

Adsorption Behaviour of Rhodamine B in Aqueous Solutions onto Mandarin Orange (*Citrus reticulata*) Peel

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The aim of this study is to examine the adsorption behaviour of rhodamine B (Rh-B) onto mandarin orange peel (*Citrus reticulata*) in aqueous solutions under various conditions. Surface morphology characterisation by FESEM showed the surface is irregular, rough, and porous. The BET surface area of the orange peels was determined to be $1.2152 \text{ m}^2\text{g}^{-1}$. The FTIR analysis confirmed the presence of oxygen-containing functional groups on the peel surface that promote Rh-B adsorption. Adsorption equilibrium was achieved within 20 minutes under acidic conditions (pH 3) at maximum dosage of 0.1 g adsorbent. The adsorption data aligned well with the Freundlich isotherm model and the maximum uptake (q_m) was 1.901 mgg^{-1} . Mandarin orange peel serves as an effective adsorbent for the removal of Rh-B from aqueous solutions.

Keywords: Effective adsorbent, cationic dye, carcinogens, electrostatic repulsion, hydrogen bonding

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Many industries, including textile, plastics, printing, rubber, and leather, discharge coloured effluents that contribute to water pollution. The textile industry is a major consumer of toxic and non-biodegradable dyes, making this a particularly critical environmental issue. However, textile dyeing wastewater is difficult to treat due to its high suspended solids content, elevated chemical oxygen demand (COD), and strongly fluctuating pH, in addition to its high temperature and intense colouration. Therefore, effective removal of colour from industrial effluents prior to discharge into water bodies [1] is necessary to reduce ecological risks [2] and comply with environmental regulations.

Widespread exposure to synthetic dyes poses severe health risks, including allergic dermatitis, skin irritation, and systemic damage to the liver, kidneys, brain, central nervous system, and reproductive health. Additionally, certain dyes have been identified as potential carcinogens and mutagens. As a synthetic xanthene dye, rhodamine B (Rh-B) presents significant health and ecological risks, acting as a known irritant and a potential carcinogen. Therefore, the effective removal of Rh-B from industrial effluents before discharge into water sources is crucial for protecting public health and minimising environmental pollution [3]. This cationic dye contains carboxyl group in its molecular structure, which enables it to exist in different molecular forms depending on solution pH [4].

Numerous methods have been developed for wastewater treatment, including photocatalysis [5], ion

flotation [6], and adsorption [7, 8]. Several factors must be considered when selecting a method for Rh-B removal from wastewater including cost, environmental impact and the efficiency of the method. Adsorption is regarded as one of the most effective methods for treating wastewater because of its widespread applicability, low cost, and simple operation [7].

Activated carbon is an effective adsorbent for removing dissolved compounds and organic pollutants due to its high specific surface area and adsorption capacity. However, its high cost and the regeneration process, which generates secondary effluent and results in a 10–15% loss of adsorbent material, limit its practical application [9]. Consequently, many researchers have sought alternatives to replace activated carbon by using agricultural waste as a good source of raw materials, such as acid activated mango (*Mangifera indica*) leaf powder [3], rice husk [10], and jackfruit peel [11].

Mandarin orange peel (*Citrus reticulata*) contains a high percentage of pectin and polygalacturonic acid [12]. This biopolymer is rich in carboxyl groups ($-\text{COOH}$), which are easily deprotonated to negatively charged carboxylate ions ($-\text{COO}^-$) in aqueous solutions at near-neutral or slightly basic pH values above the material's point of zero charge (P_{zc}) [13]. This negative surface charge creates a strong electrostatic attraction towards the positively charged quaternary ammonium centre (RN^+) of cationic dye molecules such as Rh-B, outperforming non-functionalised inorganic or carbon-based adsorbents

that rely solely on weak physical surface area interactions [14].

Mandarin orange peel is an inexpensive, readily available, and eco-friendly lignocellulosic biosorbent that holds great potential for removing dyes and other pollutants from wastewater [15]. Most previous studies of orange peel-based adsorbents have focused on the sweet orange (*Citrus sinensis*) based on the assumption that all citrus waste behaves similarly [16]. However, mandarin orange has significant structural differences compared to *C. sinensis*, such as higher ratio of soluble pectin to insoluble fibre [12], different distribution of essential oil glands, and thinner and more flexible albedo layer, which govern the expansion mechanics and chemical reactions occurring on its surface [17]. These structural density differences directly affect the adsorption process.

The structural arrangement of an organic material such as orange peel is directly influenced by the plant cultivar and therefore governs its behaviour when immersed in an aqueous dye solution. This study addresses this gap by examining the performance of mandarin orange peel for the adsorption of Rh-B. By systematically analysing the adsorption isotherms, kinetics and the influence of operational parameters such as solution pH, initial dye concentration, and contact time, this study provides fundamental insights into the use of mandarin orange peel biomass as an effective adsorbent in water treatment.

METHODOLOGY

Materials

Mandarin orange (*C. reticulata*) peels used in this study were obtained from local fruit vendors in Tanjong Malim, Perak, Malaysia. Rhodamine B (97%), hydrochloric acid and sodium hydroxide were purchased from Sigma-Aldrich. Distilled water was used as the solvent in all experiments.

Preparation and Characterisation of Orange Peel

Mandarin orange peels were washed thoroughly with distilled water to remove surface contaminants and impurities. Subsequently, the cleaned mandarin orange peels were minced and oven-dried at 60 °C for 48 hours. The dried mandarin orange peel was finely pulverised using a mortar and pestle, sieved (60 mesh) and stored in a sample bottle for further experiments.

The Hitachi 8U 8020 UHR Field Emission Scanning Electron Microscope (FESEM) was used to analyse the surface morphology of orange peels. Orange peels' FTIR spectra were obtained using the ATR technique with Thermo Nicolet Nexus Fourier Transform Infrared Spectroscopy. The surface area and porosity properties were determined using a Quantachrome Autosorb automated gas sorption

analyser (Autosorb iQ-MP/XR), under nitrogen adsorption-desorption at 77 K. Mineral contents in the mandarin orange peel were analysed using Atomic Absorption Spectrometry (AAS) model Analyst 400, Perkin Elmer for potassium (K), sodium (Na), iron (Fe), magnesium (Mg) and calcium (Ca) and CHNOS elemental analyser (Thermo Finnigan, Flash EA112) for carbon, hydrogen, nitrogen, sulphur and oxygen.

Adsorption Studies

Mass Optimisation of Orange Peels

To identify the optimum adsorbent dosage, the effect of different masses of mandarin orange peel on Rh-B adsorption was studied. Adsorbent masses of 0.1, 0.2, 0.3, 0.4, and 0.5 g were separately introduced into distinct 250 mL conical flasks. Subsequently, 50 mL of the 25 mg L⁻¹ Rh-B solution (24 °C) was added to each flask, which was then sealed with Parafilm. The mixtures were agitated on an orbital shaker at 120 rpm for 30 minutes. The suspensions were then filtered using Filtres Fiononi Grade 601 filter paper. A 15 mL aliquot of the filtrate from each sample was collected in a clean sample bottle. The residual Rh-B concentration in the samples was determined by measuring the absorbance at a wavelength of 534 nm using a UV-Vis spectrophotometer. All measurements were performed in triplicate.

The uptake at equilibrium, q_e (mg g⁻¹), was calculated using Equation (1).

$$q_e = \frac{(C_o - C_e)V}{W} \quad (1)$$

C_o is the initial liquid-phase concentration of Rh-B in mgL⁻¹, C_e is the equilibrium liquid-phase concentration of Rh-B in mgL⁻¹, V is the volume of the solution in litres, and W is the dry orange peel mass (g) [15].

pH Study

The uptake of orange peel was evaluated over a pH range of 2–10 at a fixed initial Rh-B concentration of 25 mg L⁻¹, with the solution pH adjusted to the desired value using 0.1 M HCl or 0.1 M NaOH. The adsorbent mass was kept constant at the optimum value determined from the dosage optimisation experiment, and the contact time was fixed at 30 min. Approximately 0.1 g of orange peel was weighed and placed into nine separate 250 mL conical flasks, each containing 50 mL of Rh-B solution at a concentration of 25 mgL⁻¹ across a pH range of 2–10. Each flask was then sealed with Parafilm and placed on an orbital shaker at 120 rpm for 30 minutes. The samples were then filtered (Filtres Fiononi Grade 601), and the filtrate was transferred into sample bottles immediately prior to absorbance measurement. Absorbance measurement and adsorption uptake followed the same procedure as described above.

Equilibrium Time for the Adsorption of Rhodamine B (Rh-B) onto Orange Peel.

Equilibrium time experiments were conducted at a constant Rh-B concentration of 25 mg L⁻¹ using the optimum adsorbent mass determined from the mass optimisation study. The contact time for the adsorption process was varied from 10 to 90 minutes at 10 minutes intervals. The same experimental procedure used for the pH and adsorbent mass optimisation studies was followed. Approximately 0.1 g of orange peel was weighed and transferred into separate conical flasks. Subsequently, 50 mL of 25 mg L⁻¹ Rh-B solution was added to each flask. The flasks were sealed with Parafilm and agitated on an orbital shaker at 120 rpm for the designated contact times. At each designated contact time, the sample was filtered through Filtres Fiononi Grade 601, and 15 mL of the filtrate was transferred to a sample bottle prior to absorbance measurement using an Agilent, Cary 60 Ultraviolet-Visible Spectrophotometer.

The kinetics of Rh-B adsorption on the orange peels was examined using pseudo-first-order (Equation 2) and pseudo-second-order kinetic models (Equation 3) [18].

$$\ln(q_e - q_t) = \ln q_e - k_1 t \quad (2)$$

$$\frac{t}{q_t} = \frac{1}{q_e^2 k_2} + \frac{t}{q_e} \quad (3)$$

Plotting t/q_t against t should produce a linear graph. The equilibrium uptake (q_e) and the pseudo-second-order rate constant (k_2) were determined from the slope and intercept of the linear plot, respectively. Here, q_e is the amount of adsorbate adsorbed at equilibrium (mgg⁻¹), q_t is the amount of adsorbate adsorbed at time t (mgg⁻¹), k_1 is the pseudo-first-order rate constant (min⁻¹), and k_2 is the pseudo-second-order rate constant (g.mg⁻¹ min⁻¹).

Isotherm Study

Adsorption isotherm studies were conducted using the optimal equilibrium contact time determined through equilibrium time studies. The initial concentration of rhodamine B (Rh-B) was varied from 10 to 100 mg L⁻¹. Approximately 0.1 g of orange peel was weighed and placed into ten separate conical flasks. Subsequently, 50 mL of Rh-B solution at the specified concentration was added to each flask. The flasks were then sealed with Parafilm and agitated using an orbital shaker at 120 rpm for 20 minutes. The sample filtration process and the measurement of adsorption intensity followed the same methodology as previously described.

The Langmuir isotherm is a model that describes monolayer adsorption on the surface of an adsorbent with a finite number of homogeneous adsorption sites. This model assumes that all

adsorption sites possess uniform adsorption energies and that no migration of adsorbed molecules occurs across the adsorbent surface [19]. The maximum uptake derived from this model is widely used to evaluate and optimise the performance of an adsorption system. To determine the maximum uptake, the linearised Langmuir isotherm equation (Equation 4) was employed [20].

$$\frac{C_e}{q_e} = \frac{1}{q_m b} + \left(\frac{1}{q_m}\right) C_e \quad (4)$$

Where b is the Langmuir adsorption equilibrium constant (Lmg⁻¹), which is related to the apparent adsorption energy, q_m is the maximum monolayer adsorption capacity (mgg⁻¹), C_e is the equilibrium concentration of the adsorbate in solution (mgL⁻¹). The favourability of the adsorption process can be evaluated using the dimensionless separation factor, R_L , derived from the Langmuir isotherm model, as expressed in Equation 5 [18, 21].

$$R_L = \frac{1}{1 + b C_o} \quad (5)$$

where C_o is the initial adsorbate concentration (mgL⁻¹), and b is the Langmuir adsorption equilibrium constant (Lmg⁻¹). The dimensionless separation factor, R_L , is used to evaluate the favourability of the adsorption process. The adsorption is considered unfavourable when $R_L > 1$, linear when $R_L = 1$, favourable when $0 < R_L < 1$, and irreversible when $R_L = 0$. The Freundlich isotherm describes multilayer adsorption on a heterogeneous adsorbent surface with a non-uniform distribution of adsorption energies and interactions between adsorbed molecules. The linearised Freundlich isotherm equation is expressed as Equation 6 [22-23]:

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

In the equation, q_e is the amount of adsorbed Rh-B at equilibrium (mgg⁻¹) and C_e is the equilibrium concentration of Rh-B remaining in solution. K_f is the Freundlich constant for a given adsorbate-adsorbent pair at a particular temperature, and $1/n$ is the gradient of the Freundlich graph.

RESULTS AND DISCUSSION

Characterisation of Mandarin Orange Peel

The nitrogen adsorption-desorption isotherm of mandarin orange peels at 77 K obtained is depicted in Figure 1, and the surface area and porosity characteristics are presented in Table 1. The isotherm curve exhibits type II behaviour, which is characteristic of non-porous and macroporous materials [24]. Nitrogen uptake increased gradually at low relative pressure and rose markedly at higher relative pressure ($P/P_o > 0.8$). An H3 hysteresis loop was clearly

observed in the desorption curve, indicating that the mandarin orange peels were plate-like shape with slit-shaped pores [25]. The low BET surface area of the mandarin orange peels ($1.2152 \text{ m}^2\text{g}^{-1}$) is typical for raw lignocellulosic biomass because structural components such as cellulose, hemicellulose, and pectin remain densely packed, leaving few accessible internal pores [26]. The average pore diameter (0.15183 nm) is smaller than the kinetic diameter of the nitrogen probe molecule ($\approx 0.364 \text{ nm}$) [27–28]. Nitrogen molecules cannot enter or measure pores smaller than their own molecular dimensions [27]. This unrealistically small pore diameter is a mathematical artifact that occurs when standard cylindrical or Barrett-Joyner-Halenda (BJH) models rely on surface area-to-volume geometric ratios ($4V/A$) for materials with extremely low pore

volumes ($< 10^{-4} \text{ cm}^3\text{g}^{-1}$) [29]. The observed high-pressure uptake ($P/P_0 > 0.8$) corresponds to macro-scale interparticle spaces ($> 50 \text{ nm}$) rather than true structural micropores.

The functional groups of the adsorbent were characterised using a Thermo Nicolet Nexus FTIR spectrometer over the wavenumber range of $3500\text{--}350 \text{ cm}^{-1}$. The FTIR spectrum of the mandarin orange peel is shown in Figure 2. The characteristic absorption bands indicate the presence of several functional groups and the compositional complexity of the material. The broad absorption band observed at 3233 cm^{-1} corresponds to the O–H stretching vibration, while the absorption peak at 1731 cm^{-1} is attributed to the C=O stretching vibration [30].

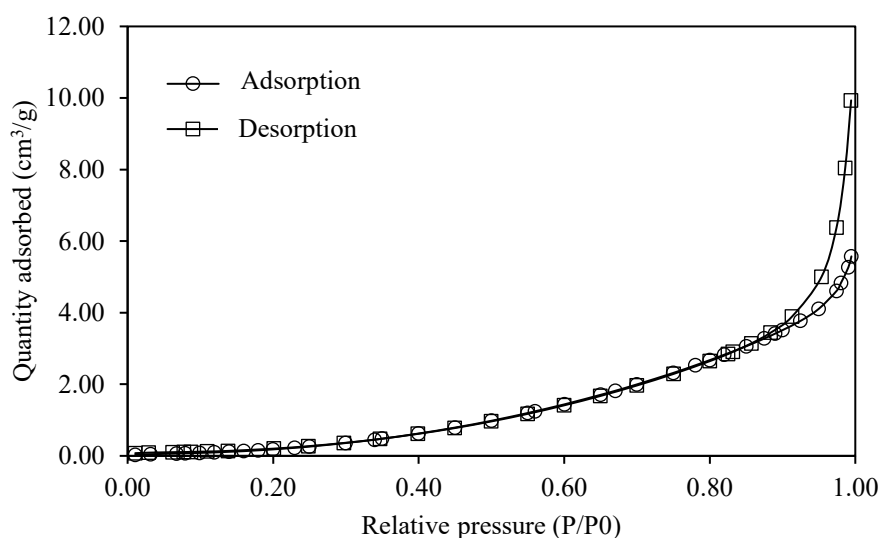


Figure 1. Adsorption-desorption of nitrogen gas onto mandarin orange peel at 77 K.

Table 1. Surface area and porosity characteristics of mandarin orange peel.

Surface area (m^2g^{-1})	Total pore volumes (cm^3g^{-1})	Average pore diameter (nm)
1.2152	4.6×10^{-5}	0.15183

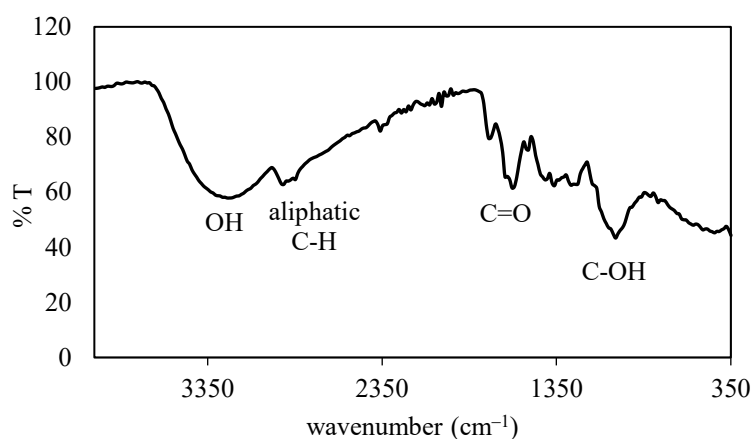


Figure 2. The FTIR spectrum of mandarin orange peel.

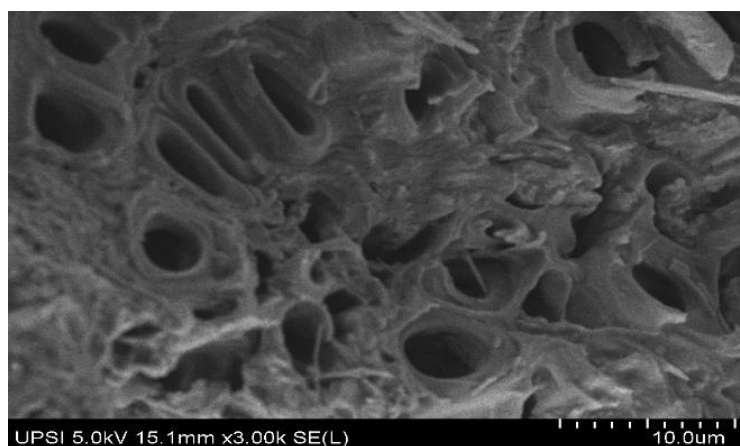


Figure 3. FESEM micrograph of mandarin orange peels.

The broadening of the O–H band is associated with intermolecular and intramolecular hydrogen bonding, which is commonly found in polymeric compounds such as alcohols, phenols, and carboxylic acids. Alongside the broad peak for hydroxyl groups, the absorption band observed in the $2800 - 2900 \text{ cm}^{-1}$ region corresponds to aliphatic C–H stretching vibrations. Together, these spectral features confirm the presence of key functional groups consistent with the major biopolymeric constituents of orange peel, namely cellulose, hemicellulose, and pectin [31]. The band at 1011 cm^{-1} corresponded to C–OH stretching of alcohol and carboxylic acid groups. These carbonyl and hydroxyl functionalities are the principal sites for hydrogen bonding between the adsorbate and the adsorbent during adsorption.

Field Emission Scanning Electron Microscope (FESEM) analysis was used to characterise the surface morphology of the mandarin orange peel. Figure 3

reveals that the adsorbent has a rough, irregular, and porous surface morphology. Pores left by the evaporation of moisture from the peel are clearly visible.

A CHNOS analyser was used to determine the elemental composition of the mandarin orange peel, and the results are summarised in Table 2. The elemental analysis confirmed the presence of carbon, hydrogen, nitrogen, and oxygen in the orange peel adsorbent, with no detectable sulphur content. The quantity of carbon and oxygen present (%) in the mandarin orange peel were 40.92 and 50.84, respectively. The high carbon and oxygen contents in the mandarin orange peel are favourable for the adsorption process [7]. Atomic Absorption Spectroscopy (AAS) analysis further confirmed the presence of several mineral elements, namely sodium (Na), potassium (K), iron (Fe), and magnesium (Mg). The detailed composition of these elements is summarised in **Table 2**.

Table 2. Elemental composition of mandarin orange peel analysed by CHNOS and AAS.

CHNOS		AAS	
Elements	%	Elements	mg.g ⁻¹
Carbon (C)	40.92	Potassium (K)	81.4
Hydrogen (H)	6.47	Sodium (Na)	117.2
Nitrogen (N)	1.12	Iron (Fe)	6.8
Oxygen (O)	50.84	Magnesium (Mg)	3.7
Sulphur	0	Calcium (Ca)	-

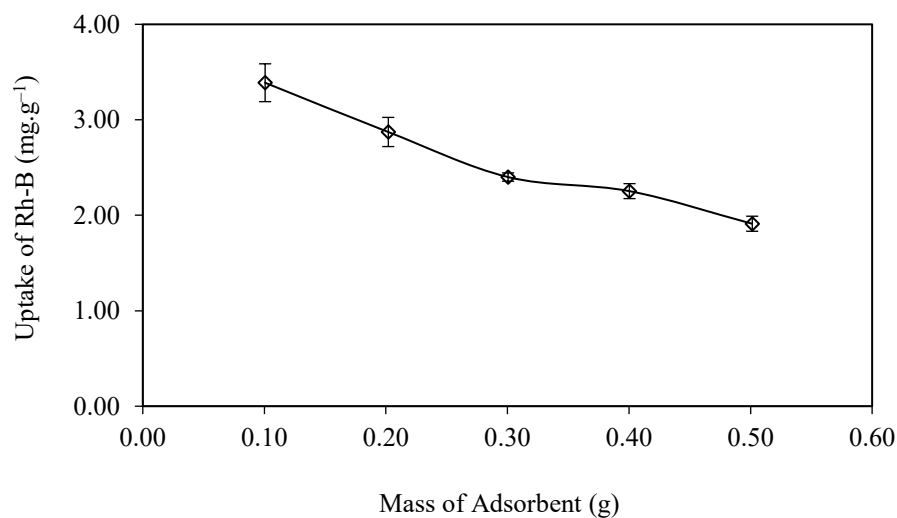


Figure 4. The uptake of Rh-B onto mandarin orange peel at different mass of adsorbent.

Adsorption Studies

Effect of Adsorbent Mass

Figure 4 shows the uptake of Rh-B onto orange peel at different adsorbent dosages. The experiments were carried out with 50 mL of 25 mgL⁻¹ Rh-B solution agitated at 120 rpm for 30 minutes. The results showed that increasing the adsorbent mass reduced Rh-B uptake (mgg⁻¹). Although a higher adsorbent dose would be expected to provide more active sites for Rh-B adsorption, increasing the dosage also increased the collision frequency between adsorbent particles, leading to the overlapping or aggregation of adsorption sites. Consequently, the number of available adsorption sites per unit mass of the adsorbent was reduced [18].

Effect of pH on Rhodamine B Adsorption

Figure 5 illustrates the effect of pH on the adsorption of Rh-B onto orange peel over a pH range of 2–10. The uptake increased as the solution pH increased from 2 to 3. However, the uptake decreased markedly at pH 4 and subsequently remained constant up to pH 10. These results indicate that the maximum uptake was achieved at pH 3. Rh-B is a cationic dye (Rh-B⁺)

containing a carboxyl group in its molecular structure, which enables it to exist in different molecular forms under varying solution pH conditions. Under strongly acidic conditions (pH < 2), the oxygen-containing functional groups (-COOH) on the mandarin orange peel surface are fully protonated (-COOH₂⁺), imparting a net positive surface charge that severely repels cationic Rh-B⁺ molecules via electrostatic repulsion. As the solution pH approaches pH 3, partial deprotonation of carboxyl groups begins to occur, yielding negatively charged carboxylate sites (-COO⁻) while keeping the surface electrostatic barrier minimal [32]. The monomeric cation Rh-B⁺ with a protonated carboxyl group (-COOH) possesses a smaller hydrodynamic radius, which facilitates rapid intraparticle diffusion into the porous matrix of the mandarin orange peel and promotes strong electrostatic interactions with deprotonated surface sites [33–34]. Furthermore, the high content of monovalent alkali metals, Na and K (Table 2) indicates that surface carboxylate groups exist as weak alkali salts (-COONa and -COOK) [35]. Monovalent Na⁺ and K⁺ ions have lower binding energies and lower ionic charges than divalent ions; monomeric cationic Rh-B⁺ can easily displace them via ion exchange at pH 3 without requiring extreme acidic conditions.

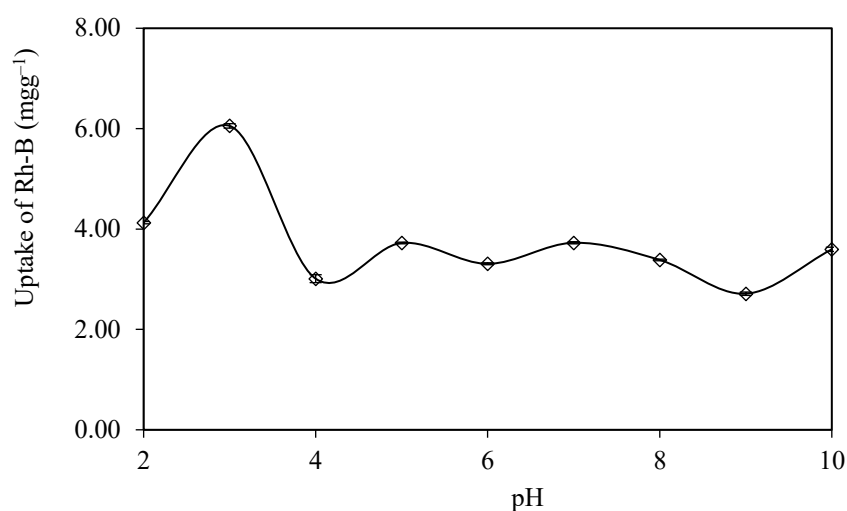


Figure 5. Effect of pH on adsorption of Rh-B onto mandarin orange peel.

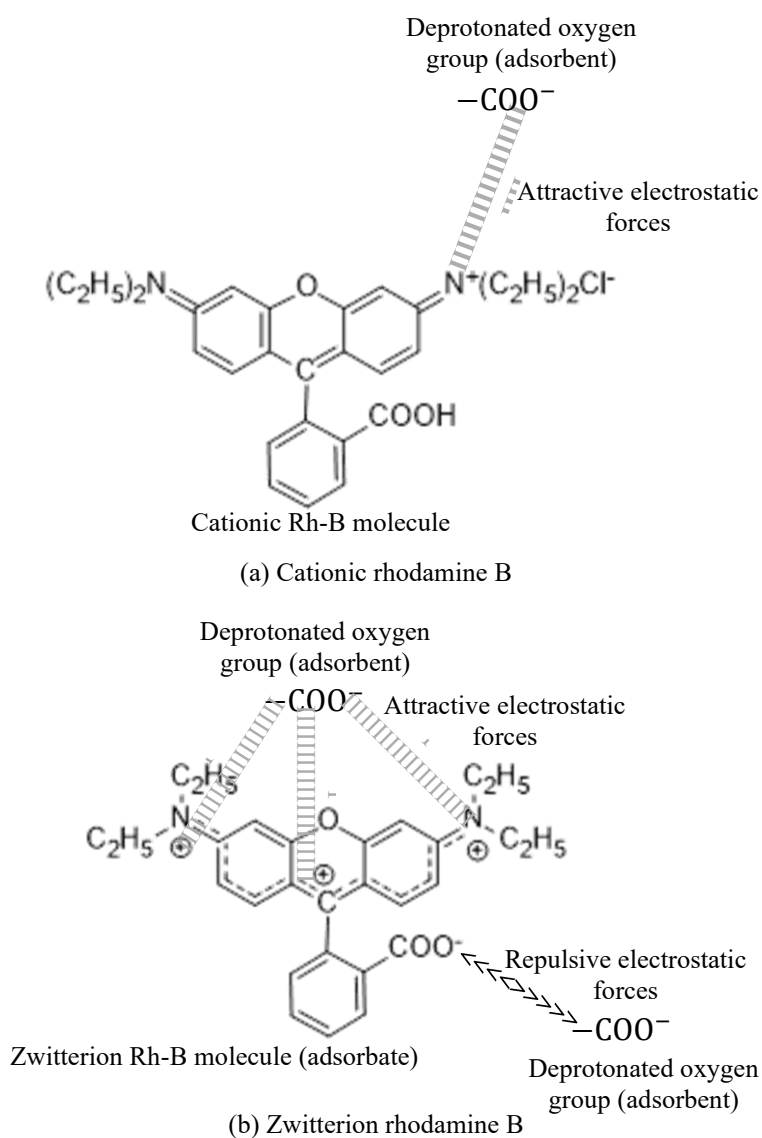


Figure 6. The interaction of cationic (a) and zwitterion (b) Rh-B with mandarin orange peel in the adsorption process.

After pH 3, the uptake of Rh-B onto mandarin orange peel decreased slightly before levelling off at higher pH values. This behaviour is attributed mainly to the speciation of the Rh-B molecule beyond its dissociation constant ($pK_a \approx 3.1$) [32, 35]. As the pH rises above 3.1, Rh-B converts from a monomeric cation ($Rh-B^+$) to a zwitterionic form ($Rh-B^\pm$) containing both a positive diethylamino group (R_3N^+) and a negative carboxylate group ($-COO^-$) [33]. The intermolecular electrostatic attraction between adjacent zwitterions drives the formation of large dye dimers, which increase the hydrodynamic diameter of the dye molecules and sterically hinder intraparticle diffusion into the biomass micropores, resulting in an initial decrease in dye uptake [32, 36]. Above pH 4, uptake becomes constant because the increasing negative charge on the deprotonated orange peel surface produces a dual effect: it attracts the cationic amine group of the zwitterion while simultaneously repelling its negative carboxylate end [34]. The balance between attractive and repulsive electrostatic forces (Figure 6), combined with pore clogging by dye aggregates, stabilises the system and prevents any further change in adsorption capacity at higher pH.

The Equilibrium Time Study

Figure 7 shows the effect of contact time on the adsorption of Rh-B onto orange peel. The adsorption capacity increased rapidly during the first 20 min, followed by a slower increase until it reached a nearly

constant value. The rapid initial adsorption was attributed to the abundance of vacant active sites on the adsorbent surface [18, 37]. After 20 minutes, only slight fluctuations in adsorption capacity were observed, reflecting the limited availability of active sites as the adsorption process approached equilibrium. Therefore, a contact time of 20 minutes was selected as the equilibrium time for the adsorption of Rh-B onto orange peel.

Figure 8a exhibits a scattered distribution of data points with no strong linear correlation, indicating that the adsorption of Rh-B onto mandarin orange peel does not conform to the pseudo-first-order kinetic model. This suggests that physical adsorption (*physisorption*) is not the primary rate-controlling step in the system [38-39]. Conversely, Figure 8b yields a well-fitted linear relationship with a high coefficient of determination ($R^2 \approx 0.9$), indicating that the process is well described by the pseudo-second-order kinetic model [40]. This strong correlation to the pseudo second order kinetic model indicates that the adsorption rate is controlled by surface-site availability on the mandarin orange peel surface [41]. Here, oxygen-containing functional groups such as carboxyl and hydroxyl groups facilitate physical interactions with the cationic Rh-B molecules [42]. Furthermore, isotherm analysis confirmed that the process is predominantly driven by physisorption. The parameters of both kinetic models are summarised in Table 3.

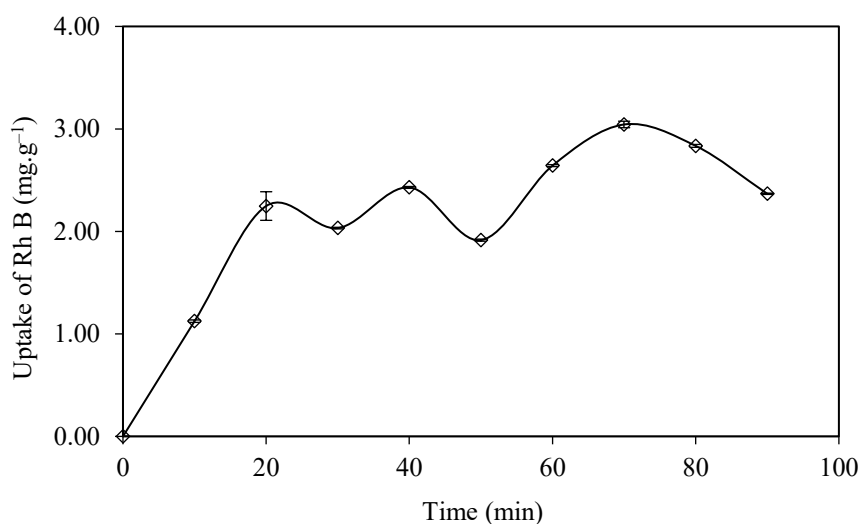


Figure 7. Effect of contact time on the adsorption of Rh-B in aqueous solution onto mandarin orange peel.

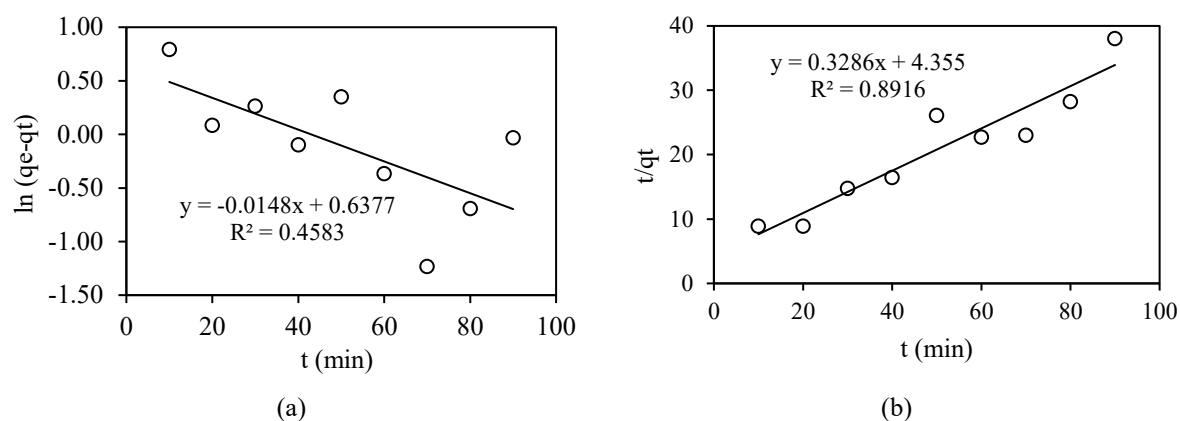


Figure 8. Pseudo-first order (a) and pseudo-second order (b) Kinetic model of the adsorption of Rh-B onto mandarin orange peel.

Table 3. Kinetics model parameters for the adsorption of Rh-B onto mandarin orange peel.

Pseudo-first order			Pseudo-second order		
$q_e \text{ (mgg}^{-1}\text{)}$	k_1	R^2	$q_e \text{ (mgg}^{-1}\text{)}$	k_2	R^2
1.892	0.0148	0.4583	3.043	0.0248	0.8916

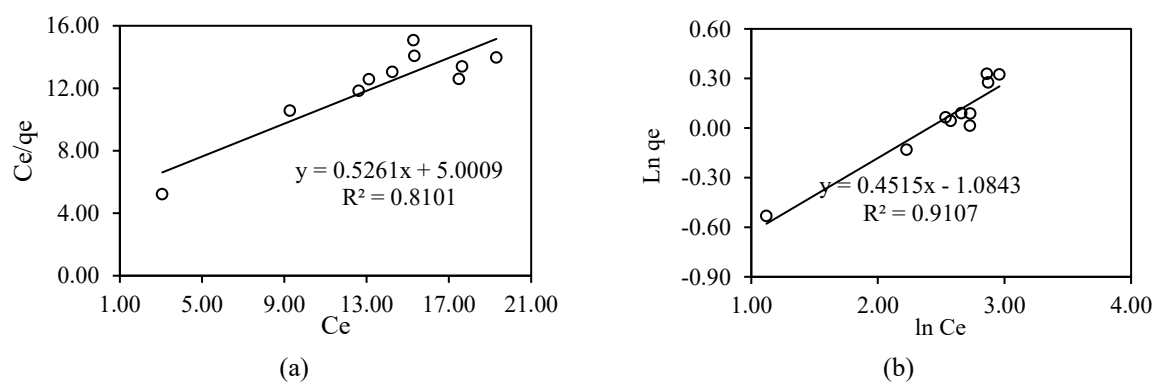


Figure 9. The Langmuir (a) and Freundlich (b) isotherm for adsorption of Rh-B onto mandarin orange peel.

Table 4. Langmuir and Freundlich parameters for the adsorption of Rh-B onto mandarin orange peel.

Langmuir			Freundlich	
$q_m \text{ (mg.g}^{-1}\text{)}$	$b \text{ (L.mg}^{-1}\text{)}$	R_L	$K_f \text{ (L.mg}^{-1}\text{)}$	$1/n$
1.901	0.1052	0.69	0.338	0.4515

Isotherm Study

The adsorption of rhodamine B (Rh-B) dye onto mandarin orange peel was investigated using the Langmuir and Freundlich isotherm models. As shown in Figure 9, the Freundlich model yielded a higher coefficient of determination ($R^2 = 0.9107$) than the Langmuir model ($R^2 = 0.8101$), indicating that the Freundlich isotherm provides a more suitable fit for describing the adsorption mechanism. The parameters of both isotherm models are summarised in Table 4. As highlighted by Pathania et al. [34] and Tran et al., 2017 [43], superior compliance with the Freundlich model signifies a physical adsorption (physisorption) process taking place on a heterogeneous surface via multilayer formation, rather than the uniform single-layer adsorption assumed by the Langmuir model. This physisorption is primarily driven by non-covalent physical interactions such as van der Waals forces, electrostatic attractions, including $\pi - \pi$ electron interactions between the aromatic rings of lignin/polyphenols and the xanthene core of Rh-B, as well as hydrogen bonding between the cationic Rh-B molecules and the active functional groups on the orange peel surface. Furthermore, the slope of the Freundlich plot gives an adsorption intensity ($1/n$) of 0.4145, corresponding to $n = 2.215$. In accordance with Al-Ghouti and Da'ana [35] and Norlaili et al., [44], a $1/n$ value within the range of $0 < 1/n < 1$ (or $1 < n < 10$) indicates that the physisorption of Rh-B onto mandarin orange peel is favourable. The slope and intercept of the Langmuir model yield a maximum adsorption capacity (q_m) of 1.901 mg g^{-1} and a Langmuir affinity constant (b) of $0.1052 \text{ L. mg}^{-1}$.

CONCLUSION

The mandarin orange peel (*C. reticulata*) is an effective adsorbent for Rh-B, owing to its carbon-rich porous structure and its carbonyl and hydroxyl functional groups. Adsorption was rapid, reaching equilibrium within 20 minutes at an optimal pH of 3. Kinetic and isotherm modelling indicated a dual mechanism in which pseudo-second-order kinetics govern the primary rate-limiting chemisorption step, while the Freundlich isotherm describes secondary multilayer physisorption on the heterogeneous surface. Mandarin orange peel therefore offers a viable, eco-friendly option for the treatment of cationic dyes in aqueous media.

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