adsorption isotherm

The Langmuir model assumes monolayer adsorption on a homogeneous surface containing finite identical adsorption sites (Langmuir, 1918):

$$\frac{C_e}{q_e} = \frac{C_e}{q_m} + \frac{1}{q_m K_L}$$

The symbol q_e is the quantity of crystal violet adsorbed per unit mass of adsorbent at the equilibrium stage. C_e represents the equilibrium concentration of crystal violet. q_m indicates the maximum adsorption capacity of the P(AAc-co-AAm) Hydrogel. K_L is the Langmuir adsorption constant determined from the intercept of the graph equation.

Freundlich adsorption isotherm

The Freundlich model describes multilayer adsorption on heterogeneous surfaces (Freundlich, 1906):

$$\ln q_e = \ln K_F + \frac{1}{n} \ln C_e$$

$q_e = (\text{mg/g})$ amount of crystal violet adsorbed per gram of hydrogel, $C_e = \text{Concentration of adsorbate (ppm) at equilibrium state}$, $n = \text{Equilibrium constant}$, and $K_F = \text{Freundlich adsorption equilibrium constant}$.

Temkin adsorption isotherm

The Temkin isotherm assumes that the heat of adsorption decreases linearly with surface coverage because of adsorbent-adsorbate interactions (Temkin and Pyzhev, 1940):

$$q_e = \frac{RT}{b} \ln C_e + \frac{RT}{b} \ln K_T$$

$$\text{If, } B = \frac{RT}{b}$$

Then the modified form of equation is,

$$q_e = B \ln K_T + B \ln C_e$$

K_T = Temkin adsorption isotherm constant, T = represents the temperature(kelvin), R = general gas constant(J/(mol.K), B = Temkin constant associated with heat of adsorption.

Analytical Procedures

Crystal violet concentrations before and after adsorption were quantified using a UV-Visible spectrophotometer calibrated with standard dye solutions. Calibration curves were constructed by plotting absorbance against known dye concentrations, and sample concentrations were determined from the resulting regression equation. All glassware was thoroughly cleaned and rinsed with distilled water before use to minimize analytical errors.

Statistical Analysis

All experiments were conducted in triplicate, and the results are presented as mean $\pm$ standard deviation (SD). Statistical analyses were performed using OriginPro (OriginLab Corporation, USA) and Microsoft Excel. Adsorption isotherm parameters were estimated by non-linear regression analysis. The goodness-of-fit of the isotherm models was assessed using the coefficient of determination (R^2) and residual error analysis. Differences among treatment means were evaluated using one-way analysis of variance (ANOVA) at a significance level of $p < 0.05$ (Montgomery, 2019).

Results and Discussion

Percentage (%) Swelling

The swelling behavior of the synthesized hydrogel exhibited a rapid initial water uptake followed by a gradual approach to equilibrium (Figure). The swelling percentage increased sharply from 0 to approximately 60% within the first 30 min and reached about 95%, 125%, and 145% after 60, 90, and 120 min, respectively. This rapid swelling phase indicates the fast penetration of water molecules into the hydrogel matrix through available pores and hydrophilic functional groups.

After the initial swelling stage, the hydrogel continued to absorb water at a slower rate. The swelling percentage increased steadily and reached approximately 340% after 1080 min (18 h). Beyond this point, only a slight increase in swelling was observed, reaching around 348–350% at 1140–1200 min. The negligible increase in swelling during the final stage suggests that the hydrogel had attained its equilibrium swelling capacity. Therefore, the maximum equilibrium swelling of the hydrogel was approximately 350%, achieved after about 18–20 h of immersion.

Where w_s and w_d is the swollen and dried weights of hydrogel, respectively. The plot between %swelling and time is shown in figure 1. The hydrogel attains %swelling of 346.15 after 20 hours. The swelling rate of the hydrogel increased initially but decreased over time. This behavior can be due to the presence of large empty spaces within the hydrogel matrix at the beginning of the swelling process, which were progressively filled with water as time passed.

The swelling behavior of the synthesized hydrogel showed a rapid initial water uptake, reaching approximately 145% swelling within the first 120 min, followed by a slower increase until equilibrium swelling (~350%) was attained after 1080–1200 min. The rapid initial swelling was attributed to the abundance of hydrophilic carboxyl ($-\text{COOH}$) and amide ($-\text{CONH}_2$) groups, which facilitated water diffusion and hydrogen-bond formation within the polymer network (Ahmed, 2015; Bashir et al., 2019). Subsequently, the swelling rate decreased due to saturation of available pores and the increasing elastic retractive forces of the cross-linked polymer chains. The equilibrium plateau indicated a balance between osmotic water absorption and network elasticity, as described by the Flory-Rehner swelling theory (Singh et al., 2020). The high equilibrium swelling capacity demonstrates the highly hydrophilic and porous nature of the hydrogel, highlighting its potential for water retention and controlled-release fertilizer applications in sustainable agriculture (Gulrez et al., 2011; Waqas et al., 2025).

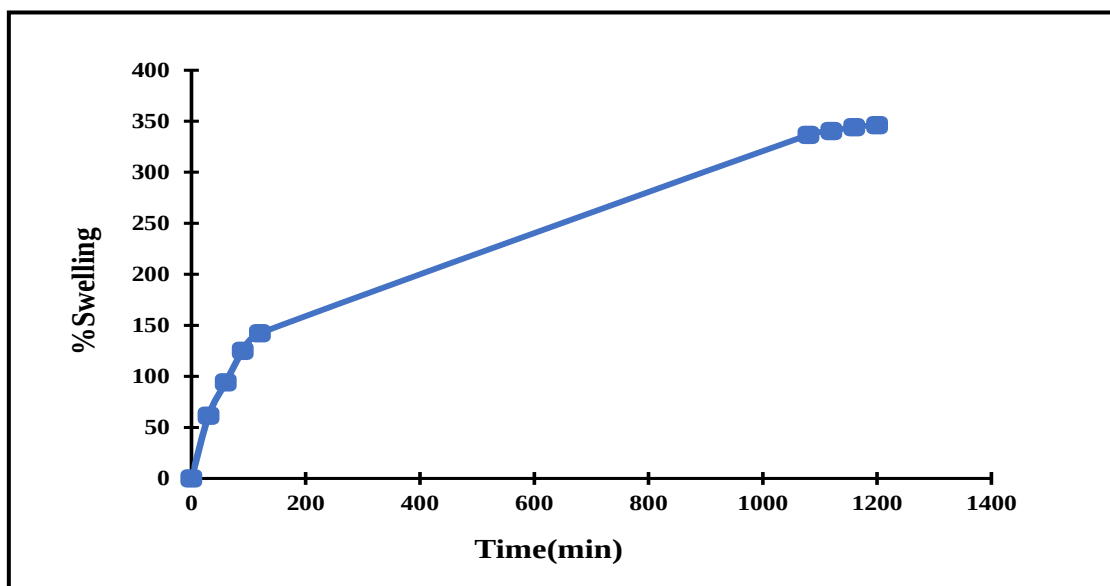


Figure 1. Swelling ratio as a function of time for p(AAc-co-AAm)

Diffusion of water into hydrogel

The linearized adsorption kinetic plot exhibited an excellent fit to the experimental data, as evidenced by the regression equation $y = 0.4414x - 3.1025$ with a very high coefficient of determination ($R^2 = 0.9892$). The strong linear relationship indicates that the selected kinetic model adequately describes the adsorption process, with approximately 98.9% of the variation in the experimental data explained by the regression model. The close clustering of experimental points around the regression line further confirms the reliability and reproducibility of the adsorption behavior.

The linearized adsorption plot exhibited an excellent fit to the experimental data, as indicated by the regression equation $y = 0.4414x - 3.1025$ and a high coefficient of determination ($R^2 = 0.9892$). The strong linear relationship suggests that the applied kinetic model adequately described the adsorption process, with approximately 98.9% of the variation in adsorption behavior explained by the model. Such a high correlation coefficient indicates efficient interaction between the adsorbate and the active sites of the hydrogel matrix, resulting in predictable adsorption behavior (Ho and McKay, 1999).

The close agreement between experimental data and the fitted line further suggests that adsorption occurred through a well-defined mechanism involving diffusion and surface binding within the polymeric network. Similar findings have been reported for hydrogel-based adsorbents, where high linearity ($R^2 > 0.98$) reflects effective sorption performance and strong adsorbate-adsorbent interactions (Ahmed, 2015; Foo and Hameed, 2010). Therefore, the synthesized hydrogel demonstrated favorable adsorption characteristics and considerable potential for controlled adsorption and environmental applications.

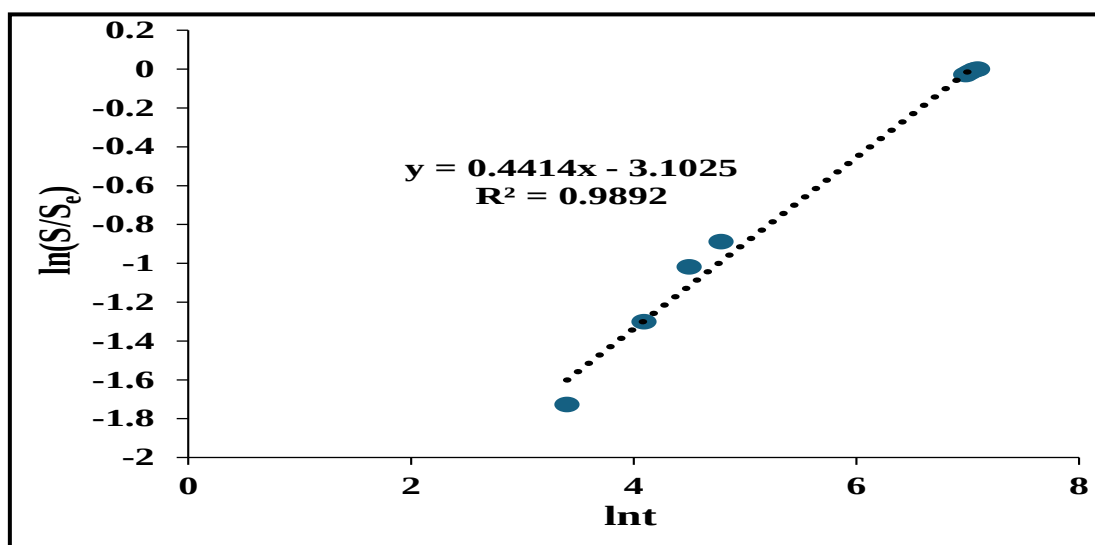


Figure 2. Plot of $\ln(S/S_e)$ vs $\ln$ time in order to study Diffusion of Water within P(AAc-co-AAm) Hydrogel

Kinetics of hydrogel Swelling

Figure 3 shows the plot of $\ln(S_e - S)$ versus time for P(AAc-co-AAm). The approximately linear relationship indicates that the sorption process follows first-order kinetics, where the rate of solute uptake is proportional to the remaining sorption capacity of the polymer. The decrease in sorption capacity with time reflects rapid occupation of available active sites followed by a gradual approach toward equilibrium. Similar first-order behavior has been reported for sorption processes involving polymeric hydrogels and other functionalized adsorbents (Ho & McKay, 1999; Crini & Badot, 2008).

Figure 4 presents the plot of t/S versus time, which is commonly used to evaluate second-order kinetics. A linear relationship would indicate that the sorption rate is dependent on the square of the remaining capacity or follows a second-order kinetic model. Comparison of the linearity of Figures 3 and 4, particularly through their respective regression coefficients (R^2), can therefore be used to identify the kinetic model that best describes sorption by P(AAc-co-AAm). Such kinetic evaluation is widely applied to distinguish the controlling mechanism of adsorption/sorption in polymeric and other functional materials (Ho & McKay, 1999; Azizian, 2004).

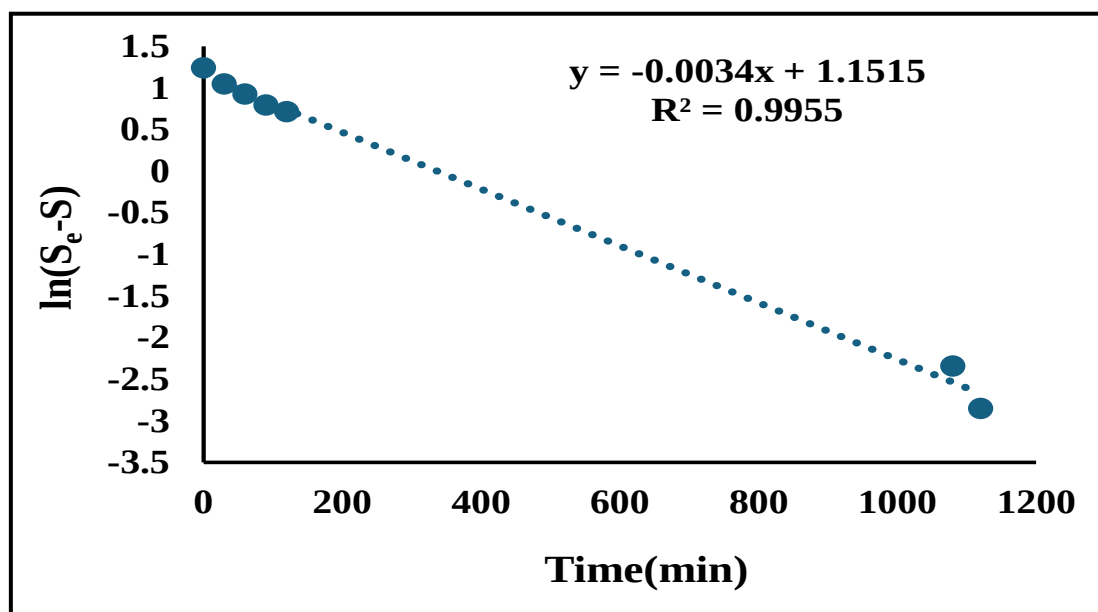


Figure 3. Plot of $\ln(S_e - S)$ vs. time for P(AAc-co-AAm)

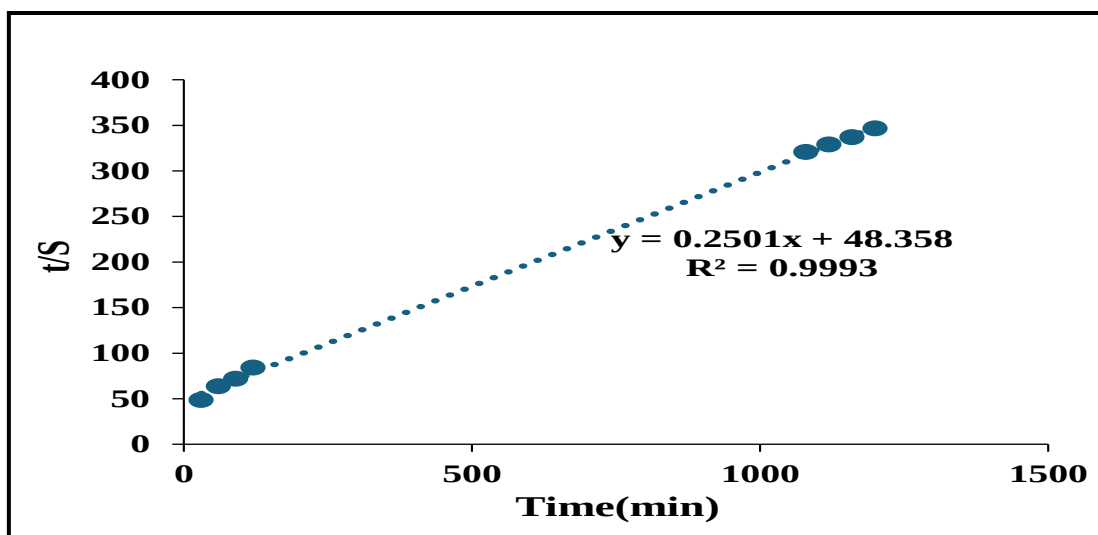


Figure 4: Plot of t/S vs Time in order to determine order of kinetics

Adsorption study

Figure 5 illustrates the time-dependent adsorption of crystal violet (CV) by the P(AAc-co-AAm) hydrogel at 30°C. The amount of CV adsorbed increased rapidly during the initial stage, followed by a gradual increase until equilibrium was approached. The

initially rapid uptake can be attributed to the availability of abundant vacant binding sites and the strong concentration gradient between the aqueous phase and hydrogel surface. As these sites became progressively occupied, the adsorption rate decreased because of reduced site availability and increasing resistance to mass transfer. Similar adsorption behavior, characterized by rapid initial uptake followed by equilibrium, has been widely reported for polymeric hydrogels and other adsorbent materials (Ho & McKay, 1999; Crini & Badot, 2008). The higher initial CV concentrations generally provided a greater driving force for mass transfer and resulted in higher adsorption capacity, indicating concentration-dependent interaction between CV molecules and the functional groups of P(AAc-co-AAm).

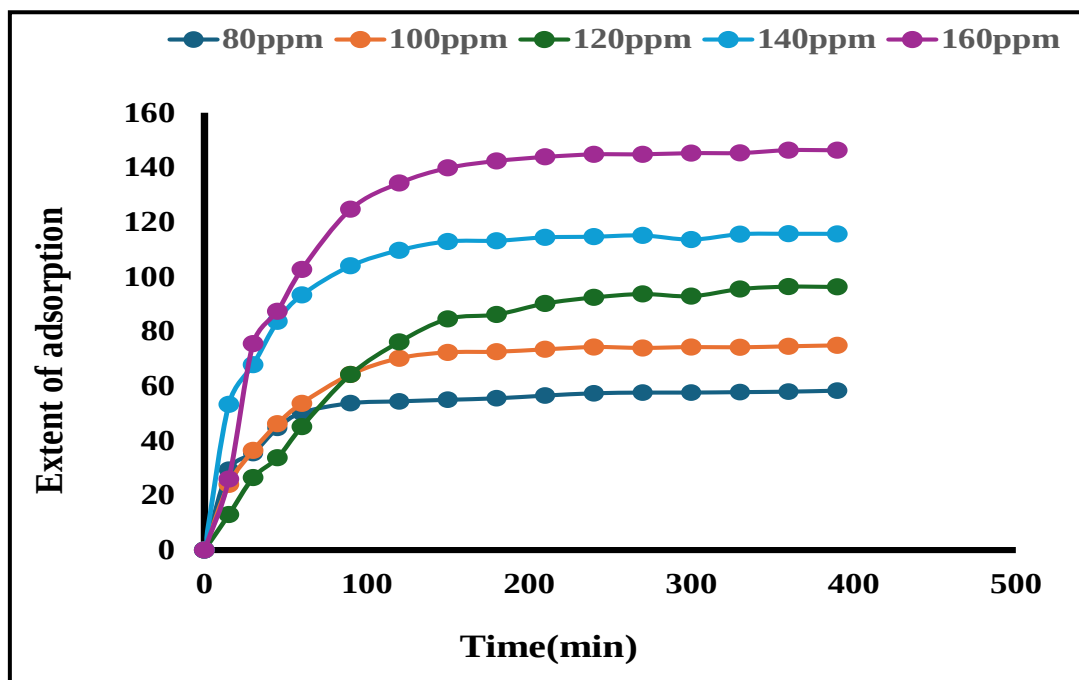


Figure 5. Plot illustrating amount of adsorbed upon p(AAc-co-AAm) hydrogel from aqueous medium against time [conditions for experiment; 100ml CV solutions (160, 140, 120, 100, 80 ppm), 30°C, p(AAc-co-AAm) = 0.09g].

Adsorption isotherms

To understand this mechanism various adsorption process, isotherms including Langmuir, Freundlich, and Temkin isotherms were used.

Langmuir adsorption isotherm

Figure 6 shows the Langmuir adsorption isotherm for crystal violet (CV) adsorption onto P(AAc-co-AAm) hydrogel. The plot indicates a positive relationship between the equilibrium concentration of CV and the adsorption capacity of the hydrogel, with the adsorption approaching a limiting value as the available binding sites became progressively occupied. The Langmuir model assumes monolayer adsorption onto a relatively homogeneous surface with a finite number of equivalent adsorption sites. The observed trend therefore suggests that CV molecules interact with specific active sites of the hydrogel until saturation is approached. The suitability of the Langmuir model can be further confirmed from the R^2 value, with a higher R^2 indicating better agreement between the experimental data and the theoretical model (Langmuir, 1918; Ho & McKay, 1999).

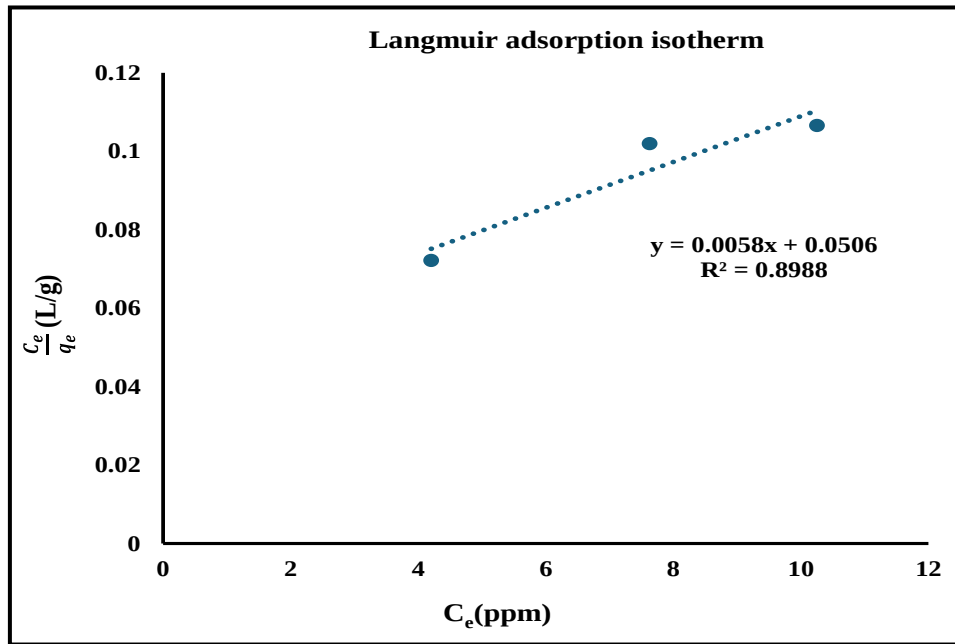


Figure 6. Langmuir Adsorption Isotherm for CV Adsorption

Freundlich adsorption isotherm

Figure 7 presents the Freundlich adsorption isotherm for crystal violet (CV) adsorption onto P(AAc-co-AAm) hydrogel. The linear relationship between $\log q_e$ and $\log C_e$ indicates that the experimental adsorption data can be described by the Freundlich model. This suggests adsorption onto a heterogeneous surface containing sites with different adsorption energies. The Freundlich parameters, particularly K_F and $1/n$, can be used to assess the adsorption capacity and favorability of CV uptake. A value of $1/n < 1$ generally indicates favorable adsorption. Similar heterogeneous adsorption behavior has been reported for dye removal using polymeric and other functionalized adsorbents (Freundlich, 1906; Crini & Badot, 2008).

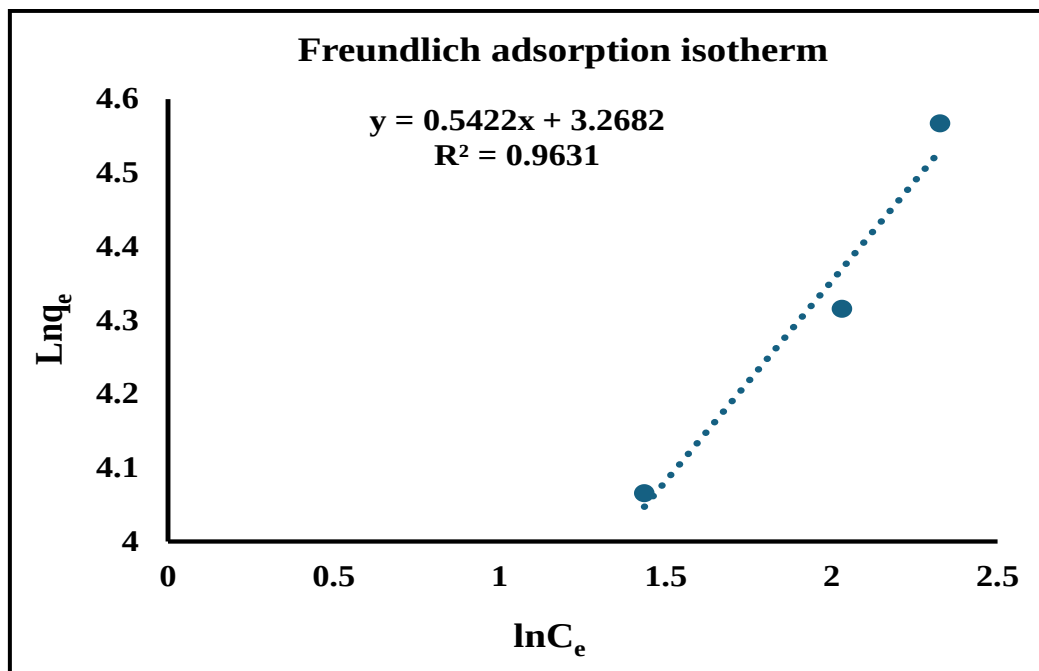


Figure 7. Freundlich adsorption isotherm for CV adsorption

Temkin adsorption isotherm

Figure 8 illustrates the Temkin adsorption isotherm for crystal violet (CV) adsorption onto P(AAc-co-AAm) hydrogel. The Temkin model considers adsorbent-adsorbate interactions and assumes that the heat of adsorption decreases linearly with

increasing surface coverage. The observed relationship between q_e and $\ln C_e$ indicates that CV adsorption is influenced by interactions between dye molecules and the active functional groups of the hydrogel. The Temkin constants can further provide information about the adsorption energy and interaction strength. Similar applications of the Temkin model have been reported for evaluating adsorption mechanisms in polymeric and other heterogeneous adsorbents (Temkin & Pyzhev, 1940; Foo & Hameed, 2010).

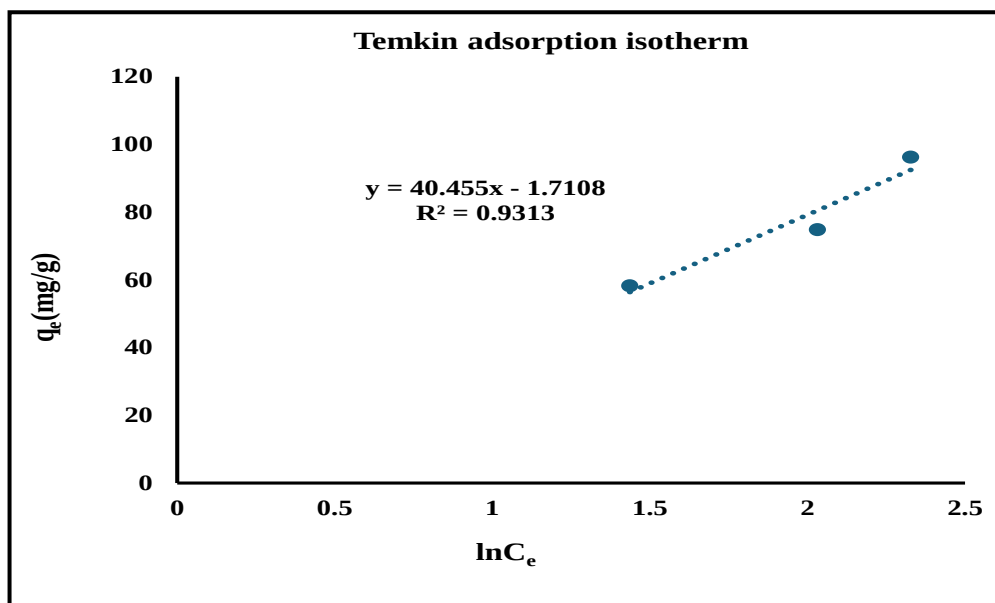


Figure 8. Temkin adsorption isotherm for CV adsorption

Different adsorption parameters

Table 1 summarizes the adsorption parameters obtained from the Langmuir, Freundlich, and Temkin models for CV adsorption onto P(AAc-co-AAm) hydrogel. The Freundlich model provided the best fit ($R^2 = 0.9631$), followed by the Temkin ($R^2 = 0.9313$) and Langmuir ($R^2 = 0.8988$) models. The relatively higher Freundlich fit indicates that CV adsorption predominantly occurred on a heterogeneous surface with adsorption sites of different energies. The Freundlich constant, $K_F = 26.26$ L/g, indicates appreciable adsorption capacity, while $n = 1.844$ (>1) suggests favorable CV adsorption. The Langmuir model estimated a maximum monolayer adsorption capacity (q_m) of 172.41 mg/g, although its lower R^2 indicates that the homogeneous monolayer assumption was less representative of the experimental system. The Temkin constant ($B = 40.455$ J/mol) further suggests appreciable adsorbate-adsorbent interactions. Overall, the results indicate that surface heterogeneity and variable adsorption energies played an important role in CV uptake by the hydrogel, with the Freundlich model best representing the experimental equilibrium data (Foo & Hameed, 2010; Ayawei et al., 2017).

Table 1 Parameters of adsorption isotherm models (Langmuir, Freundlich, and Temkin) for the adsorption of crystal violet onto p(AAc-co-AAm) hydrogel

Langmuir isotherm parameters		
K_L (L/g)	q_m (mg/g)	R^2
0.114	172.413	0.8988
Freundlich isotherm parameters		
K_F (L/g)	n	R^2
26.26	1.844	0.9631
Temkin isotherm parameters		
K_T (L/g)	B (J/mol)	R^2
0.180	40.455	0.9313

Conclusion

The adsorption studies demonstrated that P(AAc-co-AAm) hydrogel has considerable potential for the removal of crystal violet (CV) from aqueous media. CV adsorption increased rapidly during the initial contact period and gradually approached equilibrium, reflecting the progressive occupation of available adsorption sites. Kinetic analysis indicated that the adsorption process could be evaluated using both first- and second-order models, while equilibrium analysis showed that the Freundlich isotherm provided the best fit ($R^2 = 0.9631$) compared with the Temkin ($R^2 = 0.9313$) and Langmuir ($R^2 = 0.8988$) models. The Freundlich parameter $n = 1.844$ indicated favorable adsorption, whereas the Langmuir model estimated a maximum adsorption capacity of 172.41 mg g^{-1} . Overall, the results suggest that CV uptake by P(AAc-co-AAm) is mainly associated with heterogeneous adsorption sites and variable adsorbate-adsorbent interactions, supporting the potential application of this hydrogel as an effective adsorbent for dye-contaminated aqueous systems.

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