



International Journal of Advanced Scientific and
Technical Research

Available online on
<http://www.rspublication.com/ijst/index.html>

ISSN 2249-9954



Kinetics and Isotherms of Methylene Blue Adsorption onto Mahogany (Swietenia mahagoni) Fruit Shell: A Green Approach to Wastewater Treatment

Anjana Gupta[✉]1, Priyanka Rani¹, Animesh Agarwal²

¹ IFTM University, Moradabad, Uttar Pradesh, India

² Moradabad Institute of Technology, Moradabad, Uttar Pradesh, India

✉ Correspondence: anjana.05gupta@gmail.com

ARTICLE INFO

©2025 RS Publication

Paper ID: IJASTR-

687C9CBFB74FC

Received: 2025-03-26

Published: 2025-07-26

DOI:

[https://dx.doi.org/](https://dx.doi.org/10.5281/zenodo.16441333)

[/10.5281/zenodo.16](https://dx.doi.org/10.5281/zenodo.16441333)

[441333](https://dx.doi.org/10.5281/zenodo.16441333)

Page No: 52-76



ABSTRACT

Methylene Blue (MB), a cationic dye widely used in the textile and paper industries, poses significant environmental and health risks due to its persistence and toxicity in aquatic ecosystems. Traditional treatment methods for dye-laden wastewater, including coagulation–flocculation, oxidation, and chemical precipitation, often result in high operational costs and sludge generation, prompting the need for more sustainable alternatives. This study investigates the use of Mahogany Fruit Shell (MFS), an underutilized lignocellulosic waste, as a low-cost and eco-friendly biosorbent for MB removal from aqueous solutions. The MFS material was prepared through washing, drying, crushing, and sieving, followed by extensive characterization using Scanning Electron Microscopy (SEM) and Fourier Transform Infrared Spectroscopy (FTIR). Batch adsorption experiments were conducted to assess the influence of various parameters pH, contact time, initial dye concentration, adsorbent dosage, agitation speed, and temperature on dye removal efficiency.

The adsorption process exhibited strong dependence on pH and contact time, with optimal performance at pH 9 and an equilibrium time of 420 minutes. Isotherm analysis showed that the Langmuir model best fit the equilibrium data, indicating monolayer adsorption, while kinetic studies aligned with the pseudo-second-order model, suggesting chemisorption. Thermodynamic parameters confirmed the process was spontaneous and endothermic. Intraparticle diffusion analysis revealed that multiple mechanisms governed the adsorption process. Compared to conventional and alternative biosorbents, MFS demonstrated competitive adsorption capacity, underscoring its potential as a sustainable, cost-effective solution for dye removal in wastewater treatment. This study highlights the promising valorization of agricultural waste for environmental remediation applications.

KEY WORDS: Adsorption isotherms; Textile dye removal, Eco-friendly adsorbent; Low-cost adsorbent; Kinetic modeling; Wastewater treatment.

Cite This Paper :

Anjana Gupta[✉], Priyanka Ran and Animesh Agarwal (2025). "KINETICS AND ISOTHERMS OF METHYLENE BLUE ADSORPTION ONTO MAHOGANY (Swietenia mahagoni) FRUIT SHELL: A GREEN APPROACH TO WASTEWATER TREATMENT". *INTERNATIONAL JOURNAL OF ADVANCED SCIENTIFIC AND TECHNICAL RESEARCH (IJASTR)* ISSN 2249-9954, vol. 15, no. 4, 2025, pp. 52-76. DOI: <https://dx.doi.org/10.5281/zenodo.16441333>

1.0 INTRODUCTION

Among the earliest and most widely used basic dyes is Methylene Blue (MB), first synthesized by Heinrich Caro in 1878. MB is typically available as a dark green powder or crystalline solid that turns blue when dissolved in water (Garg et al., 2004). Colorants, the substances used to impart color to materials, are broadly categorized into dyes and pigments. The key distinction lies in their solubility: dyes are soluble in the application medium, enabling them to bond chemically or physically to the substrate, whereas pigments are insoluble and require a binder for application (Sharma et al., 2015). Dyes are defined as colored organic substances capable of imparting a permanent hue to textiles and other materials, resistant to degradation by light, washing, and other environmental factors (Christie, 2007).

Historically, most synthetic dyes were derived from coal tar derivatives, a byproduct of the distillation of coal (Sharma et al., 2015). Today, textile industries are among the most polluting sectors, primarily due to the large volumes of wastewater generated during dyeing and finishing processes. The discharge of colored effluents is not only aesthetically displeasing but also environmentally detrimental, as color is often perceived as a direct indicator of water pollution (Robinson et al., 2001).

Dye-containing wastewater arises both during the production of dyes and their subsequent application in industries such as textiles, paper, pulp, tanning, electroplating, food processing, and distillation. Over 100,000 commercially available dyes exist globally, with an annual production volume of approximately 700,000 tons (Forgacs et al., 2004). It is estimated that about 2% of dyes are lost during manufacturing, and up to 10% are discharged during dyeing operations, contributing significantly to environmental contamination (Robinson et al., 2001).

These colored effluents pose ecotoxicological threats due to their potential bioaccumulation in aquatic organisms, which can propagate through the food chain and ultimately affect human health (Saratale et al., 2011). Specifically, Methylene Blue can cause serious health issues: it may lead to eye burns and possible permanent damage upon contact, respiratory distress upon inhalation, and symptoms such as nausea, vomiting, excessive sweating, and methemoglobinemia upon ingestion (Oz et al., 2007). In clinical settings, however, MB has shown therapeutic applications, notably in overcoming ifosfamide-induced neurotoxicity during chemotherapy due to its synergistic pharmacological properties (Pelgrims et al., 2000).

The removal of dyes from wastewater presents significant environmental and technological challenges. Synthetic dyes are specifically engineered to be chemically and photochemically stable, making them highly resistant to degradation by light, heat, microbial activity, and oxidizing agents (Robinson et al., 2001). Commercial dye formulations are often complex mixtures comprising a variety of poorly characterized compounds, frequently lacking comprehensive structural or compositional information (Forgacs et al., 2004). Moreover, dye-containing wastewater is not a simple aqueous solution of dyes but typically includes a wide range of ancillary substances such as suspended solids, salts, surfactants, acids, alkalis, and residual process chemicals, all of which further complicate the treatment process (Ali, 2010).

The increasing application of adsorption techniques in wastewater treatment is largely due to their proven effectiveness in removing a wide array of pollutants, including synthetic dyes. Adsorption not only ensures the production of high-quality treated water, but is also widely recognized for its economic viability and operational simplicity (Crini & Badot, 2008). A critical factor influencing the success of this method is the selection of a suitable adsorbent. The development and optimization of diverse adsorbents have significantly enhanced adsorption as a practical approach to both environmental remediation and cost-effective treatment strategies.

A wide variety of adsorbents, including sand, fly ash, clay, zeolites, polymers, carbon nanotubes, activated carbon, and biomass-derived materials, have been evaluated for their adsorption capabilities. For example, sand, a naturally abundant material, has been shown to effectively adsorb methylene blue (MB) dye (Fig. 1). Bukallah et al. (2007) reported that under optimized conditions, up to 92% of MB dye was removed from aqueous solution using sand at ambient temperature.

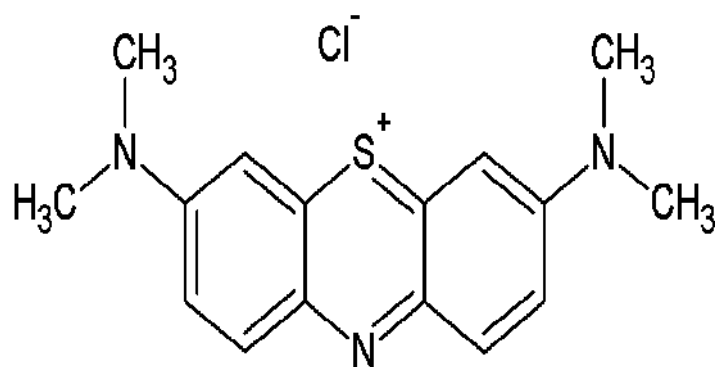


Fig. 5.1 Structure Of Methylene Blue Dye

In an advanced approach, mesoporous carbon materials were synthesized using acid- and alkali-treated zeolite X as a template and furfuryl alcohol as the carbon precursor via vapor deposition polymerization. These modified carbons exhibited outstanding adsorption capacities for MB dye. At 293 K, the carbon prepared using acid-treated zeolite X achieved a maximum adsorption capacity of 262.87 mg/g, while the one synthesized using alkali-treated zeolite X showed a remarkably higher capacity of 436.55 mg/g (Chen et al., 2011). These results underscore the effectiveness of template-assisted carbon synthesis in producing high-performance adsorbents for dye removal.

Conventional treatment processes, such as coagulation–flocculation, oxidation, chemical precipitation, filtration, and electrochemical techniques, are often less effective in decolorizing synthetic dyes, and typically result in the generation of large quantities of sludge that require secondary treatment or disposal (Robinson et al., 2001). Moreover, these processes often demand high energy inputs and the use of potentially hazardous chemicals, raising environmental and economic concerns. As a response to these limitations, recent research has shifted focus toward the development of low-cost, sustainable adsorbents derived from agricultural wastes, natural materials, and industrial by-products. These alternatives offer promising potential for large-scale implementation in dye removal applications (Demirbas, 2009).

In the present study, we introduce mahogany (*Swietenia mahagoni*) fruit shell, a novel, underutilized lignocellulosic waste, as a sustainable adsorbent for the removal of Methylene Blue (MB) from aqueous solutions. While mahogany bark has been traditionally employed in herbal medicine for treating conditions such as malaria, diabetes, hypertension, fever, and gastrointestinal disorders (Rivai et al., 2021), its fruit shell remains an unused biomass. Phytochemicals such as saponins found in mahogany are known to exhibit bioactive properties, including immunomodulation, cholesterol-lowering, and anti-inflammatory effects (Igbinosa et al., 2009).

The objective of the study was to evaluate the efficacy of mahogany fruit shell as an adsorbent, batch adsorption experiments were conducted under varying conditions of pH, contact time, agitation speed, and initial dye concentration. Adsorption equilibrium was analyzed using established isotherm models such as Langmuir and Freundlich, while the kinetics were evaluated using pseudo-first-order and pseudo-second-order models. The results demonstrated that mahogany fruit shell is an economical, effective, and eco-friendly biosorbent for the removal of Methylene Blue from wastewater.

2.0 MATERIAL AND METHODS

Batch adsorption techniques have been widely employed to evaluate the efficacy of various adsorbents in the removal of methylene blue (MB) from aqueous solutions. For instance, gypsum has demonstrated a maximum monolayer adsorption capacity of 36 mg/g, indicating moderate effectiveness in dye removal (Wang et al., 2010). Peat, a naturally occurring organic material, has also been reported as an efficient adsorbent, achieving over 90% removal efficiency across various temperatures and concentrations, with equilibrium attained within 4.5 hours (Aksu & Tezer, 2005).

2.1 Preparation of Materials and Dye Solution

In this study, untreated Mahogany Fruit Shell (MFS) was utilized as a low-cost and environmentally friendly adsorbent for dye removal. The MFS material was collected from the campus of Shivaji University. The fruit exhibits a dehiscent characteristic, where the mature shell bursts to release seeds, leaving the shell as a residual waste product with no significant conventional value. These discarded shells were gathered and processed for use as adsorbent material.

The shells were first air-dried to remove surface moisture and then thoroughly washed with tap water to eliminate adhering dirt and impurities. Subsequently, the shells were oven-dried at 383 K, cut into smaller pieces, and washed again to remove soluble coloring matter that could potentially interfere with adsorption studies. After this, the cleaned and dried material was crushed, further washed to remove any residual coloration, oven-dried again at 383 K for 24 hours, and then sieved using a BSS 25 mesh to obtain uniform particle sizes suitable for adsorption experiments. This methodology follows standard practices in the preparation of lignocellulosic biomass for adsorptive applications (Demirbas, 2008; Babel & Kurniawan, 2003).

The dye used in the study was Methylene Blue (MB), a widely used cationic dye in textile and paper industries, with the molecular formula $C_{16}H_{18}ClN_3S$ and a maximum absorption wavelength of 670 nm (Banat et al., 1996). A stock solution was prepared by dissolving 1 g of MB in 1 dm³ of deionized water. Working solutions of desired concentrations were then prepared through appropriate dilutions of the stock solution. All reagents used in the study were of analytical grade and were procured from S.D. Fine Chem Ltd., India.

2.2 Characterization of Adsorbent

The characterization of MFS was carried out using multiple analytical techniques to evaluate its structural, elemental, and surface properties. Scanning Electron Microscopy (SEM) (JEOL JSM-6360) was employed to analyze the surface morphology of the adsorbent before and after the adsorption of MB. SEM

images revealed that the surface of MFS was initially rough and irregular. After dye adsorption, the surface appeared smoother, indicating the probable formation of an adsorbed dye layer, which is consistent with physical or chemical interaction between the adsorbent and adsorbate (Foo & Hameed, 2010).

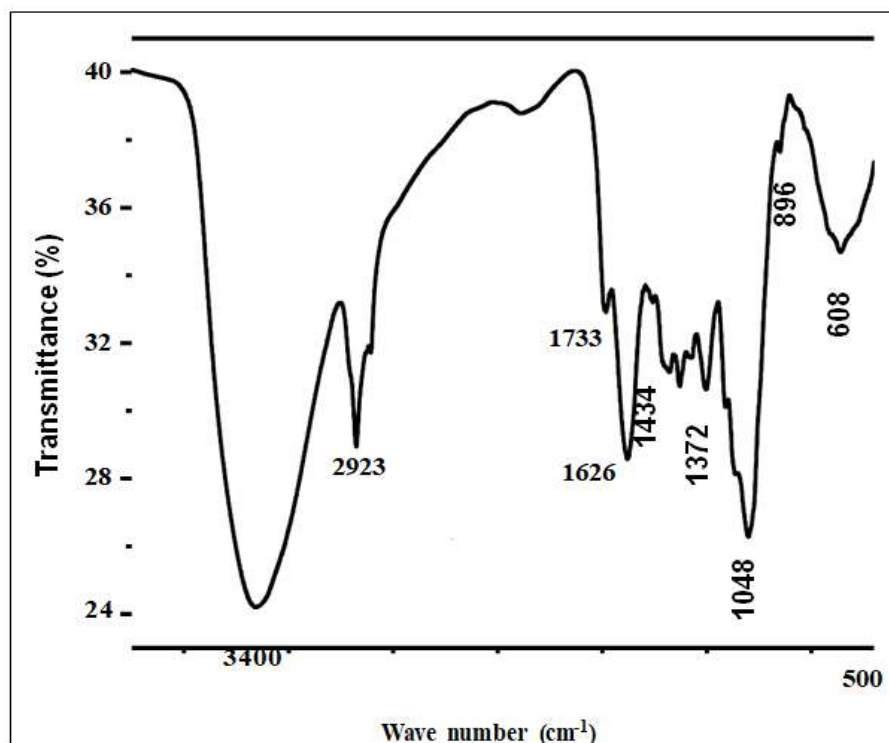


Fig.5.2 FTIR spectrum of MSF

Fourier Transform Infrared Spectroscopy (FTIR) analysis was conducted using a Perkin Elmer Spectrum 100 instrument to identify the functional groups present on the surface of the adsorbent, both before and after dye uptake. The spectrum before adsorption (Fig. 5.2) exhibited a broad peak at around 3400 cm^{-1} indicating O–H stretching vibrations, and a peak at 2923 cm^{-1} corresponding to C–H stretching. Peaks observed at 1733 , 1626 , 1434 , 1372 , 1250 , 1049 , and 896 cm^{-1} were attributed to C=O stretching (carbonyl), N–H bending (amide), $-\text{CH}_2$ vibrations (from cellulose), symmetric N=O stretching, C–O stretching, C–H bending, and =C–H bending, respectively. These functional groups suggest the presence of cellulose, hemicellulose, and lignin components in MFS, which are known to facilitate dye binding (El Haddad et al., 2013).

Quantitative elemental composition was determined using a C, H, N, S elemental analyzer (Quanta 3D FEI), which confirmed that carbon was the most abundant element in the adsorbent, consistent with the lignocellulosic nature of MFS. Other physical properties including ash content, moisture content, and bulk density were measured and are presented in Table 5.1.

2.3 Batch Adsorption Experiments

Batch adsorption experiments were employed to investigate the removal of methylene blue (MB) dye from aqueous solutions using Mahogany Fruit Shell (MFS) as the adsorbent. The initial concentration of MB was systematically varied from 100 to 700 mg/dm³, while maintaining a fixed adsorbent dosage of 450 mg/dm³ for isotherm studies. Each experiment was conducted in 250 mL Erlenmeyer flasks containing 100 mL of dye solution. The suspensions were agitated at 180 rpm using an orbital shaker for a contact time of 420 minutes to ensure equilibrium was reached. The experiments were performed at a constant temperature of 299 ± 2 K and at an initial pH of 9, which is favorable for cationic dye adsorption due to the increased number of negatively charged surface sites on the adsorbent (Crini & Badot, 2008; Rafatullah et al., 2010). For the evaluation of thermodynamic parameters, the adsorption studies were also conducted at varying temperatures ranging from 303 K to 323 K. The equilibrium adsorption capacity of MFS was calculated based on the difference between the initial and final concentrations of MB in solution, following standard adsorption protocols (Ho & McKay, 1999).

3.0 RESULT

3.1 Analysis of Adsorbent

Fourier Transform Infrared Spectroscopy (FTIR) analysis was employed to identify the functional groups involved in the adsorption process. The FTIR spectra of Mahogany Fruit Shell (MFS) before adsorption (Fig. 5.3(A)), Methylene Blue (MB) dye (Fig. 5.3(B)), and MB-adsorbed MFS (Fig. 5.3(C)) clearly demonstrate the successful interaction between MB and MFS. Spectral bands were primarily observed in the region of 2000–400 cm⁻¹, and noticeable shifts and peak merging were evident upon adsorption, indicating chemical interactions.

In Fig. 5.3(C), a peak at 1736 cm⁻¹ corresponds to C=O stretching, slightly shifted from 1733 cm⁻¹ in the original MFS spectrum, suggesting involvement of carbonyl groups. The peak at 1626 cm⁻¹ (N–H bending in MFS) and the 1601 cm⁻¹ band (C=C stretching in MB) appeared merged in the MB-loaded MFS spectrum as a broad band at 1620–1602 cm⁻¹. Similarly, the peak at 1508 cm⁻¹ (C=N stretching in MB) was shifted from 1488 cm⁻¹, and the peak at 1383 cm⁻¹ resulted from overlapping of MB and MFS bands originally at 1372 and 1396 cm⁻¹, respectively. A shift from 1356 cm⁻¹ to 1330 cm⁻¹ was also observed, indicating C–H bending in MB. Moreover, the C–O stretching peak at 1250 cm⁻¹ in MFS was slightly shifted to 1248 cm⁻¹ after adsorption. Additional merged peaks at 1051 cm⁻¹ were attributed to C=S stretching and a strong C–O peak from MFS. The aromatic C=C bending at 886 cm⁻¹ in MB was slightly shifted to 889 cm⁻¹ after adsorption, confirming dye interaction with the adsorbent.

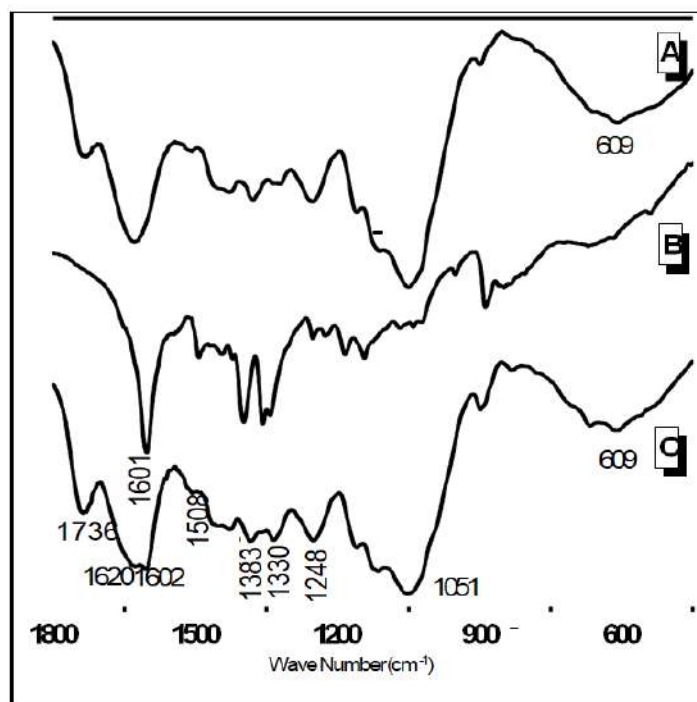


Fig.5.3 FTIR spectrum of (A) MSF, (B) MB and (C) MB adsorbed on MSF

These spectral shifts and band merging confirm the successful adsorption of MB onto MFS and are consistent with findings reported in similar FTIR-based adsorption studies (Ali et al., 2012; Hameed et al., 2009; Senthil Kumar et al., 2010). Scanning Electron Microscopy (SEM) images further corroborate the adsorption behavior. As shown in Fig. 5.4(A) and Fig. 5.4(B), the MFS surface was initially rough and porous; post-adsorption, it appeared to have a smoother texture with a visible surface coating, likely resulting from dye deposition. Similar morphological changes upon adsorption have been previously reported (Bello et al., 2017; Crini & Lichtfouse, 2019).

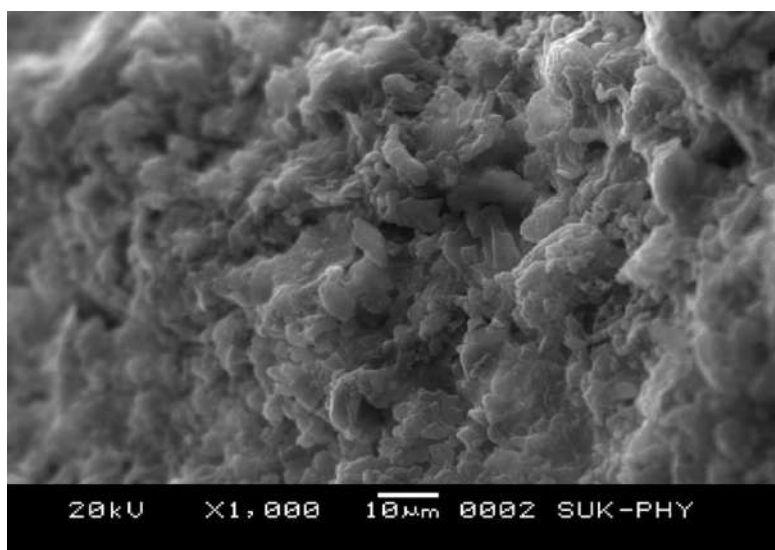


Fig.5.4 (A) SEM image before adsorption of MB

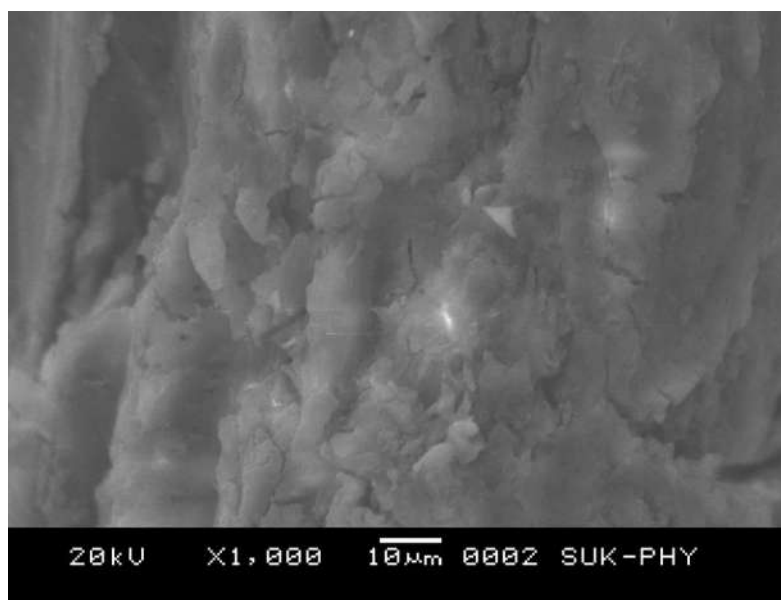


Fig.5.4 (B) SEM image after adsorption of MB

3.2 Effect of pH

pH is a critical parameter in adsorption studies due to its significant impact on the surface charge of the adsorbent and the ionization of the adsorbate. In the present study, the effect of pH on MB adsorption was investigated by varying pH from 1 to 11, using an initial dye concentration of 100 mg/dm^3 and 450 mg of MFS at a constant temperature of $299 \pm 2 \text{ K}$, with agitation at 180 rpm for 420 minutes.

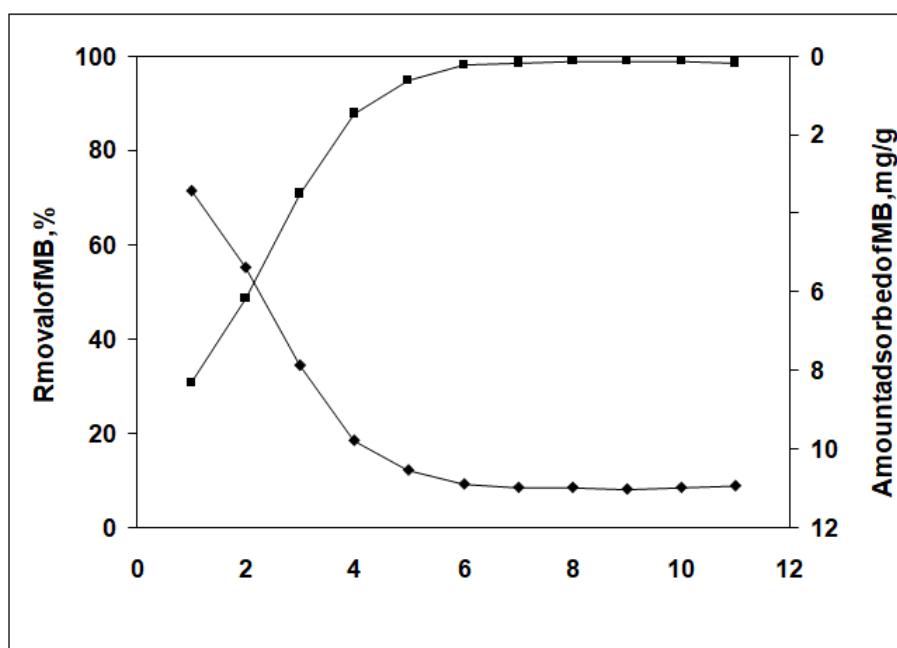


Fig.5.5 Effect of pH on removal, % and amount of MB adsorbed, mg/g
MB= 100 mg/dm^3 , Time=420min, T= $299 \pm 2 \text{ K}$, MSF=450mg, agitationspeed=180rpm

The results (Fig. 5.5) show that adsorption increased with pH, reaching a maximum at pH 9, where the removal efficiency was 99.05%, and the adsorption capacity reached 11.01 mg/g. At pH 6, the dye removal was 98.24% with a slightly lower adsorption capacity of 10.91 mg/g. Therefore, pH 9.0 was selected for subsequent experiments. The enhanced adsorption at alkaline pH is attributed to electrostatic attraction between negatively charged MFS surface and the cationic MB dye. At lower pH, competition between excess H^+ ions and MB cations for adsorption sites results in reduced dye uptake (Hameed, 2009; Cengiz & Cavas, 2008).

3.3 Effect of Contact Time

The influence of contact time on MB adsorption was examined over a range of 0 to 600 minutes using 100 mg/dm³ MB solution at pH 9, 450 mg MFS, and a constant agitation speed of 180 rpm. The results (Fig. 5.6) demonstrate rapid dye removal in the initial stages, followed by a slower adsorption rate as equilibrium approached, with saturation reached after approximately 420 minutes.

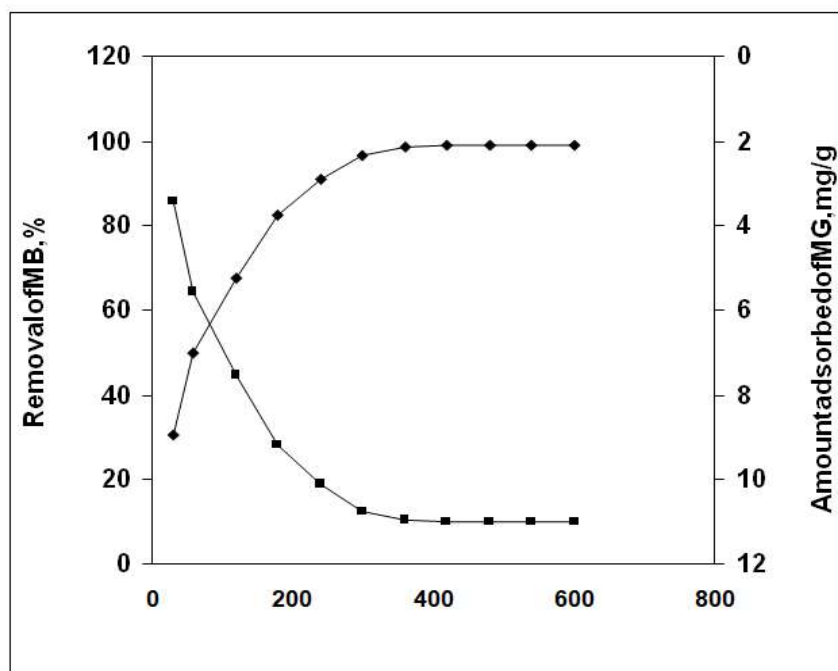


Fig.5.6 Effect of shaking period on removal, % and amount adsorbed, mg/g of MB
MB=100mg/dm³, pH=9, T=299±2K, MFS=450mg, agitation speed=180rpm

This behavior is attributed to the abundant availability of active sites during the initial phase, which become increasingly occupied over time. As the number of unoccupied sites diminishes, intraparticle diffusion and repulsive interactions between adsorbed and free dye molecules slow the adsorption process (Ho & McKay, 1999). After equilibrium was reached, further increases in contact time did not significantly affect adsorption performance. Similar kinetic behavior has been reported in adsorption studies involving

other biomass materials, such as hazelnut shells (Bulut & Aydin, 2006).

3.4 Effect of Initial Methylene Blue (MB) Concentration

The impact of initial MB concentration on the adsorption process was evaluated by varying the dye concentration from 100 to 700 mg/dm³ while maintaining other experimental parameters constant. The results (Fig. 5.7, Table 5.4) indicate that the adsorption capacity of MFS, expressed as equilibrium uptake q_e , increased from 11.01 mg/g to 50.73 mg/g with increasing initial MB concentration. This enhancement in q_e can be attributed to the higher driving force provided by the elevated concentration gradient, which helps to overcome the mass transfer resistance between the aqueous phase and the solid surface (Crini & Badot, 2008).

However, the percentage removal of MB exhibited a decreasing trend, dropping from 99.05% at 100 mg/dm³ to 65.23% at 700 mg/dm³. This inverse relationship occurs because, at higher concentrations, the available adsorption sites become saturated, leading to reduced removal efficiency. Similar trends have been observed with other adsorbents, such as meranti sawdust (Hameed et al., 2007).

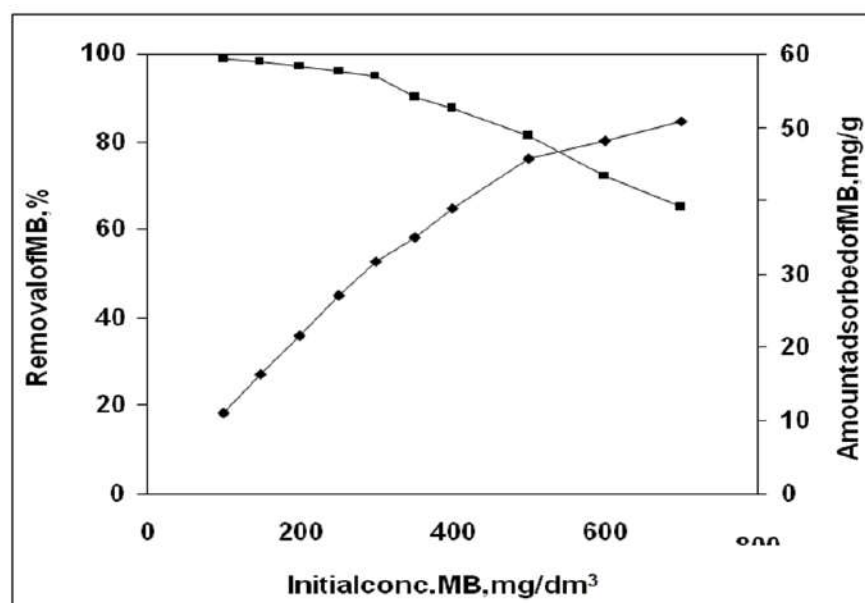


Fig.5.7 Effect of initial concentration of MB on amount adsorbed, mg/g and removal, % of MB
Time=420min, pH=9, T=299±2K, MFS=450mg, agitation speed=180rpm

3.5 Effect of Adsorbent Dosage

To investigate the influence of adsorbent dosage, the MFS amount was varied from 50 to 450 mg in a 100 mg/dm³ MB solution at a constant temperature of 299 ± 2 K. As illustrated in Fig. 5.8 and Table 5.5, the percentage of MB removal increased substantially with increasing adsorbent dosage. A minimal removal efficiency of 4.33% was observed at 50 mg of MFS, whereas a maximum removal of 99.05% was achieved with 450 mg.

This enhancement can be explained by the increase in the number of available active binding sites as more adsorbent is introduced into the system. However, the adsorption capacity per unit mass of adsorbent decreased with increasing dosage. This decline is likely due to aggregation of particles at higher dosages, which leads to a decrease in effective surface area and fewer accessible active sites per gram of adsorbent (Kannan & Sundaram, 2001; Bhattacharyya & Sharma, 2004). This phenomenon has also been documented in earlier studies (Ozer, 2006; Cengiz & Cavas, 2008).

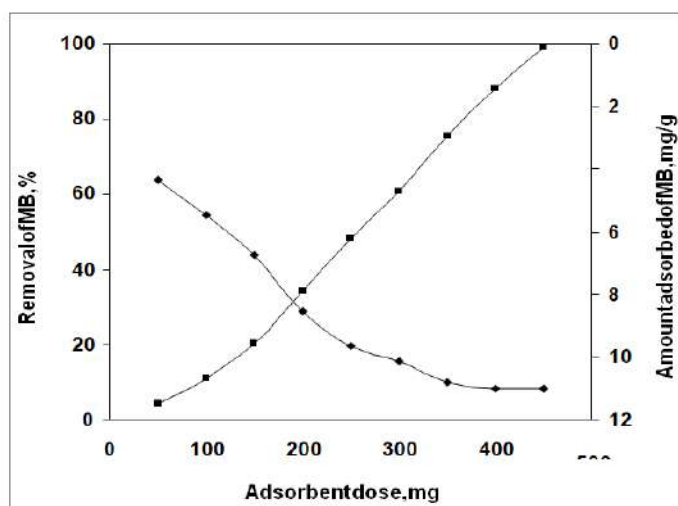


Fig. 5.8 Effect of adsorbent dosage on removal (%) and amount adsorbed (mg/g) of MB
MB=100mg/dm³, Time=420min, pH=9, T=299±2K, agitation speed=180rpm

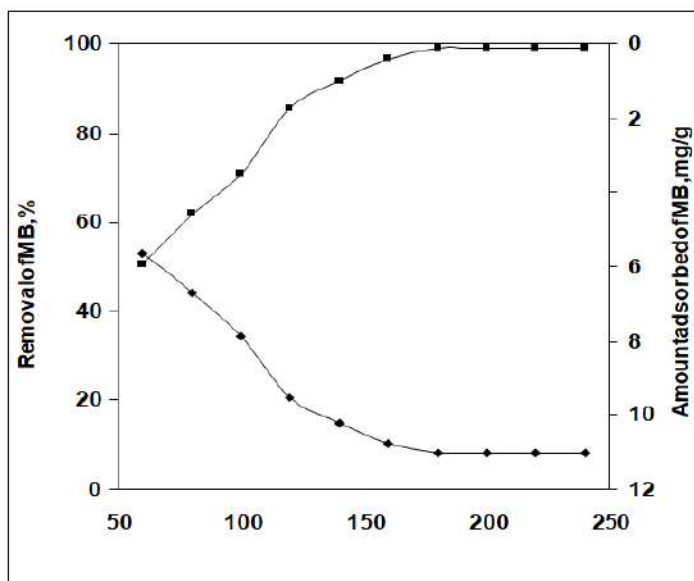


Fig. 5.9 Effect of agitating speed on removal (%) and amount adsorbed (mg/g) of MB
MB=100mg/dm³, Time=420min, T=299±2K, MFS=450mg, pH=9

3.6 Effect of Agitation Speed

Agitation speed plays a significant role in batch adsorption by influencing the thickness of the boundary layer around the adsorbent and promoting mass transfer of solutes from the bulk solution to the adsorbent surface. In this study, agitation speed was varied from 50 to 240 rpm, keeping other parameters constant.

As shown in Fig. 5.9 and Table 5.6, both the amount adsorbed and the percentage removal of MB increased with agitation speed. At 50 rpm, only 50.75% of MB was removed, whereas removal efficiency reached 99.05% at 180 rpm. Beyond this point, further increases in agitation speed had negligible impact on adsorption performance, indicating that equilibrium was achieved. Therefore, 180 rpm was selected as the optimum agitation speed for further experiments. These observations are in agreement with previous findings on agitation effects in dye adsorption studies (Sivakumar & Palanisamy, 2009; Tan et al., 2008).

4.0 DISCUSSIONS

4.1 Adsorption Isotherm

Adsorption isotherms are critical for understanding the interaction between adsorbate and adsorbent at equilibrium under constant temperature. They express the relationship between the amount of solute adsorbed per unit mass of adsorbent (q_e) and the equilibrium concentration of the solute in the solution (C_e). These models help determine the adsorption capacity and provide insights into the mechanism of adsorption (Foo & Hameed, 2010).

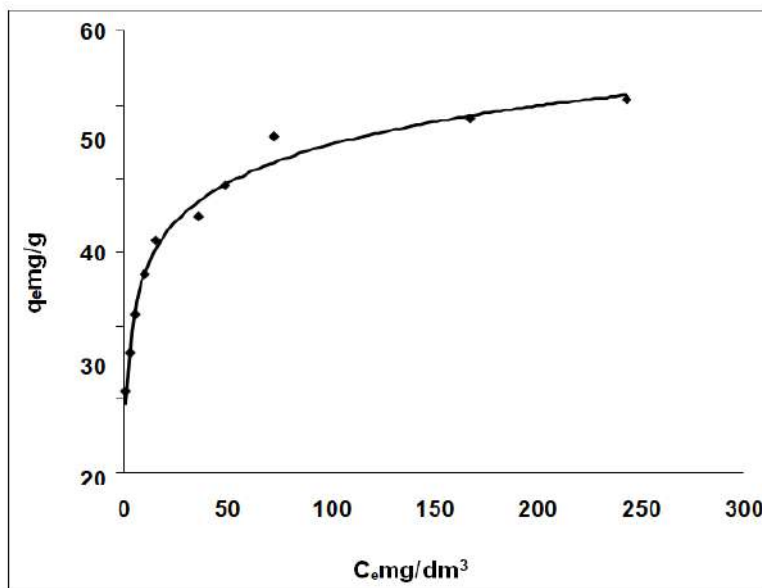


Fig. 5.10 Adsorption isotherm for adsorption of MB on MSF

Time=420min, $T=299 \pm 2K$, MFS=450mg, pH=9, agitation speed=180rpm

In the present study, the equilibrium adsorption data for methylene blue (MB) dye onto MFS were evaluated by plotting q_e against C_e (Fig. 5.10, Table 5.7). The equilibrium adsorption capacity increased with increasing dye concentration, indicating enhanced interaction between MB molecules and the adsorbent surface. Among the various adsorption isotherm models reported in the literature, the Langmuir and Freundlich models are the most widely applied and were used in this study to analyze the adsorption behavior (Crini & Badot, 2008; Tan et al., 2008).

4.2 Langmuir Isotherm

The Langmuir isotherm assumes monolayer adsorption onto a surface with a finite number of identical sites, where each site can hold only one molecule and there is no interaction between adsorbed molecules. It is widely employed to describe adsorption processes involving chemisorption or homogeneous surface energies (Langmuir, 1918).

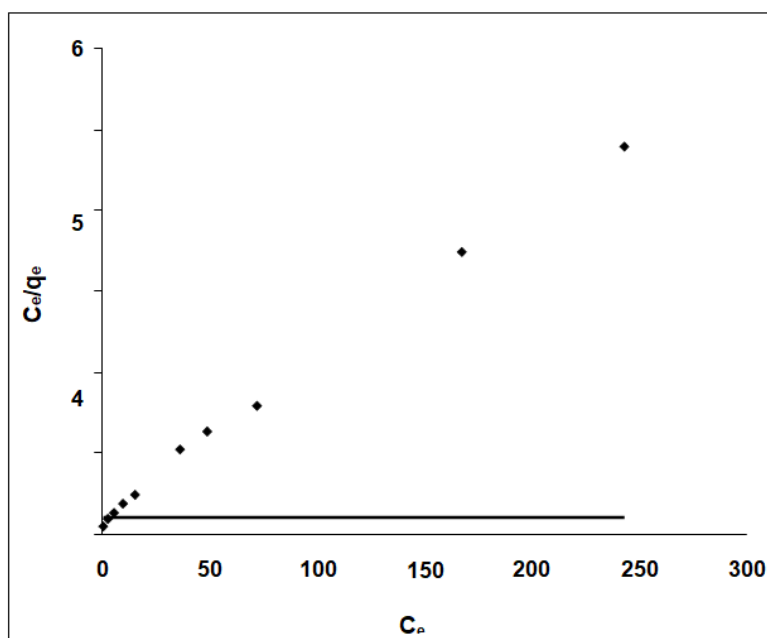


Fig. 5.11 Langmuir isotherm for adsorption of MB on MSF

Time=420min, $T=299 \pm 2K$, MFS=450mg, pH=9, agitation speed=180rpm

For the Langmuir analysis, the initial MB concentration was varied from 100 to 700 mg/dm³ under constant experimental conditions. A plot of C_e/q_e versus C_e (Fig. 5.11, Table 5.8) yielded a linear relationship, with the slope corresponding to $1/q_m$ and the intercept equal to $1/K_L q_m$, where:

- q_m : Maximum monolayer adsorption capacity (mg/g),
- K_L : Langmuir equilibrium constant (dm³/mg),
- C_e : Equilibrium concentration (mg/dm³),

- q_e : Amount adsorbed at equilibrium (mg/g).

A key parameter in Langmuir theory is the dimensionless separation factor (R_L), calculated using the expression:

$$R_L = 1 / [1 + K_L C_0]$$

where C_0 is the initial dye concentration. The R_L values ranged from 0.039 to 0.913, indicating favorable adsorption ($0 < R_L < 1$) (Weber & Chakravorti, 1974). The high correlation coefficient (R^2) obtained suggests an excellent fit of the data to the Langmuir model, confirming that MB adsorption onto MFS proceeds via monolayer coverage.

4.3 Freundlich Isotherm

The Freundlich isotherm is an empirical model that assumes multilayer adsorption on a heterogeneous surface with a non-uniform distribution of heat of adsorption over the surface. This model is particularly suitable when the adsorption sites are diverse and energetically heterogeneous (Freundlich, 1906). A plot of $\log q_e$ Vs. $\log C_e$ (Fig. 5.12, Table 5.10) produced a linear graph, from which the Freundlich constants K_F and $1/n$ were obtained from the intercept and slope, respectively:

- K_F : Freundlich constant related to adsorption capacity,
- $1/n$: Empirical parameter indicating adsorption intensity or surface heterogeneity.

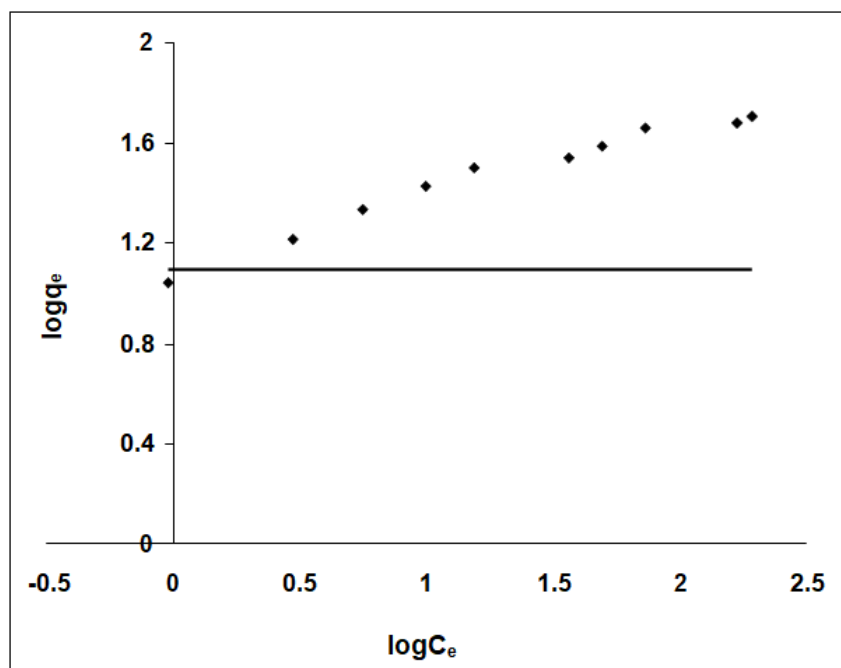


Fig. 5.12 Freundlich adsorption isotherm for adsorption of MB on MSF
Time=420min, T=299±2K, MFS=450mg, pH=9, agitation speed=180rpm

The values are listed in Table 5.11. A value of $1/n < 1$ indicates favorable adsorption and suggests that the adsorption process is physisorption in nature. However, comparison of correlation coefficients from both isotherm models revealed that the Langmuir model provided a better fit than the Freundlich model, suggesting a predominantly monolayer adsorption mechanism on a homogeneous surface.

4.4 Adsorption Kinetics

Adsorption kinetics provide insight into the rate and mechanism of adsorbate uptake by the adsorbent. In this study, kinetic experiments were conducted under constant pH, agitation speed, and temperature, while monitoring the adsorption of methylene blue (MB) onto MFS at various time intervals ranging from 0 to 420 minutes.

To elucidate the adsorption mechanism, pseudo-first-order and pseudo-second-order kinetic models were applied. The pseudo-first-order kinetic model is expressed by the Lagergren equation:

$$\log(q_e - q_t) = \log q_e - \frac{k_1}{2.303} t$$

where q_e and q_t are the adsorption capacities at equilibrium and at time t , respectively, and k_1 is the rate constant (Lagergren, 1898). A linear plot of $\log(q_e - q_t)$ Vs. t (Fig. 5.13, Table 5.12) was obtained. However, the model showed poor correlation ($R^2 = 0.932$), indicating limited applicability in describing the experimental data.

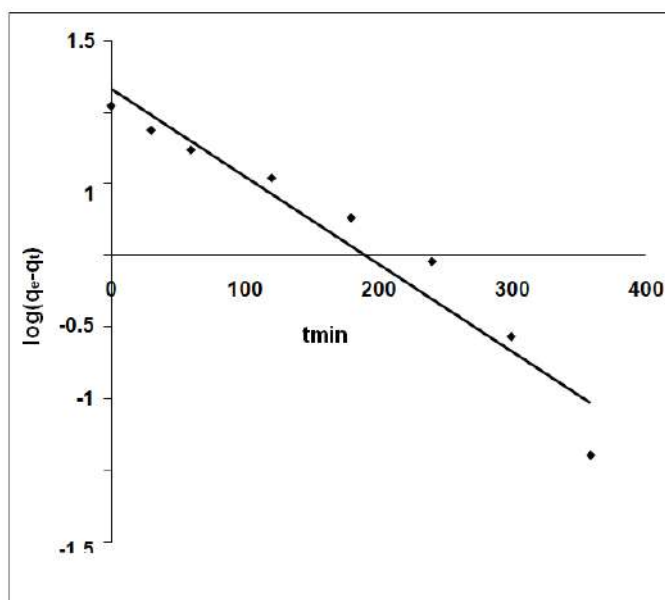


Fig. 5.13 Pseudo-first order plot for adsorption of MB on MSF
MB=100mg/dm³, T=299±2K, MFS=450mg, pH=9, agitation speed=180rpm

The pseudo-second-order kinetic model assumes chemi-sorption as the rate-limiting step and is represented by:

$$\frac{t}{q_t} = \frac{1}{k_2 q_e^2} + \frac{t}{q_e}$$

where k_2 is the rate constant of pseudo-second-order adsorption. A plot of t/q_t Vs. t (Fig. 5.14, Table 5.13) yielded a higher correlation coefficient and better alignment with experimental values (Table 5.14), suggesting that the adsorption of MB onto MFS follows the pseudo-second-order model more accurately (Ho & McKay, 1999).

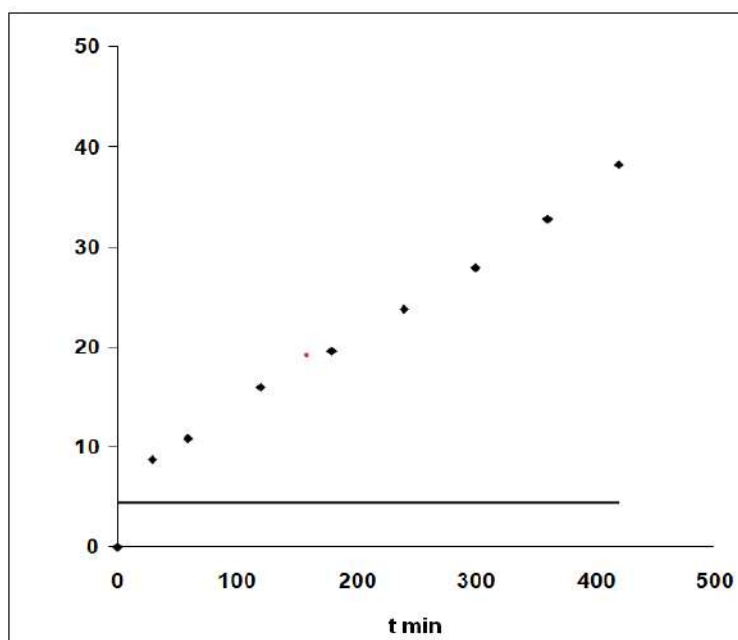


Fig. 5.14 Pseudo-second order plot for adsorption of MB on MSF

MB=100mg/dm³, T=299±2K, MFS=450mg, pH=9, agitationspeed=180rpm

4.5 Intraparticle Diffusion Study

To further examine the adsorption mechanism, the intraparticle diffusion model proposed by Weber and Morris (1963) was employed. This model evaluates whether intraparticle diffusion is the rate-limiting step during adsorption, using the equation:

$$q_t = k_{id} t^{1/2} + C$$

where k_{id} is the intraparticle diffusion rate constant and C is the intercept related to the boundary layer effect.

The plot of q_t Vs. $t^{1/2}$ (Fig. 5.15, Table 5.15) did not pass through the origin, indicating that intraparticle diffusion was not the sole rate-controlling step. Instead, adsorption involved multiple steps, including initial external surface adsorption followed by gradual intraparticle diffusion. The absence of a distinct multi-linear region in the plot suggests that both mechanisms—surface adsorption and intraparticle diffusion—were simultaneously active throughout the process (Weber & Morris, 1963).

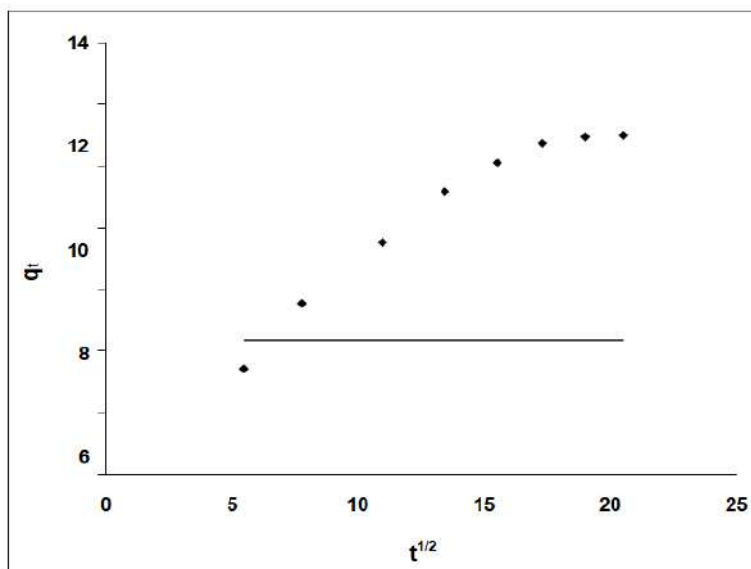


Fig. 5.15 Intraparticle diffusion plot for adsorption of MB on MSF

MB=100mg/dm³, T=299±2K, MFS=450mg, pH=9, agitation speed=180rpm

4.6 Adsorption Thermodynamics

Thermodynamic parameters provide valuable information about the nature and feasibility of the adsorption process. Experiments were conducted at temperatures ranging from 303 K to 323 K, in 5 K intervals, while keeping all other variables constant. The adsorption capacity increased from 53.05 to 61.85 mg/g with temperature, indicating an endothermic adsorption process (Fig. 5.16, Table 5.17).

Thermodynamic parameters including the standard Gibbs free energy change (ΔG°), standard enthalpy change (ΔH°), and standard entropy change (ΔS°) were calculated using the van't Hoff equation:

$$\ln K_c = \frac{-\Delta H^\circ}{RT} + \frac{\Delta S^\circ}{R}$$

where K_c is the equilibrium constant, R is the universal gas constant, and T is the temperature in Kelvin. A linear plot of $\ln K_c$ Vs. $1/T$ (Fig. 5.17, Table 5.18) allowed the determination of ΔH° and ΔS° from the slope and intercept, respectively.

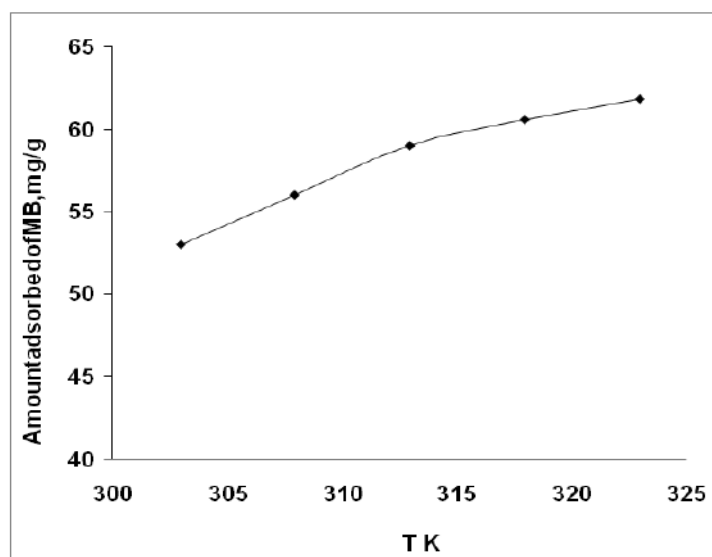


Fig. 5.16 Effect of temperature on amount adsorbed of MB on MSF
MB=700mg/dm³, Time=420min, MFS=450mg, pH=9, agitationspeed=180rpm

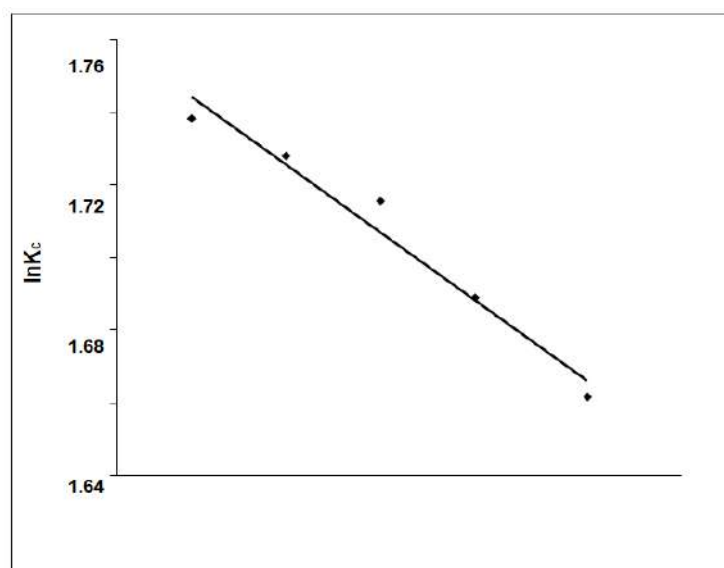


Fig. 5.17 Van't Hoff plots for adsorption of MB on MSF
MB=700mg/dm³, Time=420min, MFS=450mg, pH=9, agitationspeed=180rpm

The thermodynamic parameters listed in Table 5.19 show that the negative values of ΔG° confirm the spontaneity and feasibility of the adsorption process. The positive ΔH° value confirms its endothermic nature, and the positive ΔS° value suggests increased randomness at the solid–solution interface, possibly due to structural rearrangements or increased mobility of dye molecules during adsorption (Saha et al., 2010; Kannan & Sundaram, 2001).

4.7 Comparison of Adsorption Capacity of MFS with Other Adsorbents

The adsorption capacity of MFS was compared with that of other adsorbents reported in the literature (Table 5.20). The comparison revealed that MFS demonstrates a competitive adsorption performance for MB removal, with advantages in terms of cost-effectiveness and environmental sustainability, making it a promising material for large-scale wastewater treatment applications (Crini & Badot, 2008; Tan et al., 2008).

5.0 CONCLUSIONS

The present study demonstrates the potential of mahogany fruit shell (MFS), a low-cost and environmentally sustainable lignocellulosic waste, as an effective biosorbent for the removal of methylene blue (MB) from aqueous solutions. Through comprehensive experimental investigations, including characterization, adsorption isotherm analysis, kinetic modeling, and thermodynamic evaluation, the efficacy and underlying mechanisms of MB adsorption onto MFS were elucidated in detail.

Characterization studies using Scanning Electron Microscopy (SEM) and Fourier Transform Infrared Spectroscopy (FTIR) confirmed that the surface morphology and functional groups of MFS played significant roles in facilitating the adsorption process. SEM images revealed a rough and porous surface prior to adsorption, which became smoother following MB uptake, indicating successful dye deposition. FTIR spectra showed significant shifts and peak merging after adsorption, suggesting the involvement of hydroxyl, carboxyl, and other functional groups in chemical interaction with MB molecules.

Batch adsorption experiments indicated that the adsorption capacity and efficiency of MFS were influenced by several key operational parameters, including solution pH, contact time, initial dye concentration, adsorbent dosage, agitation speed, and temperature. Optimal adsorption was observed at pH 9, with equilibrium achieved around 420 minutes. Maximum adsorption capacity was found to increase with rising initial dye concentration, though the percentage removal efficiency decreased at higher concentrations due to saturation of active sites. Increased adsorbent dosage and agitation speed enhanced dye removal, while higher temperatures favored adsorption, indicating the endothermic nature of the process.

Adsorption isotherm analysis showed that the equilibrium data fitted better to the Langmuir model than the Freundlich model, suggesting monolayer adsorption on a homogeneous

surface. The maximum monolayer adsorption capacity (q_{max}) calculated from the Langmuir model confirms the high uptake potential of MFS compared to many other low-cost adsorbents reported in the literature.

Kinetic studies revealed that the adsorption of MB onto MFS followed a pseudo-second-order model more closely than the pseudo-first-order model, indicating that chemisorption might be the rate-limiting step involving valence forces through sharing or exchange of electrons between adsorbent and adsorbate. Intraparticle diffusion analysis suggested that dye uptake occurred via a multi-step process involving both surface adsorption and gradual pore diffusion, with no single mechanism solely responsible for the adsorption process.

Thermodynamic parameters further supported the spontaneous and endothermic nature of the adsorption. The negative Gibbs free energy change (ΔG°) values confirmed the feasibility of the process, while the positive enthalpy change (ΔH°) indicated heat absorption during dye adsorption. The positive entropy change (ΔS°) reflected increased disorder at the solid-liquid interface, possibly due to desolvation and structural changes occurring on the adsorbent surface.

In summary, this study confirms that MFS is a highly promising biosorbent for the removal of MB from wastewater. Its high adsorption efficiency, coupled with advantages such as low cost, abundance, renewability, and ease of processing, make it an attractive alternative to conventional adsorbents. Furthermore, the valorization of this otherwise discarded biomass contributes to waste minimization and promotes sustainable environmental practices. Future research could focus on the regeneration and reuse potential of MFS, column studies for continuous-flow treatment, and scale-up for industrial applications.

Acknowledgements: The authors are grateful to the IFTM University, University of Moradabad (U.P.), India and also to the Moradabad Institute of Technology, Moradabad (U.P.), India for this opportunity of carrying out the research work and.

Author's Contribution- The authors have equally contributed in the research work and also in drafting the manuscript. The supports received are duly mentioned in the acknowledgement section.

Funding- No funding in any form has been received by any of the author for current work.

Conflicts of Interests- The authors declare that they have no competing or conflicts of interests.

Reference

1. Aksu, Z., & Tezer, S. (2005). Biosorption of reactive dyes on the green alga *Chlorella vulgaris*. *Process Biochemistry*, 40(3-4), 1347–1361.
2. Ali, H. (2010). Biodegradation of synthetic dyes—A review. *Water, Air, & Soil Pollution*, 213(1), 251–273. <https://doi.org/10.1007/s11270-010-0382-4>
3. Ali, I., Asim, M., & Khan, T. A. (2012). Low cost adsorbents for the removal of organic pollutants from wastewater. *Journal of Environmental Management*, 113, 170–183. <https://doi.org/10.1016/j.jenvman.2012.08.028>
4. Amini, M., Younesi, H., Bahramifar, N., Lorestani, A. A. Z., Ghorbani, F., Daneshi, A., & Sharifzadeh, M. (2011). Application of response surface methodology for optimization of lead biosorption in an aqueous solution by *Aspergillus niger*. *Journal of Hazardous Materials*, 154(1–3), 694–702. <https://doi.org/10.1016/j.jhazmat.2007.10.102>
5. Babel, S., & Kurniawan, T. A. (2003). Low-cost adsorbents for heavy metals uptake from contaminated water: A review. *Journal of Hazardous Materials*, B97(1–3), 219–243. [https://doi.org/10.1016/S0304-3894\(02\)00263-7](https://doi.org/10.1016/S0304-3894(02)00263-7)
6. Banat, F., Al-Asheh, S., & Al-Makhadmeh, L. (1996). Utilization of raw and activated date pits for the removal of phenol from aqueous solutions. *Chemical Engineering & Technology*, 23(10), 921–926. [https://doi.org/10.1002/1521-4125\(200010\)23:10<921::AID-CEAT921>3.0.CO;2-C](https://doi.org/10.1002/1521-4125(200010)23:10<921::AID-CEAT921>3.0.CO;2-C)
7. Bello, O. S., Ahmad, M. A., & Ahmad, N. (2017). Adsorptive performance of agricultural waste-based adsorbents for malachite green dye removal from aqueous solutions. *Journal of Cleaner Production*, 141, 1376–1397. <https://doi.org/10.1016/j.jclepro.2016.09.029>
8. Bhattacharyya, K. G., & Sharma, A. (2004). Adsorption of methylene blue on kaolinite. *Applied Clay Science*, 24(1–2), 31–49. <https://doi.org/10.1016/j.clay.2003.12.007>
9. Bukallah, S. B., Rauf, M. A., & AlAli, S. S. (2007). Adsorption of methylene blue on sand from aqueous solution. *Chemical Engineering Journal*, 132(1–3), 73–77. <https://doi.org/10.1016/j.cej.2007.01.009>
10. Bulut, Y., & Aydin, H. (2006). A kinetics and thermodynamics study of methylene blue adsorption on wheat shells. *Desalination*, 194(1–3), 259–267. <https://doi.org/10.1016/j.desal.2005.10.032>
11. Cengiz, S., & Cavas, L. (2008). A natural biosorbent, *Tectona grandis* L. for removal of Methylene Blue dye from aqueous solutions. *Journal of Hazardous Materials*, 153(3), 995–1000. <https://doi.org/10.1016/j.jhazmat.2007.09.042>
12. Cengiz, S., & Cavas, L. (2008). Removal of methylene blue by invasive marine seaweed: *Caulerpa racemosa* var. *cylindracea*. *Journal of Hazardous Materials*, 161(2–3), 1454–1460. <https://doi.org/10.1016/j.jhazmat.2008.04.107>
13. Chen, J., Wang, Z., Zhang, S., & Yu, Y. (2011). Preparation and adsorption properties of mesoporous carbons templated from zeolite X for methylene blue removal. *Journal of Hazardous Materials*, 190(1–3), 1023–1030. <https://doi.org/10.1016/j.jhazmat.2011.04.008>

14. Christie, R. M. (2007). *Colour Chemistry*. Royal Society of Chemistry.
15. Crini, G. (2006). Non-conventional low-cost adsorbents for dye removal: A review. *Bioresource Technology*, 97(9), 1061–1085. <https://doi.org/10.1016/j.biortech.2005.05.001>
16. Crini, G., & Badot, P. M. (2008). Application of chitosan, a natural aminopolysaccharide, for dye removal from aqueous solutions by adsorption processes using batch studies: A review of recent literature. *Progress in Polymer Science*, 33(4), 399–447. <https://doi.org/10.1016/j.progpolymsci.2007.11.001>
17. Crini, G., & Lichtfouse, E. (2019). Advantages and disadvantages of techniques used for wastewater treatment. *Environmental Chemistry Letters*, 17, 145–155. <https://doi.org/10.1007/s10311-018-0785-9>
18. Demirbas, A. (2008). Heavy metal adsorption onto agro-based waste materials: A review. *Journal of Hazardous Materials*, 157(2–3), 220–229. <https://doi.org/10.1016/j.jhazmat.2008.01.024>
19. Demirbas, A. (2009). Agricultural based activated carbons for the removal of dyes from aqueous solutions: A review. *Journal of Hazardous Materials*, 167(1–3), 1–9. <https://doi.org/10.1016/j.jhazmat.2008.12.114>
20. El Haddad, M., Regti, A., Laamari, M. R., Mamouni, R., & Saffaj, N. (2013). Removal of methylene blue from aqueous solution using Moroccan clay. *Journal of Materials and Environmental Science*, 4(6), 1033–1040.
21. Foo, K. Y., & Hameed, B. H. (2010). Insights into the modeling of adsorption isotherm systems. *Chemical Engineering Journal*, 156(1), 2–10. <https://doi.org/10.1016/j.cej.2009.09.013>
22. Forgacs, E., Cserháti, T., & Oros, G. (2004). Removal of synthetic dyes from wastewaters: A review. *Environment International*, 30(7), 953–971. <https://doi.org/10.1016/j.envint.2004.02.001>
23. Freundlich, H. (1906). Over the adsorption in solution. *Journal of Physical Chemistry*, 57, 385–470.
24. Garg, V. K., Gupta, R., Yadav, A. B., & Kumar, R. (2004). Dye removal from aqueous solution by adsorption on treated sawdust. *Bioresource Technology*, 89(2), 121–124. [https://doi.org/10.1016/S0960-8524\(03\)00174-0](https://doi.org/10.1016/S0960-8524(03)00174-0)
25. Gupta, V. K., & Suhas. (2009). Application of low-cost adsorbents for dye removal—A review. *Journal of Environmental Management*, 90(8), 2313–2342. <https://doi.org/10.1016/j.jenvman.2008.11.017>
26. Hameed, B. H. (2009). Spent tea leaves: A new non-conventional and low-cost adsorbent for removal of basic dye from aqueous solutions. *Journal of Hazardous Materials*, 161(2–3), 753–759. <https://doi.org/10.1016/j.jhazmat.2008.04.019>
27. Hameed, B. H., Ahmad, A. A., & Aziz, N. (2007). Isotherms, kinetics and thermodynamics of acid dye adsorption on activated palm ash. *Chemical Engineering Journal*, 133(1–3), 195–203. <https://doi.org/10.1016/j.cej.2007.01.032>

28. Han, R., Zhang, L., Song, C., Zhang, M., Zhu, H., & Zhang, L. (2009). Characterization of modified zeolite and adsorption of methylene blue and aromatic compounds from aqueous solution. *Colloids and Surfaces A: Physicochemical and Engineering Aspects*, 328(1–3), 97–102. <https://doi.org/10.1016/j.colsurfa.2008.06.065>
29. Ho, Y. S., & McKay, G. (1999). Pseudo-second order model for sorption processes. *Process Biochemistry*, 34(5), 451–465. [https://doi.org/10.1016/S0032-9592\(98\)00112-5](https://doi.org/10.1016/S0032-9592(98)00112-5)
30. Hunger, K. (2003). *Industrial Dyes: Chemistry, Properties, Applications*. Wiley-VCH.
31. Igbinosa, O. O., Igbinosa, E. O., & Aiyegoro, O. A. (2009). Antimicrobial activity and phytochemical screening of stem bark extracts from *Jatropha curcas* (Linn). *African Journal of Pharmacy and Pharmacology*, 3(2), 058–062.
32. Kannan, N., & Sundaram, M. M. (2001). Kinetics and mechanism of removal of methylene blue by adsorption on various carbons: A comparative study. *Dyes and Pigments*, 51(1), 25–40. [https://doi.org/10.1016/S0143-7208\(01\)00056-0](https://doi.org/10.1016/S0143-7208(01)00056-0)
33. Lagergren, S. (1898). Zur Theorie der sogenannten Adsorption gelöster Stoffe. *Kungliga Svenska Vetenskapsakademiens Handlingar*, 24(4), 1–39.
34. Langmuir, I. (1918). The adsorption of gases on plane surfaces of glass, mica and platinum. *Journal of the American Chemical Society*, 40(9), 1361–1403. <https://doi.org/10.1021/ja02242a004>
35. Molina-Sabio, M., & Rodríguez-Reinoso, F. (2004). Role of chemical activation in the development of carbon porosity. *Colloids and Surfaces A: Physicochemical and Engineering Aspects*, 241(1–3), 15–25. <https://doi.org/10.1016/j.colsurfa.2004.04.007>
36. Namasivayam, C., & Kanchana, N. (1992). Waste banana pith as adsorbent for the removal of Rhodamine B from aqueous solution. *Waste Management*, 12(5), 283–295. [https://doi.org/10.1016/0956-053X\(92\)90064-J](https://doi.org/10.1016/0956-053X(92)90064-J)
37. Oz, M., Lorke, D. E., & Petroianu, G. A. (2007). Methylene Blue and Alzheimer's Disease. *Biochemical Pharmacology*, 74(7), 1074–1083. <https://doi.org/10.1016/j.bcp.2007.07.017>
38. Ozer, D. (2006). Removal of Pb(II) ions from aqueous solutions by sulphuric acid-treated wheat bran. *Journal of Hazardous Materials*, 141(3), 753–761. <https://doi.org/10.1016/j.jhazmat.2006.07.009>
39. Pelgrims, J., De Vos, F. Y., Van den Brande, J., Schrijvers, D., & Prové, A. (2000). Methylene blue in the treatment and prevention of ifosfamide-induced encephalopathy: Report of 20 cases and a review of the literature. *British Journal of Cancer*, 82(2), 291–294. <https://doi.org/10.1054/bjoc.1999.0911>
40. Rafatullah, M., Sulaiman, O., Hashim, R., & Ahmad, A. (2010). Adsorption of methylene blue on low-cost adsorbents: A review. *Journal of Hazardous Materials*, 177(1–3), 70–80. <https://doi.org/10.1016/j.jhazmat.2009.12.047>

41. Rivai, H., Rozi, F., & Jaya, A. (2021). Phytochemical screening and pharmacological activities of *Swietenia mahagoni* (L.) Jacq: A review. *Journal of Natural Sciences Research*, 11(3), 1–8.
42. Robinson, T., McMullan, G., Marchant, R., & Nigam, P. (2001). Remediation of dyes in textile effluent: A critical review on current treatment technologies with a proposed alternative. *Bioresource Technology*, 77(3), 247–255. [https://doi.org/10.1016/S0960-8524\(00\)00080-8](https://doi.org/10.1016/S0960-8524(00)00080-8)
43. Saha, P., Chowdhury, S., Gupta, S., & Kumar, I. (2010). Insight into adsorption thermodynamics. *Chemical Engineering Journal*, 160(1), 23–31. <https://doi.org/10.1016/j.cej.2010.03.025>
44. Saratale, R. G., Saratale, G. D., Chang, J. S., & Govindwar, S. P. (2011). Bacterial decolorization and degradation of azo dyes: A review. *Journal of the Taiwan Institute of Chemical Engineers*, 42(1), 138–157. <https://doi.org/10.1016/j.jtice.2010.06.006>
45. Senthil Kumar, P., Ramalingam, S., & Sathyaselvabala, V. (2010). Removal of methylene blue dye from aqueous solution by sorption onto *Ficus benghalensis* leaf powder. *Asian Journal of Chemistry*, 22(8), 6093–6098.
46. Sharma, Y. C., Srivastava, V., & Singh, V. K. (2015). *Dyes and Pigments: Chemistry and Applications*. Nova Science Publishers.
47. Sivakumar, P., & Palanisamy, P. N. (2009). Adsorption studies of basic red 29 by a non-conventional activated carbon prepared from *Euphorbia antiquorum* L. *International Journal of ChemTech Research*, 1(3), 502–510.
48. Sivakumar, V., Chen, W. H., & Lin, J. G. (2009). Sonochemical degradation of azo dyes in aqueous solution. *Ultrasonics Sonochemistry*, 16(6), 838–843. <https://doi.org/10.1016/j.ultsonch.2009.02.008>
49. Tan, I. A. W., Ahmad, A. L., & Hameed, B. H. (2008). Adsorption of basic dye on high-surface-area activated carbon prepared from coconut husk: Equilibrium, kinetic and thermodynamic studies. *Journal of Hazardous Materials*, 154(1–3), 337–346. <https://doi.org/10.1016/j.jhazmat.2007.10.031>
50. Wang, X., Liu, Y., & Wang, J. (2010). Adsorption of dyes onto gypsum: equilibrium, kinetics, and thermodynamic studies. *Desalination*, 259(1–3), 22–28.
51. Weber, T. W., & Chakravorti, R. K. (1974). Pore and solid diffusion models for fixed-bed adsorbers. *AIChE Journal*, 20(2), 228–238. <https://doi.org/10.1002/aic.690200204>
52. Weber, W. J., & Morris, J. C. (1963). Kinetics of adsorption on carbon from solution. *Journal of the Sanitary Engineering Division*, 89(2), 31–60.
53. Zhao, B., Wang, Y., & Wang, C. (2013). Removal of synthetic dyes from wastewater using membrane technologies: A review. *Desalination and Water Treatment*, 51(37–39), 7654–7664. <https://doi.org/10.1080/19443994.2013.792520>