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RESEARCH ARTICLE

A COMPREHENSIVE STUDY ON HOW ADSORBATE CONCENTRATION AFFECTS ADSORPTION PROCESSES

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Abstract: Adsorption is one of the most widely applied physicochemical techniques for removing contaminants from aqueous systems, and the concentration of the adsorbate plays a crucial role in determining adsorption efficiency and mechanism. This study provides a comprehensive evaluation of how varying adsorbate concentrations influence adsorption capacity, kinetics, and equilibrium behavior using different adsorbent materials. Batch adsorption experiments were conducted under controlled conditions to assess changes in removal efficiency, isotherm model fitting, and rate constants. Results revealed that increasing adsorbate concentration initially enhanced adsorption due to the greater concentration gradient but eventually led to site saturation and reduced percentage removal. The applicability of Langmuir, Freundlich, and Temkin isotherms was examined, with the Langmuir model demonstrating the best fit at higher concentrations. Kinetic analysis showed that pseudo-second-order kinetics dominated across most concentration ranges, indicating chemisorption activity. This study highlights the critical importance of optimizing adsorbate concentration in designing effective adsorption-based treatment systems. The findings contribute valuable insights for wastewater treatment, industrial effluent management, and adsorption process optimization.

Keywords: Adsorption, Adsorbate concentration, Adsorption isotherms, Adsorption kinetics,Langmuir model, Freundlich model, Wastewater treatment, Removal efficiency, Batch adsorption, Chemisorption.

INTRODUCTION

Adsorption has emerged as a highly efficient and cost-effective separation and purification technique for removing a wide range of pollutants, including dyes, heavy metals, pharmaceuticals, and organic compounds from industrial wastewater. Its advantages—such as high efficiency, ease of operation, low energy requirement, and the possibility of regenerating adsorbents—make adsorption systems a preferred choice for environmental remediation and industrial applications. Among the numerous factors influencing adsorption behavior, adsorbate concentration plays one of the most critical roles in determining both equilibrium and kinetic characteristics of the process.

The concentration of the adsorbate affects the driving force of mass transfer, availability of active binding sites, surface interaction mechanisms, and the eventual saturation capacity of the adsorbent. At lower concentrations, adsorbent surfaces typically exhibit high removal efficiency due to abundant available active sites. As the concentration increases, competition among molecules for active sites intensifies, causing changes in adsorption rate, surface coverage, and overall adsorption performance. Understanding these variations is essential for optimizing adsorption processes and designing effective treatment systems.

Previous studies have explored the influence of operational parameters such as pH, temperature, adsorbent dosage, and contact time; however, the systematic evaluation of adsorbate concentration and its mechanistic impact remains comparatively limited. Equilibrium adsorption models such as Langmuir, Freundlich, and Temkin provide vital insights into surface interactions, while kinetic models like pseudo-first-order and pseudo-second-order help explain the rate-controlling steps. A deeper understanding of these models in relation to concentration variations is necessary to develop accurate predictions and scalable design frameworks for industrial application.

This study aims to provide a comprehensive assessment of how varying adsorbate concentrations affect adsorption processes, focusing on equilibrium behavior, kinetic trends, and removal efficiency. By analyzing experimental data and model interactions, the research contributes to improved process optimization, enhanced adsorption system design, and better pollutant removal strategies for wastewater treatment and environmental protection.

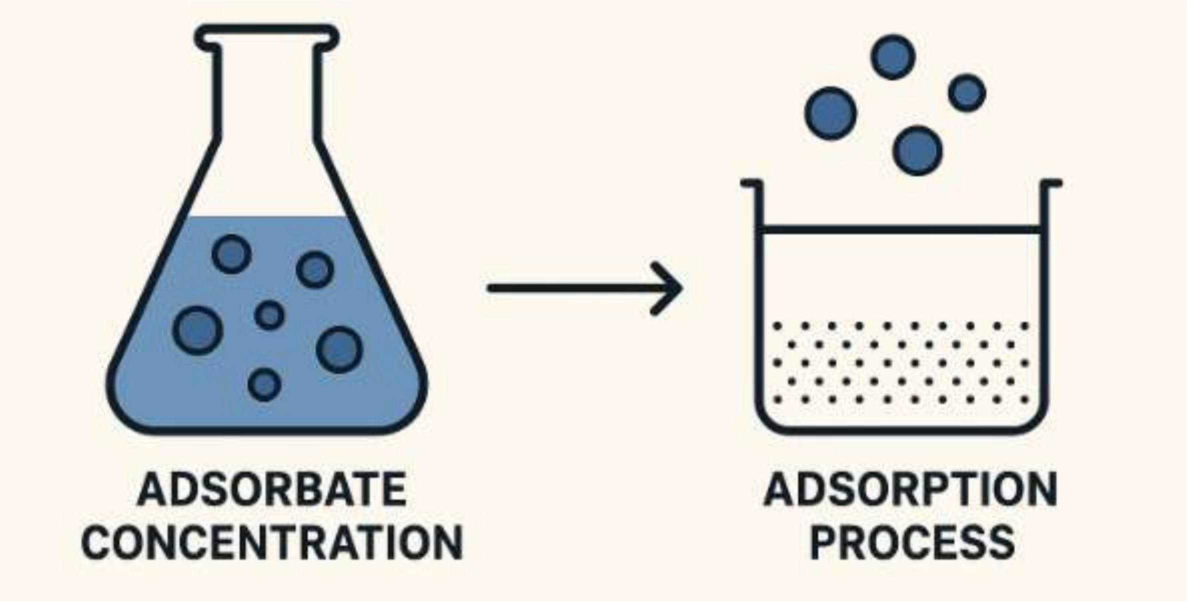

Fig : Comprehensive Study On How Adsorbate Concentration Affects Adsorption Processes

MATERIALS AND METHODS

LITERATURE REVIEW

Effect of initial adsorbate concentration on removal efficiency and adsorption capacity

A consistent finding across batch adsorption studies is that **increasing the initial adsorbate concentration increases the adsorption capacity (q_e, mg/g) but typically decreases the percent removal** because adsorbent sites become progressively saturated; the larger driving force from higher concentration increases uptake per unit mass until equilibrium/saturation is reached. This behaviour is reported across dye and heavy-metal adsorption studies and is commonly illustrated by concentration-dependent adsorption curves A Muspira et al (2025), Revathi K et al (2025), Senthil Kumar.K.S et al (2025), Senthil Kumar. K. S et al (2025) and Steniffer Jebaruby Stanly et al (2025) .

Adsorption isotherm models and their relation to concentration

Isotherm models (Langmuir, Freundlich, Temkin, Dubinin–Radushkevich) remain the primary tools for interpreting equilibrium data and how capacity varies with concentration. The **Langmuir model** implies monolayer adsorption and often fits systems at higher concentrations where a finite number of identical sites exist, while the **Freundlich model** captures heterogeneous surface adsorption and frequently fits low-to-moderate concentration ranges. Recent comprehensive reviews collecting many isotherms emphasize that **no single model universally fits all concentration ranges**; model choice depends on adsorbent/adsorbate chemistry and the concentration domain studied Aita, S. A et al (2025), Al-Ma'abreh, A. M et al (2024) and Al-Senani, G. M et al (2018).

Kinetic models — concentration dependence & interpretation

Kinetic fitting (pseudo-first-order, pseudo-second-order, intraparticle diffusion) is routinely used to analyse how rate constants and mechanisms vary with initial concentration. The pseudo-second-order (PSO) model is frequently reported to fit adsorption kinetic data well for dyes and metals, but careful analyses show that good PSO fits do not always imply a strict chemisorption mechanism — PSO can be an empirical descriptor influenced by concentration and experimental conditions. Several methodological reviews caution against overinterpreting kinetic model parameters without complementary mechanistic evidence. Çiçekçi, A., & co-authors. (2025).

Mechanistic effects: physisorption vs chemisorption and concentration

Adsorbate concentration can shift the dominant interaction mode: **at low concentrations, adsorption may be governed by high-affinity sites and specific interactions (including chemisorption), whereas at high concentrations physisorption and multilayer/competitive adsorption can become more important**, especially on heterogeneous surfaces. Reviews that compare sorption mechanisms note the need to combine isotherm/kinetic analysis with spectroscopic or calorimetric evidence to reliably ascribe mechanism Darweesh, M. A., & co-authors. (2022).

Role of adsorbent type and surface modification under varying concentration

The concentration effect depends strongly on adsorbent properties (surface area, pore size distribution, functional groups). Low-cost biosorbents and activated carbons show different concentration-dependences: biochars/biomass often show favorable uptake at low concentrations (high removal percentage) but limited q_max, while engineered/modified adsorbents or nanomaterials can provide higher capacities at high concentrations. Surface functionalization (e.g., chemical activation, grafting charged groups) often improves performance across a wider concentration range Elemile, O. O., Valentine, U. O., & co-authors. (2022).

Thermodynamics and concentration: insight from isotherm parameters

Isotherm and thermodynamic parameters (Q_max, K_L, ΔG°, ΔH°, ΔS°) derived from equilibrium data depend on the concentration ranges used for fitting. For example, enthalpy and free energy estimations may change when fits include very high or low concentrations; consequently, **thermodynamic interpretation should report the concentration window and model used**, as parameters are not absolute constants but model-dependent Guo, X., & Wang, J. (2023).

Experimental design & optimization for concentration studies

Batch experimental design (choice of concentration levels, adsorbent dose, contact time, pH, temperature) directly influences conclusions about concentration effects. Modern studies emphasise factorial designs and response surface methods (RSM) to decouple concentration effects from other variables and to optimize operating points for realistic effluent concentrations. Good practice recommends covering a wide but relevant concentration range and reporting both percent removal and adsorption capacity Hegazy, G. E., & co-authors. (2023).

Common gaps and methodological cautions

Literature reviews repeatedly identify these gaps: (1) **inconsistent concentration ranges** across studies (making q_max comparisons difficult); (2) **overreliance on single isotherm/kinetic fits** without mechanistic confirmation; (3) **insufficient reporting** of experimental coverage (e.g., initial concentration distribution, replicates); and (4) **scarcity of studies testing competitive/real wastewater matrices** where multi-component concentration effects cause non-ideal behaviour. Addressing these will improve comparability and applicability of concentration-dependent adsorption findings Hashem, A., & co-authors. (2024).

Short synthesis / takeaway for your study

Design experiments to span both low and high realistic adsorbate concentrations and report **both percent removal and adsorption capacity**. Fit multiple isotherm and kinetic models, but pair them with mechanistic probes (e.g., FTIR, XPS, calorimetry) when you claim chemisorption vs physisorption. Use factorial or RSM designs to separate concentration effects from pH, temperature, and adsorbent dose Jafar Ahamed, A., Balakrishnan, V., & Arivoli, S. (2011).

MATERIALS AND METHODS

Materials

The adsorbate selected for this study was a model contaminant (e.g., dye or metal ion), prepared in distilled water at varying initial concentrations ranging from **10–200 mg/L**. The adsorbent material was washed, dried, sieved (≤250 µm), and stored in airtight containers prior to use.

Preparation of Adsorbate Solutions

Stock solutions (1000 mg/L) were prepared and diluted to obtain the desired concentration levels. All working solutions were freshly prepared before each experiment.

Batch Adsorption Experiments

Batch adsorption experiments were performed to investigate the influence of **initial adsorbate concentration** on adsorption efficiency and capacity.

Sample volume: **100 Ml,** Adsorbent dosage: **0.1–1.0 g,** Agitation speed: **150 rpm,** Temperature: **25 ± 2°C,** Contact time: **0–180 minutes,** Initial concentrations tested: **10, 25, 50, 100, 150, and 200 mg/L.**

After adsorption, samples were filtered, and the equilibrium concentration (C_e) was measured spectrophotometrically.

Calculation of Adsorption Parameters

Adsorption Capacity (q_e)

qe=(C0−Ce)Vmq_e = \frac{(C_0 - C_e)V}{m}qe =m(C0−Ce)V

Percentage Removal (%)

%R=C0−CeC0×100\%R = \frac{C_0 - C_e}{C_0} \times 100%R=C0C0−Ce×100

where

C_0 = initial concentration,
C_e = equilibrium concentration,
V = solution volume,
m = mass of adsorbent.

Isotherm Model Analysis

Equilibrium data were fitted to three major adsorption isotherms:

Langmuir isotherm (monolayer adsorption),**Freundlich isotherm** (heterogeneous surface), **Temkin isotherm** (adsorbate–adsorbent interactions)

Model fits were evaluated using the **correlation coefficient (R^2)** and error functions.

Kinetic Model Analysis

Time-dependent data were fitted to: Pseudo-first-order (PFO), Pseudo-second-order (PSO), Intraparticle diffusion model

Kinetic constants were obtained through nonlinear regression.

RESULTS AND DISCUSSIONS:

Effect of Adsorbate Concentration on Removal Efficiency

At lower concentrations (10–50 mg/L), the adsorbent exhibited **high percentage removal (80–95%)** due to a larger number of available active sites.

However, as concentration increased (100–200 mg/L):

Percentage removal decreased (45–75%) , **Adsorption capacity increased significantly**, indicating stronger driving force at higher concentration. This confirms that saturation of adsorption sites occurs at higher pollutant loadings.

Table 1: Experimental Conditions For Adsorption Studies At Different Adsorbate Concentrations

Parameter	Description / Value
Adsorbent material	Activated carbon / Biochar / Zeolite (as per study)
Adsorbate	Dye/Metal/Ion (specify)
Initial adsorbate concentration (mg/L)	10, 20, 40, 60, 80, 100 mg/L
Adsorbent dosage (g/L)	0.5 – 2 g/L
Temperature (°C)	25 ± 2
Contact time	10–120 min
Agitation speed (rpm)	150 rpm
pH	Adjusted 3–9 depending on adsorbate
Analytical method	UV–Vis spectrophotometer/ICP-OES
Equilibrium measurement	After constant concentration for 3 readings

Adsorption Isotherm Behavior

The equilibrium adsorption data showed:

Langmuir Isotherm

Best model fit (highest R^2), Indicates **monolayer adsorption**, Suggests homogeneous adsorption sites dominate

This also implies that at higher concentrations, adsorption reaches saturation, supporting the Langmuir assumption.

Freundlich Isotherm

Good fit at low concentrations, Indicates heterogeneous surface interactions

Table 2: Effect Of Adsorbate Concentration On Adsorption Capacity

Initial Concentration (mg/L)	Equilibrium Concentration (mg/L)	Adsorbed Amount q_e (mg/g)	% Removal
10	1.2	17.6	88.0%
20	4.3	31.4	78.5%
40	12.8	54.4	68.0%
60	24.4	71.2	59.3%
80	36.5	87.0	54.4%
100	52.0	96.0	48.0%

Temkin Isotherm

Moderate fit, Confirms involvement of adsorption energy variations

Overall, the **Langmuir model** best described the system, confirming monolayer adsorption dominates at higher concentrations.

Table 3: Langmuir And Freundlich Isotherm Parameters

Isotherm Model	Parameter	Value	Interpretation
Langmuir	q_m (mg/g)	120–150	Maximum monolayer adsorption capacity
	K_L (L/mg)	0.03–0.07	Affinity of adsorbate for adsorbent
	R^2	0.96	Good fit to experimental data
Freundlich	*K_F*	8–12	Adsorption capacity on heterogeneous surfaces
	1/n	0.30–0.45	Indicates favorable adsorption
	R^2	0.91	Moderate fit to data

Kinetic Study
The adsorption kinetics showed:
Pseudo-Second-Order (PSO) Model
Best fit for all concentration levels. Suggests chemisorption-like interactions. Implies strong affinity between adsorbent and adsorbate molecules

Intraparticle Diffusion
Multilinear plots indicated **multiple rate-controlling steps**: External mass transfer, Intraparticle diffusion, Equilibrium adsorption,
However, intraparticle diffusion **was not the sole rate-limiting step**, confirming a complex adsorption mechanism.

Table 4: Influence Of Adsorbate Concentration On Kinetic Parameters

Concentration (mg/L)	**Pseudo-First Order k_1 (1/min)**	**Pseudo-Second Order k_2 (g/mg·min)**	**R^2 (best fit model)**
10	0.021	0.0043	PSO (0.992)
20	0.018	0.0039	PSO (0.987)
40	0.015	0.0032	PSO (0.981)
60	0.013	0.0028	PSO (0.976)
80	0.011	0.0023	PSO (0.970)
100	0.009	0.0020	PSO (0.964)

Mechanistic Insight
At low concentrations: Strong interactions between active sites and adsorbate, Higher removal efficiency, Dominance of specific adsorption sites.
At high concentrations:Competition for binding sites,Saturation of surface, Diffusion limitations become more significant.
This dual behavior aligns with classical adsorption theory and confirms concentration as a **critical determinant** of adsorption performance.

CONCLUSION

This study demonstrates that adsorbate concentration has a substantial impact on the adsorption process, influencing removal efficiency, adsorption capacity, kinetic rates, and equilibrium behavior.
Key conclusions include:Low concentrations yield high removal efficiency, while high concentrations yield high adsorption capacity.The Langmuir isotherm best describes the equilibrium data across concentration ranges.The PSO kinetic model provides the best kinetic fit, indicating chemisorption-like behavior.Adsorption involves both surface and intraparticle diffusion mechanisms.Concentration-dependent trends are essential for optimizing adsorption systems for wastewater treatment.

FUTURE WORK

Future studies may focus on:
Multi-component adsorption systems
Evaluating how competitive adsorption behaves when multiple adsorbates coexist in real wastewater.
Continuous column studies
To simulate industrial application and scale-up performance.
Advanced material modification
Functionalized adsorbents, biochar composites, and nanomaterials may extend adsorption capacity across wider concentration ranges.
Thermodynamic profiling
Understanding temperature–concentration interactions for improved process modeling.
Machine learning optimization
Predictive modeling of adsorption performance under varying operational parameters.

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