Utilizing Jackfruit Peel as a Sustainable Adsorbent for Methylene Blue Dye: Adsorption Efficiency and Isotherm Analysis

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Abstract

This study investigates the potential of jackfruit peel, an agricultural waste, as a sustainable and low-cost adsorbent for removing methylene blue (MB) dye from wastewater. Adsorption parameters, including adsorbent dosage (0.15–0.45 g), initial dye concentration (5–300 mg/L), pH (3–9), temperature (30–55 °C), and contact time (3–90 minutes), were systematically optimized. The highest adsorption capacity (36.48 mg/g) was achieved within 5 minutes, indicating rapid kinetics and strong dye affinity. The process was most effective at pH 9, consistent with the pH_{pzc} value of 4.92, which enhances electrostatic attraction between the negatively charged adsorbent surface and the cationic dye. Isotherm fitting revealed multilayer adsorption on a heterogeneous surface, as described by the Freundlich and Temkin models. Surface characterization showed an irregular morphology and a BET surface area of 4.006 m²/g. Thermodynamic analysis confirmed that the process is spontaneous and endothermic. The substantial annual availability of jackfruit peel, along with its sustainable processing and high adsorption efficiency, makes it an excellent eco-friendly adsorbent for wastewater treatment. This abundant by-product offers a cost-effective alternative to traditional adsorbents and demonstrates its practical utility in removing pollutants like methylene blue dye. Additionally, its chemical-free preparation process ensures that jackfruit peel is safe, scalable, and environmentally friendly, making it a viable solution for both community-level and industrial-scale applications.

Keywords: Jackfruit peel, Sustainable adsorbent, Adsorption efficiency, Isotherm Analysis

1. Introduction

Environmental issues arising from the dyeing industry have become a global concern due to the discharge of wastewater containing dyes and chemicals into natural water sources, which negatively impacts ecosystems and human health. The dyes used in the dyeing process are often complex chemical substances that are not easily biodegradable in nature. When released untreated, these dyes can cause long-term degradation of water quality, reduce light penetration in aquatic environments, and disrupt photosynthesis in aquatic plants, ultimately harming aquatic life and biodiversity. Moreover, the toxic and carcinogenic nature of many dyes poses serious risks to both aquatic organisms and humans through bioaccumulation and biomagnification in the food chain. Therefore, the development of efficient and environmentally friendly wastewater treatment methods is crucial to mitigate these adverse effects. [1–3]

Methylene blue (MB), a common cationic dye, contains aromatic amines known to be potentially carcinogenic. Prolonged exposure to MB can cause severe health issues, including increased heart rate, vomiting, shock, tissue damage, and other systemic complications. Its widespread use in textile, paper, and pharmaceutical industries make it a prevalent pollutant in industrial effluents. Consequently, effective removal of MB from wastewater is essential to protect environmental and public health on a global scale. [4]

Various chemical and physical treatment methods have been developed for dye removal, including membrane composite filtration, [5] photocatalysis, [6] coagulation-flocculation, [7] and adsorption. [8] Among these, adsorption has emerged as a particularly effective technique due to its simplicity, versatility, and cost-effectiveness. [9] Adsorption processes do not require complex infrastructure, are easy to operate and maintain, generate minimal sludge compared to chemical treatments, and can be applied to a wide range of contaminants. Moreover, adsorption enables the recovery and regeneration of adsorbents, making it a sustainable and environmentally friendly approach to wastewater treatment. [10]

In recent years, considerable attention has been given to natural and low-cost adsorbent materials derived from agricultural byproducts and waste materials, which provide an eco-friendly alternative to conventional synthetic adsorbents. Examples include bagasse from sugarcane [11], coconut shells [12], corn cobs [13] and fruit peels [14]. These materials are abundant, renewable, biodegradable, and often require minimal processing, thereby reducing both economic and environmental costs associated with adsorbent production and disposal. [15]

Jackfruit (*Artocarpus heterophyllus*) is cultivated across all regions of Thailand and prefers a hot, humid climate. According to the Department of Agricultural Extension national production totaled 69,560 tons per year, with an average price of 13.10 baht/kg, yielding a market value of 911.24 million baht. Approximately 60% of this yield is jackfruit peel, generating around 41,736 tons of agricultural waste annually. [16]

Jackfruit peel, an abundant agricultural byproduct, has attracted attention for its potential as a natural adsorbent in environmental remediation. Its availability and inherent surface properties make it a promising candidate for removing pollutants such as synthetic dyes from wastewater. Utilizing such biomass not only addresses agricultural waste management but also aligns with circular economy principles by transforming waste into value-added materials. In addition, the preparation process of jackfruit peel as an adsorbent is simple, non-complex, and does not involve the use of chemicals, making it environmentally friendly. This allows for practical application by farmers and community enterprises in treating dye-contaminated wastewater from traditional textile production. Furthermore, it can also be scaled up for use in industrial settings, as the raw material is abundantly available and the production cost is relatively low. Integrating these natural adsorbents into wastewater treatment systems presents a sustainable strategy to mitigate dye pollution and reduce dependence on non-biodegradable synthetic materials. [17] Previous studies have shown that oven dried jackfruit peel can adsorb dyes, but with limited capacity (1.98–4.361 mg/g) [18] compared to activated carbon derived from jackfruit peel, which achieves significantly higher values (10.43–400.06 mg/g). [19] However, the preparation of activated carbon requires chemical treatment and high energy input. This highlights the need for simpler, low-cost, and eco-friendly alternatives with improved adsorption performance. /

This study investigates the potential of jackfruit peel (*Artocarpus heterophyllus*), an abundant and underutilized agricultural by-product, as a low-cost, biodegradable, and eco-friendly adsorbent for the removal of methylene blue (MB) dye from aqueous solutions. Given the increasing environmental concerns over dye pollution in industrial effluents, especially from textile operations, the development of sustainable adsorbents derived from biomass offers a promising alternative to conventional treatment methods. Jackfruit peel is locally available, renewable, and typically discarded as waste, yet it holds significant potential for value-added applications.

From a sustainability perspective, the use of jackfruit peel aligns with the principles of circular economy by transforming organic waste into a functional material for environmental remediation. Its preparation requires minimal energy and chemical input, resulting in a low carbon footprint. Moreover, the material is safe, biodegradable, and compatible with decentralized or small-scale treatment systems—making it especially suitable for rural or resource-limited communities. The valorization of such biomass not only reduces environmental burdens from agricultural waste disposal but also decreases reliance on synthetic, non-renewable adsorbents. The research systematically explores the influence of key operational parameters—including adsorbent dosage, initial dye concentration, pH, and temperature—on dye removal efficiency. Adsorption isotherms and thermodynamic analyses ($\Delta G°$, $\Delta H°$, $\Delta S°$) are also conducted to evaluate the mechanism and spontaneity of the adsorption process. Surface morphology, examined through Scanning Electron Microscopy (SEM), provides insights into the porous structure and functional sites of the jackfruit peel. By integrating performance evaluation with sustainability considerations, this study aims to highlight jackfruit peel as a viable and environmentally responsible solution for wastewater treatment. The findings contribute to the advancement of green technologies and promote the utilization of renewable resources in addressing water pollution challenges, particularly in the dyeing and textile industries. [20]

2. Materials and Methods

The Jackfruit peel (Artocarpus heterophyllus) was sourced from Narathiwat Province. Methylene blue (MB) dye was procured from Sigma-Aldrich, Bangalore, India. The molecular structure of methylene blue as well as its physicochemical characteristics are shown in **Figure 1** and **Table 1**, respectively. The optical density of the dye solution was measured using a UV–vis spectrophotometer (Shimadzu 1800), the absorbance of MB solutions at the maximum wavelength (λ_{max}) of 665 nm. [21],[22] Reagents used in the experiments were of analytical grade.

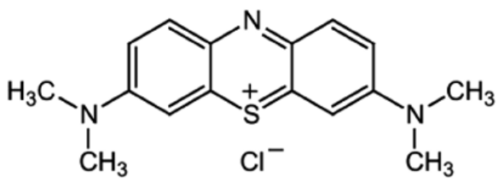

Figure 1 Methylene blue molecular structure

Table 1 Methylene blue physicochemical properties

Parameters	Value
Molecular formula	$C_{16}H_{18}ClN_3S$
Molecular weight	319.85 g.mol^{-1}
Dye family	Basic
Maximum wavelength (λ_{max})	664–665 nm
Solubility	Highly soluble in water
Density	~1.25 g/cm^3 (solid form)
Charge	Positive (cationic dye)

2.1 Preparation of materials

The jackfruit peel was cut into small pieces, approximately 1 × 1 cm^2 in size, washed thoroughly, and then dried in a hot air oven at 50°C for 24 hours. The dried pieces were ground into a fine powder and sifted through a 0.25 mesh sieve. The powder was then dried again at 60°C for 24 hours, resulting in light brown jackfruit peel powder, which was stored in a moisture-absorbing container. The preparation process of the jackfruit peel adsorbent is shown in **Figure 2**.

Figure 2 The preparation process of the jackfruit peel adsorbent.

2.2 Characterization techniques

The surface morphology of the prepared jackfruit peel adsorbent was examined using a scanning electron microscope (SEM, Quanta 400), revealing a porous and heterogeneous structure. To further investigate its textural properties, the specific surface area was determined by the Brunauer–Emmett–Teller (BET) method [23], using a high-pressure volumetric analyzer (Quantachrome Instruments, version 5.21). The BET surface area was calculated from a five-point nitrogen adsorption isotherm, with data collected up to a relative pressure (P/P_0) of 0.3. Ultra-high-purity nitrogen (N_2) was used as the adsorbate during the analysis.

2.3 Adsorption experiments

The adsorption performance of the prepared jack fruit peel was evaluated using methylene blue (MB) as a model dye. A UV–Visible spectrophotometer was employed to measure the absorbance of MB solutions at the maximum wavelength (λ_{max}) of 665 nm. The initial and residual concentrations of MB were determined to calculate the adsorption efficiency.

The experiments were conducted under varying operational conditions to determine the optimal parameters for effective dye removal. The experimental steps are shown in **Figure 3**.

The studied parameters included adsorbent dosage, initial dye concentration, pH of the dye solution, and temperature. The contact time was maintained at a constant 90 minutes for all experiments.

The study of the amount of jackfruit peel adsorbent was conducted using different amounts of jackfruit peel: 0.15, 0.30, and 0.45 grams, with a methylene blue dye concentration of 10 mg/L and a volume of 100 mL. The mixture was then shaken at 320 rpm, and samples of the methylene blue dye were collected at 3, 5, 10, 30, 60, and 90 minutes until adsorption equilibrium was reached. The samples were then centrifuged at 3000 rpm for 5 minutes, and the absorbance was measured using a UV-Vis spectrophotometer at the maximum wavelength (λ_{max}) of methylene blue, which is 665 nm.

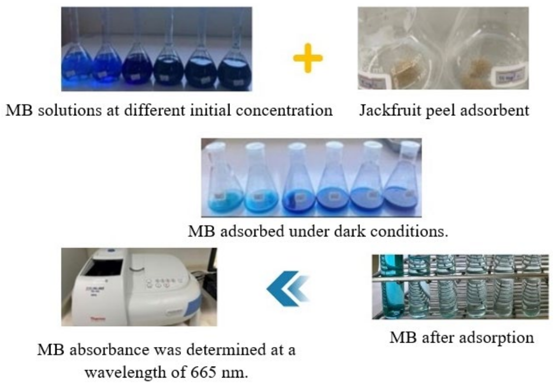

Figure 3 Adsorption experimental process

The study of the effect of MB concentration on adsorption, that was conducted by varying the dye concentrations to different levels: 5, 10, 50, 100, 150, and 300 mg/L. A 0.15 g sample of jackfruit peel was placed in a 250 mL conical flask, and methylene blue dye at the different concentrations was added. The mixture was then shaken at 320 rpm, and samples of the methylene blue dye were collected at 3, 5, 10, 30, 60 and 90 minutes until adsorption equilibrium was reached. The samples were then centrifuged at 3000 rpm for 3 minutes. The absorbance of the dye was measured, and the amount of methylene blue remaining in the solution was analyzed using a spectrophotometer.

The effect of pH on methylene blue (MB) dye adsorption was investigated at pH levels of 3, 5, and 9. A 0.15 g sample of jackfruit peel was added to a 250 mL conical flask containing 100 mL of methylene blue dye solution at a concentration of 150 mg/L, adjusted to the specified pH levels. The mixtures were then shaken at 320 rpm, and samples were collected at 3, 5, 10, 30, 60, and 90 minutes to monitor adsorption equilibrium. Following the adsorption process, the samples were centrifuged at 3000 rpm for 3 minutes. The absorbance of the dye was measured, and the amount of methylene blue remaining in the solution was determined using a UV-Vis spectrophotometer.

The effect of temperature on the adsorption of methylene blue (MB) dye was studied at 30°C, 35°C, and 55°C. A 0.15 g sample of jackfruit peel was placed in a 250 mL conical flask, and 100 mL of 150 mg/L methylene blue dye solution was added. The mixture was then shaken at the respective temperatures at a speed of 320 rpm. Samples were collected at 3, 5, 10, 30, 60, and 90 minutes until adsorption equilibrium was reached. The samples were then centrifuged at 3000 rpm for 3 minutes. The absorbance of the dye was measured, and the amount of methylene blue remaining in the solution was analyzed using a spectrophotometer.

The supernatant from all samples was analyzed using UV–Vis spectroscopy to determine absorbance and assess the remaining dye concentration. Each experiment was conducted in triplicate to ensure accuracy and reproducibility. The percentage removal of methylene blue (MB), which evaluates the adsorption efficiency of the prepared jackfruit peel, was calculated using Eq. (1). The equilibrium adsorption capacity (mg/g), representing the amount of pollutant adsorbed under specified conditions, was calculated using Eq. (2). In these equations, V (L) and W (g) represent the solution volume and adsorbent mass, respectively. The equations and definitions of the variables are presented below. [24]

$$\%\ \text{removal} = \left(\frac{C_i - C_e}{C_i}\right) \times 100 \quad (1)$$

$$q_e = \left(\frac{C_i - C_e}{W}\right) \times V \quad (2)$$

where:

Ci = initial concentration (mg/L)
C_e = equilibrium concentration (mg/L)
q_e = equilibrium adsorption capacity, (mg/g)
V = solution volume (L)
W= adsorbent mass (g)

2.4 The pH at point of zero charge

The pH at point of zero charge (pH_{pzc}) was determined using the drift method. A 0.10 M HCl and NaOH solution were employed to adjust the pH of a 0.01 M NaCl solution, covering a range from pH 2 to 10. One gram of jackfruit peel was added to each solution and left for 24 hours at room temperature. [25],[26]

2.5 Adsorption isotherm

Equilibrium data were used to evaluate the applicability of different adsorption isotherm models, including the Freundlich and Temkin isotherms, as expressed in Eq. (3) and Eq. (4). The Freundlich isotherm describes adsorption on heterogeneous surfaces with a non-uniform distribution of heat of adsorption and affinities. The Freundlich coefficients K_f and 1/n can be determined by linear regression from a plot of logq_e versus logC_e based on the linearized logarithmic form of the Freundlich equation. [26]

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

where:

C_e = equilibrium concentration (mg/L)
q_e = equilibrium adsorption capacity, (mg/g)
K_f = Freundlich constant

Here, K_f indicates the relative adsorption capacity of the adsorbent in relation to bonding energy, while n is the heterogeneity factor representing deviation from linear adsorption behavior. The plot was constructed at 293.15 K to obtain the Freundlich constants. [27]

The Temkin isotherm considers the effects of adsorbate–adsorbate interactions on adsorption process. This model postulates that the heat of adsorption of all molecules in the layer decrease linearly with increasing surface coverage due to these interactions. The linear form of the Temkin equation is given by Eq. (4). [28]

$$q_e = B \ln A + B\ ln\ C_e \quad (4)$$

where:

A = Temkin equilibrium binding constant (L/g)
B = constant related to the heat of adsorption and is expressed as *B* = RT/b, R is the universal gas constant (8.314J.mol^{-1}·K). T is the absolute temperature (K) and b is the Temkin constant, typically expressed (J/mol).

The constants *A* and *B* can be obtained from the slope and intercept of the linear plot of q_e versus lnC_e. A higher value of *A* implies stronger adsorbent–adsorbate binding affinity, whereas a positive *B* value suggests that adsorption is exothermic and the surface is energetically homogeneous within the studied concentration range.

3. Results and Discussion

3.1 SEM and BET analysis

The surface morphology of the jackfruit peel adsorbent was examined using scanning electron microscopy (SEM) at various resolutions: 100 µm with 200 × magnification (**Figure 4(a)**), 10 µm with 500× magnification (**Figure 4(b)**), and 1 µm with 500 × magnification (**Figure 4(c)**). SEM images revealed a heterogeneous surface with irregular shapes, sizes, and pore distributions. This non-uniform morphology significantly enhances the adsorption capacity of jackfruit peel by providing diverse surface features that facilitate stronger interactions with dye molecules. The varying pore sizes also allow for multilayer adsorption, accommodating dye molecules of different sizes.

The surface area of jackfruit peel powder was measured using the Multi-Point BET method, yielding a value of 4.006 m²/g. A larger surface area increases the number of active sites and contact area, enhancing adsorption efficiency. Despite its moderate surface area, the results indicate that jackfruit peel powder has sufficient surface availability for effective adsorption. This finding is consistent with previous studies that demonstrated strong adsorption performance despite moderate surface areas [29]. The high correlation coefficient (r = 0.993728) from the BET analysis further confirms the accuracy and reliability of the measurement.

The heterogeneous surface and moderate surface area of jackfruit peel make it an effective adsorbent for dye removal, with diverse surface features and pore sizes that enhance adsorption efficiency.

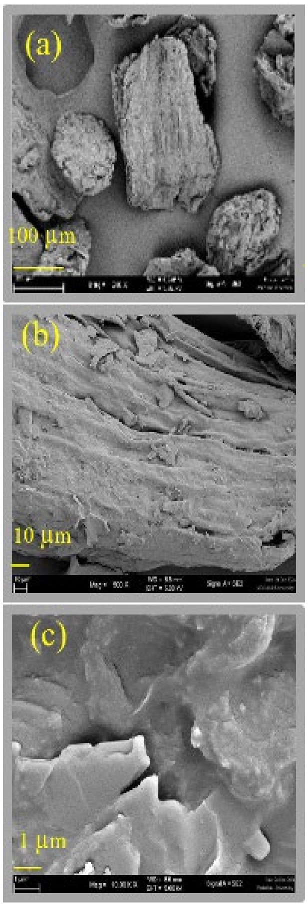

Figure 4 SEM images of the jackfruit peel adsorbent at different magnifications: (**a**) 200× magnification with a scale bar of 100 µm, (**b**) 500× magnification with a scale bar of 10 µm, and (**c**) 500× magnification with a scale bar of 1 µm.

Effect of adsorbent dosage on adsorption efficiency as shown in **Figure 5**, increasing the adsorbent dosage from 0.15 g to 0.45 g significantly improved the percentage adsorption of methylene blue (MB) over time. After 90 minutes of contact, the highest dye removal was achieved using 0.45 g of jackfruit peel (92.70 %) followed by 0.30 g (80.80 %) and 0.15 g (54.91%). This trend aligns with the expectation that higher adsorbent dosages provide more available surface area and active binding sites, thereby enhancing adsorption efficiency. Interestingly, despite the increase in percentage adsorption with increasing adsorbent mass, the adsorption capacity per unit mass (mg/g) exhibited an inverse relationship, as shown in the lower plot of **Figure 6**. The highest adsorption capacity values were recorded at adsorbent dosages of 0.15 g (36.48 mg/g), 0.30 g (16.58 mg/g), and 0.45 g (10.13 mg/g), respectively, about 5 minutes after the adsorption process. The results progressively decreased with increasing adsorbent dosage. This inverse trend may be attributed to the overlapping or aggregation of adsorption sites at higher dosages, which could reduce the effective surface area available for dye binding. Additionally, at higher adsorbent doses, the equilibrium dye concentration may become too low relative to the available surface area, thereby limiting further uptake per gram of adsorbent. Furthermore, the data show that equilibrium was nearly reached within the first 5–10 minutes for all dosages, indicating rapid dye uptake and a strong initial affinity between MB molecules and jackfruit peel. This rapid equilibrium phase, followed by a plateau, suggests that external mass transfer resistance was minimal, and the later stages of adsorption may be controlled by intraparticle diffusion or surface binding equilibrium. Overall, these findings highlight the importance of optimizing adsorbent dosage to achieve a balance between removal efficiency and adsorption capacity, particularly in practical applications where cost-effectiveness and adsorbent reusability are key considerations.

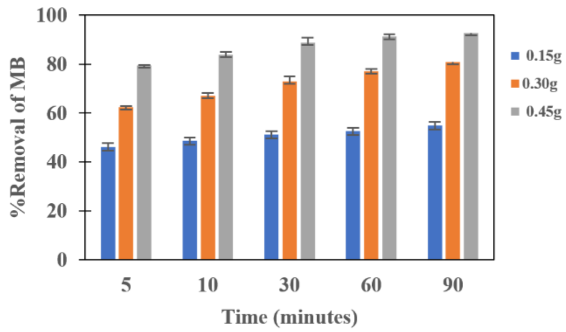

Figure 5 The % removal of MB over time (5–90 minutes) using three different adsorbent dosages of jackfruit peel: 0.15 g, 0.30 g, and 0.45 g.

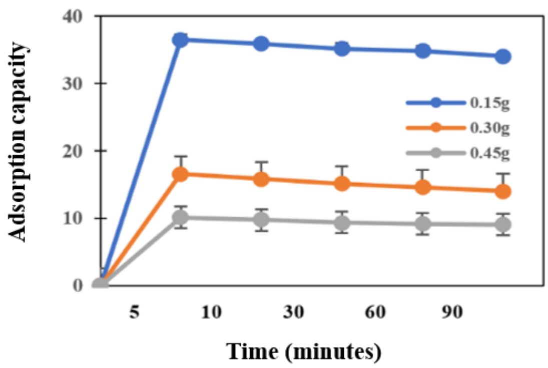

Figure 6 Adsorption capacity (mg/g) as a function of contact time (5–90 minutes) for different jackfruit peel dosages (0.15, 0.30, and 0.45 g).

The effect of initial methylene blue (MB) concentration on both percentage removal and adsorption capacity of jackfruit peel (0.15 g) was examined across various contact times. As shown in **Figure 7**, increasing the dye concentration from 5 to 150 mg/L enhanced removal efficiency at all time intervals, reaching over 90% at 150 mg/L after 90 minutes. However, removal efficiency declined at 300 mg/L, likely due to saturation of the adsorbent active sites. As shown in **Figure 8**, a clear trend is observed: at all concentrations, the adsorption capacity increased rapidly within the first few minutes and gradually plateaued as equilibrium was approached. At higher initial dye concentrations (100–300 mg/L), the adsorption capacity reached significantly higher values, with q_e exceeding 40 mg/g for both the 150 mg/L and 300 mg/L solutions. This can be attributed to the greater concentration gradient, which enhances the driving force for mass transfer, allowing more dye molecules to interact with the available binding sites on the adsorbent. In contrast, at lower concentrations (5–10 mg/L), the q_t values remained below 5 mg/g due to the limited number of dye molecules in the solution. The sharp rise in q_t during the first 2–3 minutes suggests that adsorption occurs rapidly at the initial stage, likely due to the abundance of active sites and strong dye–adsorbent affinity. The subsequent plateau phase indicates that the surface becomes saturated or that equilibrium is reached, and further adsorption is limited by the decreased availability of binding sites or a reduced concentration gradient.

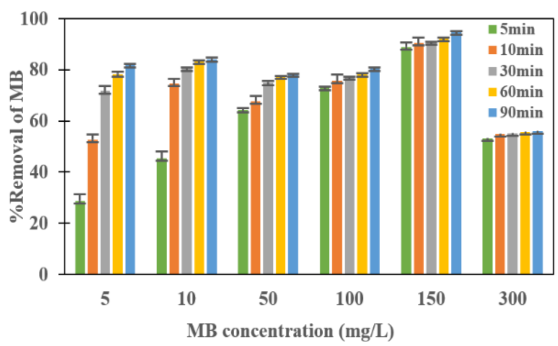

Figure 7 The % removal of MB over time (5–90 minutes) using at different concentrations(5, 10, 50, 100, 150, and 300 mg/L).

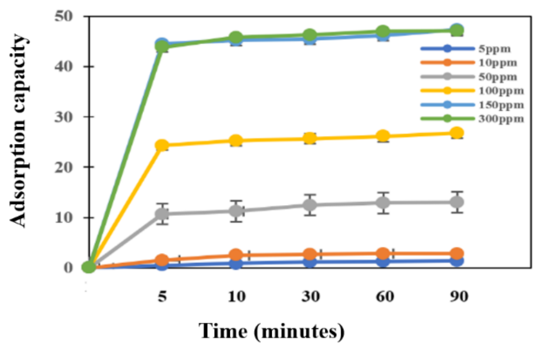

Figure 8 The adsorption capacity (mg/g) of jackfruit peel (0.15 g) as a function of contact time for MB at various initial concentrations (5–300 mg/L).

The effect of pH on methylene blue (MB) adsorption is shown in **Figure 9**. The percentage removal of MB increased with both time and pH. At time intervals, adsorption was highest at pH 9 and lowest at pH 3. For example, after 90 minutes, MB removal at pH 9 exceeded 79.6%, while removal at pH 5 and pH 3 was about 71.1% and 55.5%, respectively. These results suggest that alkaline conditions favor the adsorption of MB onto the jackfruit peel adsorbent. **Figure 10** shows the corresponding adsorption capacity (q_e) over time. The q_e values were consistently highest at pH 9 across all contact times, reaching nearly 3.5 mg/g at 90 minutes, compared to approximately 2.5 mg/g at pH 5 and 1.8 mg/g at pH 3. The rapid increase in q_e during the first 5–10 minutes indicates fast initial adsorption, particularly under alkaline conditions. The enhanced adsorption at higher pH can be attributed to reduced electrostatic repulsion. Methylene blue (MB) is a cationic dye, and under alkaline conditions (pH>7), the surface of the adsorbent becomes more negatively charged, thereby promoting electrostatic attraction between the dye molecules and the jackfruit peel. This observation is consistent with previous research that utilized jackfruit leaf as an adsorbent for malachite green, another cationic dye, which demonstrated similar adsorption behavior under alkaline conditions. [27] [30]

In contrast, at low pH, protonation of the adsorbent surface occurs, which suppresses MB adsorption due to electrostatic repulsion.

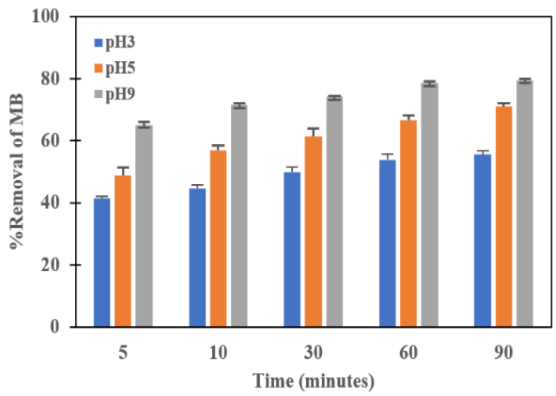

Figure 9. Effect of solution pH on the percentage removal of methylene blue (MB) by jackfruit peel.

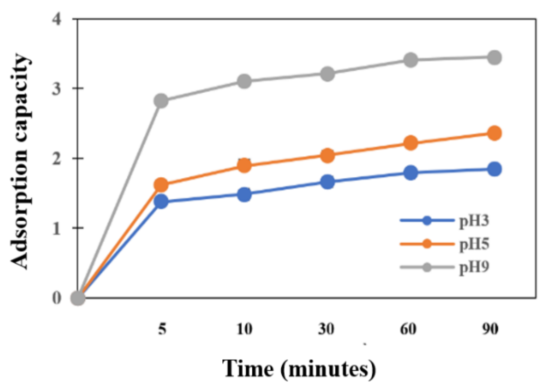

Figure 10 Effect of solution pH on the adsorption capacity of jackfruit peel.

As shown in **Figure 11**, the effect of temperature on adsorption indicates that the percentage removal of MB increased with time and reached similarly high levels (above 80%) at all temperatures tested (30°C, 35°C, and 55°C) by 30 minutes. However, noticeable differences were observed during the early stage (e.g., 5 minutes), where the removal efficiency at 35°C was highest (~79%), followed by 55°C (~67%) and 30°C (~46%). This suggests that a moderate temperature (35°C) may accelerate the initial adsorption rate more effectively than lower or higher temperatures. In **Figure 12**, adsorption capacity trends (mg/g) confirm these observations. The q_t values increased sharply within the first 2–3 minutes for all temperatures and gradually approached equilibrium. At 2 minutes, 35°C resulted in the highest adsorption capacity (~2.7 mg/g), compared to ~2.2 mg/g at 55°C and ~1.5 mg/g at 30°C. However, by 6 minutes, all curves converged with similar final capacities (~2.8–2.9 mg/g), indicating that equilibrium was eventually reached regardless of temperature. [29] The improved performance at 35°C may be attributed to enhanced molecular mobility and reduced solution viscosity, which promote faster diffusion of dye molecules toward active sites. In contrast, higher temperatures (e.g., 55°C) may lead to slight desorption or deformation of surface functional groups, reducing net adsorption in the early stage. Lower temperatures (30°C) may slow down diffusion and adsorption kinetics. The thermodynamic parameters offer valuable insight into the adsorption behavior of methylene blue (MB) onto jackfruit peel. The positive enthalpy change ($\Delta H° = +1.13$ kJ/mol) confirms an endothermic process, with higher temperatures enhancing dye uptake. The positive entropy change ($\Delta S° = +17.11$ J/mol·K) indicates increased molecular disorder at the solid–liquid interface, likely due to the release of water molecules or rearrangement of dye structures. Negative Gibbs free energy values ($\Delta G°$) across all temperatures confirm that the process is spontaneous and thermodynamically favorable. In comparison to activated carbon, which typically requires intensive chemical and thermal treatments, jackfruit peel presents a greener, low-energy alternative. These findings underscore its viability for low-cost, sustainable dye removal in both community-scale and industrial wastewater treatment applications.

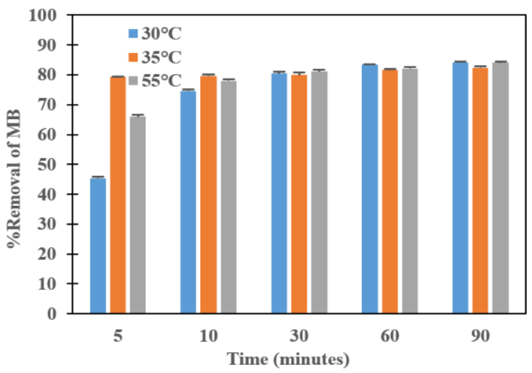

Figure 11 Effect of temperature on the percentage removal of methylene blue (MB) by jackfruit peel.

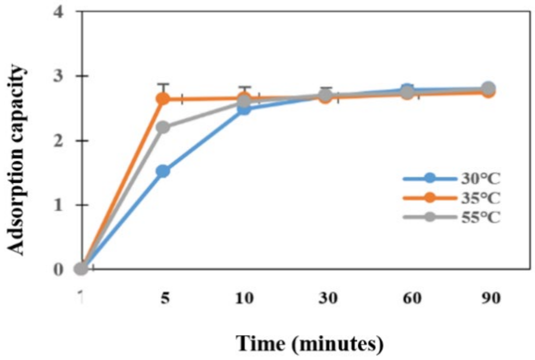

Figure 12 Effect of temperature on the adsorption capacity of jackfruit peel.

When compared with other low-cost adsorbents, the adsorption capacity of jackfruit peel (36.48 mg/g) surpasses that of Ruzi grass (14.01 mg/g) [31], spent tea leaves (12.7 mg/g) [32], and dried bamboo shoot shells (29.24 mg/g). [33] These findings highlight jackfruit peel's strong potential as a viable, low-cost, and eco-friendly adsorbent for dye-contaminated wastewater treatment, particularly in the textile industry.

3.2 The pH_{pzc} of the jackfruit peel adsorbent surface.

As shown in **Figure 13**, the pH at point of zero charge (pH_{pzc}) of the jackfruit peel adsorbent is 4.92. At pH values below this point, the surface of the adsorbent carries a positive charge, which repels the cationic methylene blue (MB) dye, thereby reducing adsorption. Conversely, at pH values above the pH_{pzc}, the surface becomes negatively charged, promoting electrostatic attraction between the adsorbent and the MB dye. This explains the enhanced adsorption observed under alkaline conditions and aligns with experimental results indicating higher adsorption efficiency in basic environments. These findings are consistent with previous reports on MB adsorption using other types of adsorbents. [26][34-35]

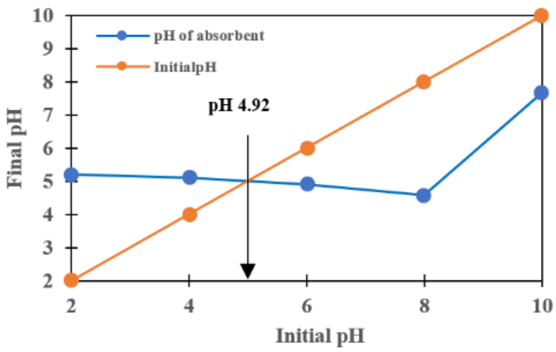

Figure 13 The point of zero charge (pzc) of the jackfruit peel adsorbent surface was evaluated by the pH drift method.

3.3 Adsorption Isotherm Analysis

The adsorption behavior of the system was further evaluated using the Freundlich isotherm model, which assumes a heterogeneous surface with a non-uniform distribution of adsorption heat and affinities over the surface. The linearized form of the Freundlich isotherm is expressed as Eq. (3). The plot as shown in **Figure 14**, a linear regression was performed by plotting $\log q_e$ against $\log C_e$, yielding a well fitted straight line. From the slope and intercept of the linear plot, the values of the Freundlich constants were determined K_f = 26.29, n = 5.17. The value of n > 1 suggests that the adsorption process is favorable under the studied conditions. [36] Furthermore, the relatively high value of K_f indicates that the adsorbent possesses a significant capacity for solute uptake.

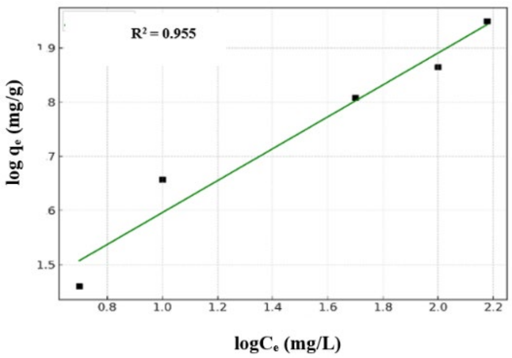

Figure 14 Plot of $\log q_e$ versus $\log C_e$ Freundlich adsorption isotherm

The adsorption data were further analyzed using the Temkin isotherm model to account for adsorbent–adsorbate interactions and the gradual decline in the heat of adsorption with increasing surface coverage. The linearized form of the Temkin isotherm provided a good fit to the experimental data, as evidenced by the strong correlation observed in the plot of q_e versus $\ln C_e$. as shown in **Figure 15**. The Temkin constant A, which reflects the equilibrium binding constant, was relatively high (9.20 L/g), suggesting a strong affinity between the adsorbate and the adsorbent, particularly at lower concentrations. This indicates that the adsorption sites were readily accessible and energetically favorable during the initial stages of adsorption. Moreover, the positive value of constant B (9.70 $J.mol^{-1}$), which is associated with the heat of adsorption, supports the assumption that the adsorption process involves chemisorption mechanisms in which the heat of adsorption decreases linearly rather than abruptly. This linear decline is characteristic of a relatively homogeneous adsorbent surface and uniform binding energies across available sites. Although the Temkin model accurately described the adsorption behavior over most of the tested concentration range, a slight deviation was observed at the highest concentration. This deviation may indicate the onset of surface saturation or structural rearrangement of the adsorbent at higher loading levels, which could affect the accessibility of binding sites or alter adsorbate–adsorbent interactions.

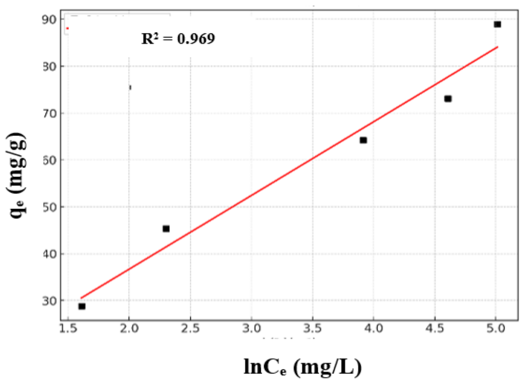

Figure 15 Plot of q_e versus $\ln C_e$ Temkin isotherm adsorption isotherm

3.4 Thermodynamic Results

Thermodynamic parameters were calculated based on the Van't Hoff plot [37] using the linear relationship between $\log(q_e/C_e)$ and 1/T. The enthalpy change (ΔH°) was determined to be +1.13 kJ/mol, confirming that the adsorption process is endothermic. The positive entropy change (ΔS° = +17.11 J/mol·K) indicates increased randomness at the solid–liquid interface. Gibbs free energy values (ΔG°) at all tested temperatures were negative, suggesting the adsorption of MB onto jackfruit peel is spontaneous under the experimental conditions. These thermodynamic results support the feasibility of using jackfruit peel as a sustainable adsorbent.

4. Conclusion

Jackfruit peel is an effective and sustainable adsorbent for the removal of methylene blue (MB) dye from wastewater. Increasing the adsorbent dose enhances dye removal efficiency; however, the adsorption capacity per unit mass decreases at higher dosages due to site overlap and reduced dye concentration. Equilibrium is rapidly reached within 5–10 minutes, indicating strong initial affinity between the dye and adsorbent, with minimal mass transfer resistance. The adsorption process is pH-dependent, with optimal removal under alkaline conditions. Temperature affects the initial adsorption rate, with the highest uptake observed at 35°C, while equilibrium adsorption capacity remains stable across the tested temperature range. Surface characterization via SEM imaging revealed a heterogeneous surface, with irregular shapes, sizes, and pore distributions. These features align with the results from BET analysis, which showed a surface area of 4.006 m²/g. The surface area supports effective adsorption, particularly through multilayer adsorption, as described by the Freundlich and Temkin isotherms. The Freundlich model suggests multilayer adsorption on sites with varying affinities, while the Temkin model indicates a decrease in adsorption energy as surface coverage increases.

The pH_{pzc} of jackfruit peel favors the adsorption of cationic dyes, further enhancing its performance. Thermodynamic analysis confirmed that the adsorption process is spontaneous (ΔG° < 0) and endothermic (ΔH° = +1.13 kJ/mol), with increased disorder at the solid–liquid interface (ΔS° = +17.11

J/mol·K). Temperature adjustments show improved adsorption performance at 35°C, which aligns with the positive ΔH° value, indicating that higher temperatures enhance the adsorption process. However, equilibrium adsorption remains relatively constant across the tested temperatures. These findings confirm jackfruit peel as a viable, low-cost, and environmentally friendly adsorbent for dye-contaminated wastewater treatment, particularly in the textile industry.

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6. References

[1] Y. Liu, J. Chen, D. Duan, Z. Zhang, C. Liu, W. Cai, and Z. Zhao, "Environmental Impacts and Biological Technologies Toward Sustainable Treatment of Textile Dyeing Wastewater: A Review," *sustainability*, vol. 16, no. 24, p. 10867, 2024, Art. no. 10867., doi: 10.3390/su162410867.

[2] K. Badawi, M. A. Elkodous and G. A. M. Ali, "Recent advances in dyes and metal ions removal using efficient adsorbents and novel nano-based materials: An overview," *RSC Advances*, vol. 11, no. 58, pp. 36528–36553, 2021, doi: 10.1039/D1RA06892J.

[3] M. A. D. F. Alarcón, C. R. Pacheco, K. G. Bustos, K. T. Meza, F. Terán-Hilares, D. A. P. Tanaka, G. J. C. Andrade and R. Terán-Hilares, "Efficient Dye Removal from Real Textile Wastewater Using Orange Seed Powder as Suitable Bio-Adsorbent and Membrane Technology," *water*, vol. 14, no. 24, 2022, Art. no. 4104, doi: 10.3390/w14244104.

[4] I. Khan, K. Saeed, I. Zekker, B. Zhang, A. H. Hendi, A. Ahmad, S. Ahmad, N. Zada, H. Ahmad,L. A. Shah, T. Shah and I. Khan, "Review on Methylene Blue: Its Properties, Uses, Toxicity and Photodegradation," *water*, vol. 14, no. 2, Jan. 2022, Art. no. 242, doi: 10.3390/w14020242

[5] A. A. E. Elfiky, M. F. Mubarak, M. Keshawy, I. E. T. El Sayed and T. A. Moghny, "Removing of cationic dyes using self-cleaning membranes-based PVC/nano-cellulose combined with titanium aluminate," *Environmental Science and Pollution Research*, vol. 30, no. 32, pp. 79091–79105, doi: 10.1007/s11356-023-27691-x.

[6] K. Sonu, S. H. Puttaiah, V. S. Raghavan and S. S. Gorthi, "Photocatalytic degradation of MB by TiO_2: Studies on recycle and reuse of photocatalyst and treated water for seed germination," *Environmental Science and Pollution Research*, vol. 28, no. 35, pp. 48742–48753, 2021, doi: 10.1007/s11356-021-13863-0.

[7] N. M. Daud, S. R. S. Abdullah, H. A. Hasan, A. R. Othman and N. 'Izzati Ismail, "Coagulation-flocculation treatment for batik effluent as a baseline study for the upcoming application of green coagulants/flocculants towards sustainable batik industry," *Heliyon*, vol. 9, no. 6, 2023, Art. no. e17284, doi: 10.1016/j.heliyon.2023.e17284.

[8] M. Akhtar, M. Sarfraz, M. Ahmad, N. Raza and L. Zhang, "Use of low-cost adsorbent for wastewater treatment: Recent progress, new trends, and future perspectives," *Desalination and Water Treatment*, vol. 321, 2025, Art. no. 100914. doi: 10.1016/j.dwt.2024.100914.

[9] M. Hupian, M. Galamboš, E. Viglašová, O. Rosskopfová, V. V. Kusumkar and M. Daňo, "Activated carbon treated with different chemical agents for pertechnetate adsorption," *Journal of Radioanalytical and Nuclear Chemistry*, vol. 333, no. 4, pp. 1815–1829, 2024, doi: 10.1007/s10967-024-09399-5.

[10] B. G. Fouda-Mbanga, O. Onotu and Z. Tywabi-Ngeva, "Advantages of the reuse of spent adsorbents and potential applications in environmental remediation: A review," *Green Analytical Chemistry*, vol. 11, 2024, Art. no. 100156, doi: 10.1016/j.greeac.2024.100156.

[11] K. Al-Mokhalelati, I. Al-Bakri and N. A l Shibeh Al Wattar, "Adsorption of methylene blue onto sugarcane bagasse-based adsorbent materials," *Journal of Physical Organic Chemistry*, vol. 34, no. 7, 2021, Art. no. e4193. doi: 10.1002/poc.4193.

[12] R. H. Khuluk, A. Rahm'''at, B. Buhani and S. Suharso, "Removal of Methylene Blue by Adsorption onto Activated Carbon from Coconut Shell (Cocos Nucifera L.)," *Indonesian Journal of Science and Technology*, vol. 4, no. 2, pp. 229–240, 2019, doi: 10.17509/ijost.v4i2.18179.

[13] Y. Wang, Y. Zhou, G. Jiang, P. Chen and Z. Chen, "One-step fabrication of carbonaceous adsorbent from corncob for enhancing adsorption capability of methylene blue removal," *Scientific Reports*, vol. 10, no. 1, 2020, Art. no. 12515, doi: 10.1038/s41598-020-68591-1.

[14] U. Michael-Igolima, S. J. Abbey, A. O. Ifelebuegu and E. U. Eyo, "Modified Orange Peel Waste as a Sustainable Material for Adsorption of Contaminants," *materials*, vol. 16, no. 3, 2023, Art. no. 1092, doi: 10.3390/ma16031092.

[15] S. Kainth, P. Sharma and O. P. Pandey, "Green sorbents from agricultural wastes: A review of sustainable adsorption materials," *Applied Surface Science Advances*, vol. 19, 2024, Art. no. 100562, doi: 10.1016/j.apsadv.2023.100562.

[16] T. Luangkaew, "Jackfruit Research and Development" Department of Agriculture, Bangkok, Thailand, Final Rep., 2021.

[17] S. Satyam and S. Patra, "Innovations and challenges in adsorption-based wastewater remediation: A comprehensive review," *Heliyon*, vol. 10, no. 9, 2024, Art. no. e29573, doi: 10.1016/j.heliyon.2024.e29573.

[18] M. Jayarajan, R. Arunachalam and G. Annadurai, "Agricultural Wastes of Jackfruit Peel Nano-Porous Adsorbent for Removal of Rhodamine Dye," *Asian*

Journal of Applied Sciences, vol. 4, no. 3, pp. 263–270, 2011, doi: 10.3923/ajaps.2011.263.270.

[19] K. N. T. Tran, B. N. Hoang, K. O. T. Nguyen, H. T. T. Nguyen, S. C. Phung, H. T. Do and C. Q. T. Ngo, "Manufacture of Activated Carbon Adsorbents from Jackfruit Waste for Removal of Heavy Metals and Dyes from Wastewater: A Review," *Indonesian Journal of Chemistry.*, vol. 22, no. 2, pp. 565–575, 2022, doi: 10.22146/ijc.69538

[20] N. B. Allou, M. A. Tigori, A. A. Koffi, M. Halidou, N. S. Eroi, P. Atheba and A. Trokourey, "Methylene blue magnetic adsorption separation process from aqueous solution using corn cob," *Scientific African*, vol. 21, 2023, Art. no. e01828, doi: 10.1016/j.sciaf.2023.e01828.

[21] N. T. A. Nguyen and H. Kim, "Ag_3PO_4-Deposited $TiO_2@Ti_3C_2$ Petals for Highly Efficient Photodecomposition of Various Organic Dyes under Solar Light," *nanomaterials*, vol. 12, no. 14, 2022, Art. no. 2464, doi: 10.3390/nano12142464.

[22] N. R. Izan, M. M. Zainol, A. H. Nordin, M. Asmadi, S. L. Wong, M. A. I. Azhar and N. H. Alias, "Removal of Methylene Blue via Adsorption using Magnetic Char Derived from Food Waste," *MALAYSIAN JOURNAL OF CHEMISTRY*, vol. 24, no. 2, pp. 283–292, 2022, doi: 10.55373/mjchem.v24i2.283.

[23] S. Brunauer, P. H. Emmett and E. Teller, "Adsorption of Gases in Multimolecular Layers," *Journal of the American Chemical Society*, vol. 60, no. 2, pp. 309–319, 1938, doi: 10.1021/ja01269a023.

[24] M. Kosmulski, "The pH dependent surface charging and points of zero charge. X. Update," *Advances in Colloid and Interface Science*, vol. 319, 2023, Art. no. 102973, doi: 10.1016/j.cis. 2023.102973.

[25] R. T. Kapoor, M. Rafatullah, M. R. Siddiqui and M. Alam, "Adsorptive potential of coconut fruit shell biochar as low-cost adsorbent for sequestration of rhodamine B dye: kinetics, thermodynamics and phytotoxicity studies," *Biomass Conversion and Biorefinery*, 2024, doi: 10.1007/s13399-024-05688-x.

[26] M. Das and C. Mishra, "Jackfruit leaf as an adsorbent of malachite green: recovery and reuse of the dye," *SN Applied Sciences*, vol. 1, no. 5, 2019, Art. no. 483. doi: 10.1007/s42452-019-0459-7.

[27] V. O. Shikuku and T. Mishra, "Adsorption isotherm modeling for methylene blue removal onto magnetic kaolinite clay: a comparison of two-parameter isotherms," *Applied Water Science*, vol. 11, no. 6, 2021, Art. no. 103, doi: 10.1007/s13201-021-01440-2

[28] R. Brahma, S. Ray, P. K. Nayak and K. Shridha, "Sustainable Valorization of Jackfruit Peel Waste: Bio-Functional and Structural Characteriz*ood Bioengineering*, vol. 4, no. 1, pp. 88–100, 2025, doi: 10.1002/fbe2.70004

[29] T. M. Eldeeb, U. O. Aigbe, K. E. Ukhurebor, R. B. Onyancha, M. A. El-Nemr, M. A. Hassaan, S. Ragab, O. A. Osibote, and A. El Nemr, "Adsorption of methylene blue (MB) dye on ozone, purified and sonicated sawdust biochars," *Biomass Conversion and Biorefinery*, vol. 14, no. 8, pp. 9361–9383, 2022, doi: 10.1007/s13399-022-03015-w.

[30] P. Senthil Kumar, P. Sebastina A. Fernando, R. Tanvir Ahmed, R. Srinath, M. Priyadharshini, A. M. Vignesh and A. Thanjiappan, "EFFECT OF TEMPERATURE ON THE ADSORPTION OF METHYLENE BLUE DYE ONTO SULFURIC ACID–TREATED ORANGE PEEL," *Chemical Engineering Communications*, vol. 201, no. 11, pp. 1526–1547, 2014, doi: 10.1080/00986445.2013. 819352**.**

[31] P. Kaewmeechai, J. Pakpoolpuy, T. Pathomnithipinyo, W. Sophadit, and A. Jaturapiree, "The Removal of Methylene Blue Dye by Using Ruzi Grass as an Adsorbent Material," in *Proc. 14th NPRU Nat. Acad. Conf.*, Nakhon Pathom, Thailand, Jul. 7–8, 2022, pp.233–242.

[32] N. Muhamad, S. Paothong, U. Tansom and P. Soontornnon, "Adsorptive Removal of Textile Dye by Spent Tea Leaves," Yala Rajabhat University, Yala, Thailand, Research Rep., 2016.

[33] P. Ouengsirisawad and C. Ruangviriyachai, "Adsorption of Methylene Blue Dye Using Dried Shell of Bamboo Shoots," presented at the National and International Graduate Research Conference 2016 (NIGRC 2016), Khon Kaen University, Khon Kaen, Thailand, Jan. 15, 2016, Paper PMP21.

[34] I. Ghosh, S. Kar, T. Chatterjee, N. Bar and S. K. Das, "Removal of methylene blue from aqueous solution using *Lathyrus sativus* husk: Adsorption study, MPR and ANN modelling," *Process Safety and Environmental Protection*, vol. 149, pp. 345–361, 2021, doi: 10.1016/j.psep.2020.11.003.

[35] S. Sawasdee and P. Watcharabundit, "Characterization and Adsorption Mechanism of Methylene Blue Dye by Mesoporous Activated Carbon Prepared from Rice Husks," *Environment and Natural Resources Journal*, vol. 21, no. 5, pp. 458–470, 2023, doi: 10.32526/ennrj/21/20230074

[36] I. Kurnia, S. Karnjanakom, I. Irkham, H. Haryono, Y. A. Situmorang, A. Indarto, A. R. Noviyanti, Y. W. Hartati and G. Guan, "Enhanced adsorption capacity of activated carbon over thermal oxidation treatment for methylene blue removal: kinetics, equilibrium, thermodynamic, and reusability studies," *RSC Advances*, vol. 13, pp. 220–227, 2023, doi: 10.1039/d2ra06481b.

[37] N. I. I. Zamri, S. L. N. Zulmajdi, N. Z. A. Daud, A. H. Mahadi, E. Kusrini and A. Usman, "Insight into the adsorption kinetics, mechanism, and thermodynamics of methylene blue from aqueous solution onto pectin-alginate-titania composite microparticles," *SN Applied Sciences*, vol. 3, no. 2, 2021, Art. no. 222, doi: 10.1007/s42452-021-04245-9.