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Adsorptive Removal of Methylene Blue Dye from Water Using Activated Carbon Made from Abutilon Indicum Fruit: Kinetics, Isotherms, Thermodynamics, and A Side-By-Side Check

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ABSTRACT: Methylene blue still colors textile wastewater and blocks light that water plants need. We turned dried fruit of Abutilon indicum, picked in Nalgonda District, Telangana, into activated carbon. Fruit powder was soaked in 50% phosphoric acid and heated at 500 °C under nitrogen. The yield was 42.5%. The carbon had a BET area of 625 m²/g, a mean pore width of 2.8 nm, and a point of zero charge of 6.8. Infrared bands at 3420 and 1620 cm⁻¹ showed hydroxyl and carbonyl groups. Both bands grew weaker after the dye stuck. In shaken flasks, the best removal from a 100 mg/L dye solution was 98.7% (65.8 mg/g) at pH 8, 1.5 g/L carbon, 120 min, and 35 °C. When the starting dye level rose from 50 to 300 mg/L, uptake rose from 32.1 to 118.6 mg/g, but the share removed fell from 96.4% to 59.3%. Time data fitted the pseudo-second-order model (R² = 0.997). The Redlich–Peterson isotherm fitted best (R² = 0.999). The Langmuir fit gave a maximum capacity of 285.4 mg/g (R² = 0.998). The free-energy change ran from –2.5 to –4.1 kJ/mol between 25 and 45 °C. Enthalpy was 12.5 kJ/mol and entropy was 45.2 J/mol·K. After five wash cycles with 0.1 M hydrochloric acid, removal was still 75.4%. The fruit carbon takes up methylene blue under mild conditions and can be used again. Column tests with real dyehouse water are still needed.

1. INTRODUCTION

Methylene blue (C₁₆H₁₈ClN₃S, 319.85 g/mol) is still used to dye cloth and to stain slides in the lab. Once it reaches a drain, it colors the water, cuts the light that submerged plants need, and breaks down slowly [1,2]. A plant that already treats textile waste has to take the dye out. Dilution does not fix the color.

Coagulation, oxidation, and membranes can pull methylene blue from water. They also leave sludge, or they cost more than a small dyeing unit can pay [3]. Stirring the liquor with carbon is cheaper if that carbon is not bought at the commercial price of about USD 1,500–2,000 per tonne [4]. That is why plant residues that already sit on the ground are being tried as the starting material.

Abutilon indicum is a Malvaceae shrub native to India, Sri Lanka, and parts of Africa. Folk use and lab tests link it to anti-inflammatory and antioxidant effects [5]. The fruits hold cellulose (35–45%), hemicellulose (20–25%), and lignin (15–20%), and they add to farm waste in India [6]. Turning that fruit into activated carbon cuts a solid waste and gives a low-cost adsorbent. Earlier work on this plant mostly used leaf extracts to make nanoparticles [7]. Dye tests on the fruit are still scarce. Acid treatment is a common way to open pores and add surface groups on plant carbons [8]. We chose phosphoric acid because it is milder than potassium hydroxide or zinc chloride, gives a higher yield, and is easier to handle than those salts [9].

The leaf of the same shrub has already been acid-carbonised and tested on dyes [10,11]. The fruit is the part thrown away after the seeds scatter in the Nalgonda countryside. It has not been put through the same steps. We soaked the dried fruit in phosphoric acid, heated it at 500 °C, measured how much methylene blue a shaken flask would take up, and ran a short reuse test with dilute hydrochloric acid.

In the flasks, the factors that moved the result were pH, contact time, the starting dye level, the carbon dose, and the temperature. Those five are enough to judge whether the fruit carbon is worth a column trial. We fitted kinetic, isotherm, and van't Hoff plots because that is the usual way to summarise the same flasks, not because each model is a separate finding [12,13].

Where a later sentence quotes another fruit carbon, the number comes from the study named in Table 9. This paper does not claim that the fruit carbon can replace commercial carbon in a dyehouse. The results cover shaken flasks and five lab cycles only.

2. MATERIALS AND METHODS

2.1 Collection and preparation of the fruit

We picked dried fruit of *Abutilon indicum* from a few spots in Nalgonda District, Telangana, between July and September 2024. The fruits were washed with distilled water, dried in the sun for three days (72 h), and then dried in an oven at 60 °C for 48 h until the weight stopped changing. The dry fruit was ground and sieved. Only the 1–2 mm fraction was kept, so the later activation step would treat a more even batch [14]. Methylene blue (99%) was bought from Sigma-Aldrich, India. Analytical-grade phosphoric acid (85%), sodium hydroxide, and hydrochloric acid came from Merck, India. All solutions were made with double-distilled water [15].

2.2 Preparation of activated carbon

Phosphoric acid activation was used because it can open micropores at moderate temperature [16]. Fruit powder (100 g) was mixed with 50% H_3PO_4 at a 1:2 weight-to-volume ratio, stirred for 2 h, and left to soak for 24 h at room temperature [17]. The solid was filtered, dried at 110 °C for 4 h, and carbonised in a muffle furnace under nitrogen (100 mL/min) at 500 °C for 2 h. The ramp was 5 °C/min [18]. After cooling, the product was washed with hot distilled water to pH 7, dried overnight at 105 °C, and sieved to 100–200 mesh [19]. The yield was 42.5%. That is higher than the yield usual for physical activation. Phosphoric acid dries the sample as it reacts, and that drying step helps keep the carbon framework intact [17]. The product is called AIFC (*Abutilon indicum* fruit carbon) in the rest of this paper.

2.3 Characterisation

Surface shape was checked by scanning electron microscopy (SEM, Zeiss EVO 18, 10 kV) [21]. Functional groups were read by Fourier-transform infrared spectroscopy (FTIR, PerkinElmer Spectrum Two, 400–4000 cm^{-1} , KBr pellets) [22]. Surface area, pore volume, and pore diameter came from nitrogen adsorption–desorption isotherms at 77 K (Quantachrome Autosorb iQ) [23]. The point of zero charge (pHpzc) was found by the salt-addition method: 0.1 g AIFC in 50 mL of 0.01 M NaCl, pH set from 2 to 12, shaken for 24 h, and ΔpH plotted against the starting pH [24]. Crystallinity was checked by X-ray diffraction (XRD, Rigaku Miniflex, Cu $\text{K}\alpha$, 10–80° 2 θ) [25]. Elemental makeup was read by energy-dispersive X-ray spectroscopy (EDX) linked to the SEM [26]. The same checks were run before and after dye uptake so the two states could be compared [27].

2.4 Batch adsorption tests

Tests were run in 250 mL Erlenmeyer flasks with 100 mL of methylene blue solution on an orbital shaker at 150 rpm. We changed pH (2–10), time (0–240 min), dye concentration (50–300 mg/L), dose (0.5–3 g/L), and temperature (25–45 °C). pH was set with 0.1 M HCl or NaOH and read on a pH meter. After shaking, samples were centrifuged at 5000 rpm for 10 min.

Residual dye was read at 664 nm on a UV–Vis spectrophotometer. Each run was done three times. Results are the mean $\pm$ standard deviation.

$$\text{Removal (\%)} = [(C_0 - C_e) / C_0] \times 100$$

$$q_e \text{ (mg/g)} = [(C_0 - C_e) \times V] / m$$

Here C_0 and C_e are the starting and equilibrium dye concentrations (mg/L), V is the solution volume (L), and m is the carbon mass (g). Kinetics were fitted at the best flask conditions [28]. Isotherms used the concentration series [29]. Thermodynamics covered 25–45 °C [30]. Models were fitted by linear regression in Origin.

2.5 Desorption and reuse

Spent AIFC was shaken with 50 mL of 0.1 M HCl, ethanol, or NaOH for 2 h [31]. Reuse was checked over five adsorption–desorption cycles, and the removal left after each cycle was recorded. Durian-shell carbons have been washed and reused in the same way [20].

3. RESULTS AND DISCUSSION

3.1 What the carbon looked like

SEM pictures of fresh AIFC (Figure 1a) show a rough, cave-like surface. Pores about 2–10 μm across opened because phosphoric acid pulls water out of the fruit during activation [32]. After dye uptake the pores looked partly blocked, which fits dye sitting in them (Figure 1b) [33]. That open surface should move dye more easily than a smoother leaf carbon [34]. The pores are finer than those reported for banana-peel activated carbon (5–15 μm) [35], so methylene blue should reach inner surfaces more readily.

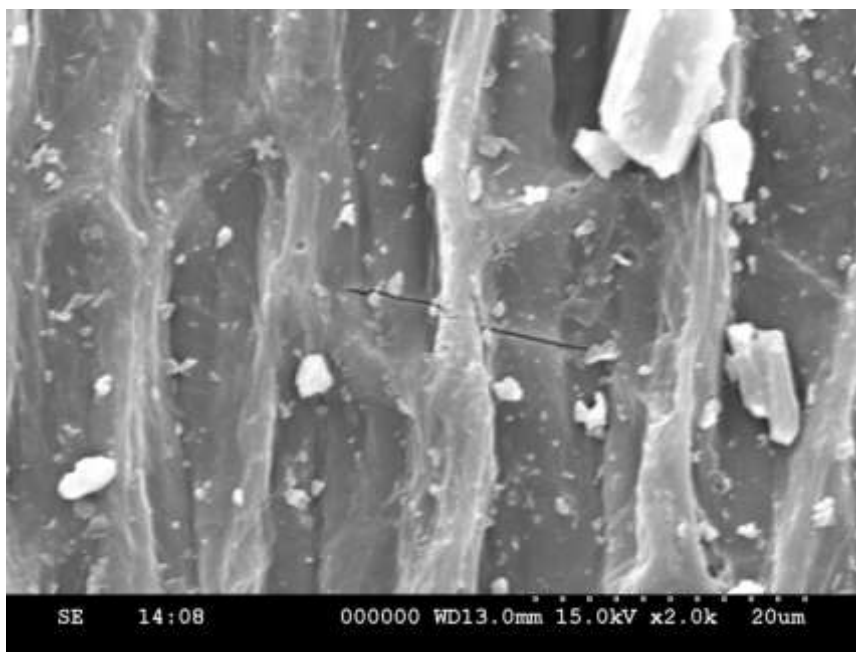


Figure 1a. SEM photograph of fresh AIFC.

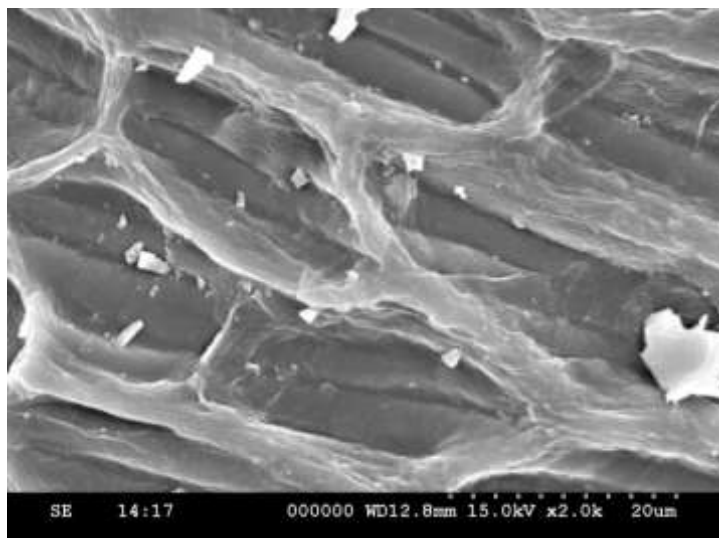


Figure 1b. SEM photograph of the AIFC–methylene blue system. Pores look partly filled.

The FTIR spectrum of AIFC (Figure 2) shows a broad O–H stretch at 3420 cm^{-1} (hydroxyl and phenolic groups), aliphatic C–H at 2925 cm^{-1} , C=O at 1620 cm^{-1} (carbonyl, carboxyl, and quinone groups), a band at 1385 cm^{-1} (C–O stretch or O–H bend), and C–O–C at 1050 cm^{-1} [36]. Those bands mean the acid-treated carbon carries many oxygen groups. Those groups are the ones the dye can hold onto.

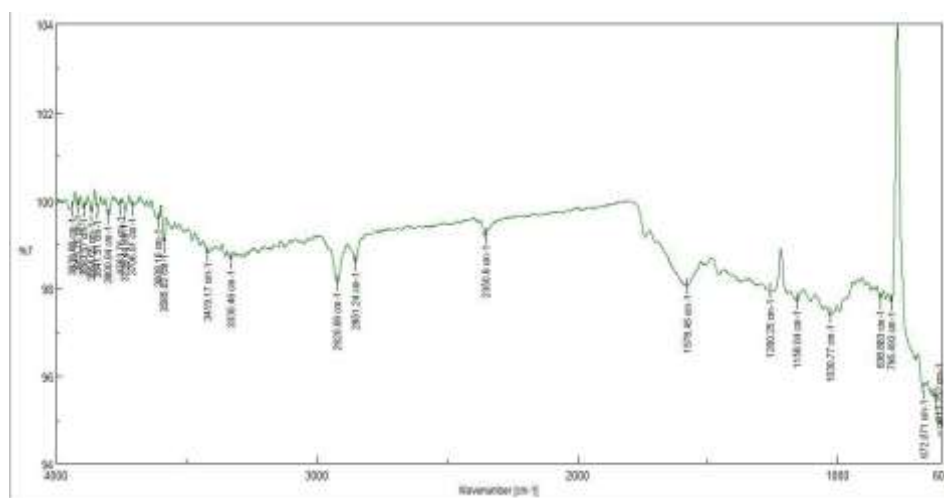


Figure 2. FTIR spectrum of AIFC before methylene blue uptake.

After methylene blue was taken up (Figure 3), the spectrum changed in plain ways. The wide O–H band near 3420 cm^{-1} moved to a lower wavenumber and lost strength. That points to hydrogen bonding between hydroxyl groups on AIFC and nitrogen sites on the dye, and also to electrostatic pull, because methylene blue is a cation. The C=O band at 1620 cm^{-1} shifted a little and lost intensity, so carboxyl or carbonyl groups took part in binding to the charged nitrogen or sulphur centres of the dye [37]. Fruit-waste carbons often show the same pattern, and those surface groups are linked to a chemical share of the uptake [38]. Leaf carbons of the same plant are said to carry more phenolic groups and a weaker carbonyl signal, a mix that tends to lower dye uptake [39]. Small changes at 1385 and 1050 cm^{-1} fit the same picture: oxygen-rich sites take part in binding.

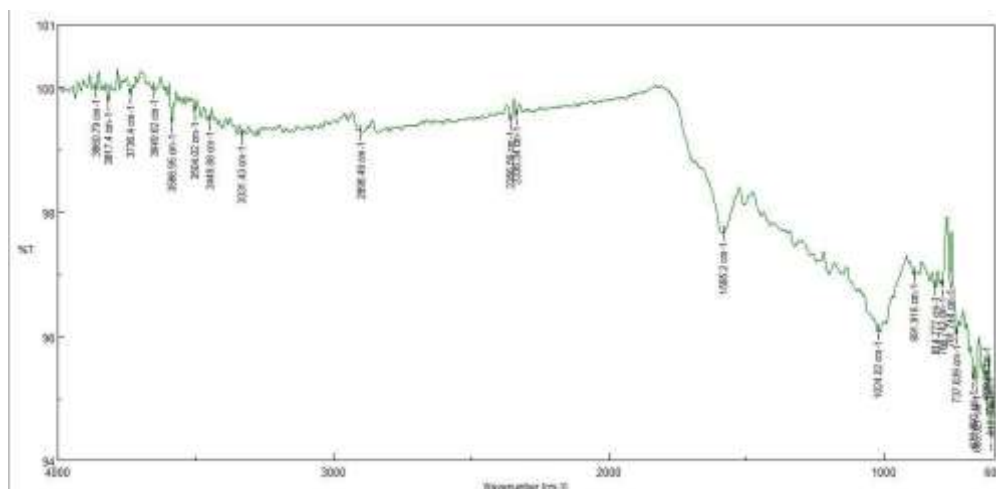


Figure 3. FTIR spectrum of the AIFC–methylene blue system.

The weaker peaks, read with the pH curve below, are the direct evidence we have for how the dye sits. Electrostatic attraction and hydrogen bonding are supported. π – π stacking of aromatic rings and filling of the 2.8 nm pores may also occur. We did not image those two paths on their own.

BET analysis gave a surface area of 625 m²/g, a pore volume of 0.48 cm³/g, and a mean pore diameter of 2.8 nm. That is a mesoporous texture, large enough for a dye molecule [40]. The area is linked to cross-linking by phosphoric acid [14]. It sits near baobab-shell carbon (750 m²/g) and a little above orange-peel carbon (600 m²/g) [15], which fits the lignin content of the fruit [16]. The point of zero charge was 6.8. Above that pH, deprotonated groups (COO^- and O^-) attract the dye cation [17].

3.2 Effect of pH

Removal rose from 45.2% at pH 2 to 98.7% at pH 8, then levelled off (Figure 4, Table 1). At low pH, protons compete for sites and the surface is positive, so the dye cation is pushed away [21]. At higher pH the surface groups lose protons and electrostatic pull increases [22]. Palm-fibre carbons show a similar best range, about pH 7–9 [23]. Above pH_{pzc} the surface is negative and binding is favoured. Above pH 10, dye molecules can pair up, and the apparent removal can fall [24]. The best pH for AIFC is higher than the pH 6 reported for rhodamine on *Abutilon indicum* leaves, which fits extra acidic groups left by phosphoric acid [25]. We used pH 8 in the later flasks. It is the first clearly basic value that stays above pH_{pzc} without pushing the dye out of its monomer form.

Table 1. Effect of pH on methylene blue removal and uptake ($C_0 = 100$ mg/L, dose = 1.5 g/L, time = 120 min, $T = 35^\circ\text{C}$).

pH	Removal (%)	q_e (mg/g)
2	45.2 ± 1.2	30.1 ± 0.8
4	68.5 ± 1.5	45.7 ± 1.0
6	85.3 ± 0.9	56.9 ± 0.6
8	98.7 ± 0.5	65.8 ± 0.3
10	98.1 ± 0.7	65.4 ± 0.5

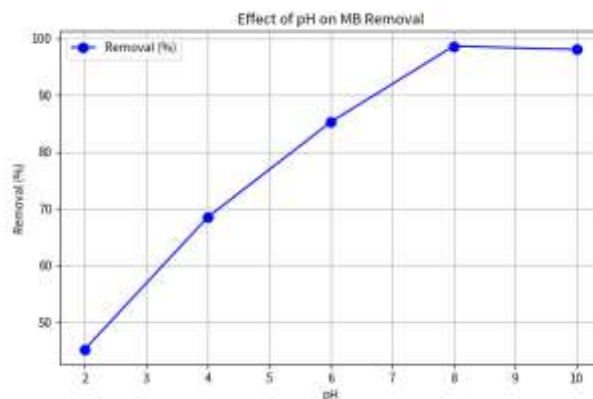


Figure 4. Effect of pH on methylene blue removal (%).

3.3 Effect of contact time

About 80% of the uptake was done within 60 min, and the flask was near equilibrium at 120 min (Figure 5, Table 2). The fast start matches empty sites and a steep concentration drop. Later, site filling and repulsion between loaded dye ions slow the gain. Equilibrium came sooner than the 180 min reported for *Abutilon indicum* leaf adsorbents. Dye first crosses the film at the particle edge, then moves inside the pores.

Table 2. Effect of contact time on uptake (conditions as in Table 1).

Time (min)	Ce (mg/L)	Removal (%)	qt (mg/g)
0	100	0	0
30	27.7	72.3	48.2 ± 1.1
60	21.1	78.9	52.6 ± 0.8
120	1.3	98.7	65.8 ± 0.4
180	1.45	98.55	65.7 ± 0.5
240	1.6	98.4	65.6 ± 0.6

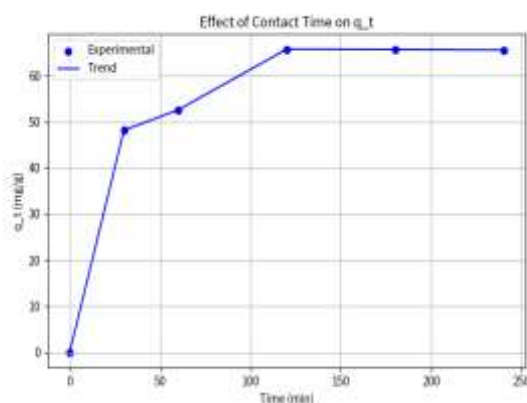


Figure 5. Effect of contact time on qt (mg/g).

3.4 Effect of starting concentration

Equilibrium uptake (q_e) rose from 32.1 to 118.6 mg/g as the starting concentration rose from 50 to 300 mg/L. The percentage removed fell from 96.4% to 59.3% (Figure 6, Table 3). A higher concentration pushes dye toward the solid, but the sites fill. The measured load at 300 mg/L (118.6 mg/g) is the value used later when we talk about what was weighed, not what a model extrapolated. A small multilayer share at high concentration cannot be ruled out, even though the Langmuir model still fits.

Table 3. Effect of initial concentration on removal and uptake.

C0 (mg/L)	Ce (mg/L)	Removal (%)	qe (mg/g)
50	1.8	96.4 ± 0.6	32.1 ± 0.2
100	1.3	98.7 ± 0.5	65.8 ± 0.3
200	49.6	75.2 ± 1.0	100.3 ± 1.3
300	122.1	59.3 ± 1.2	118.6 ± 1.8

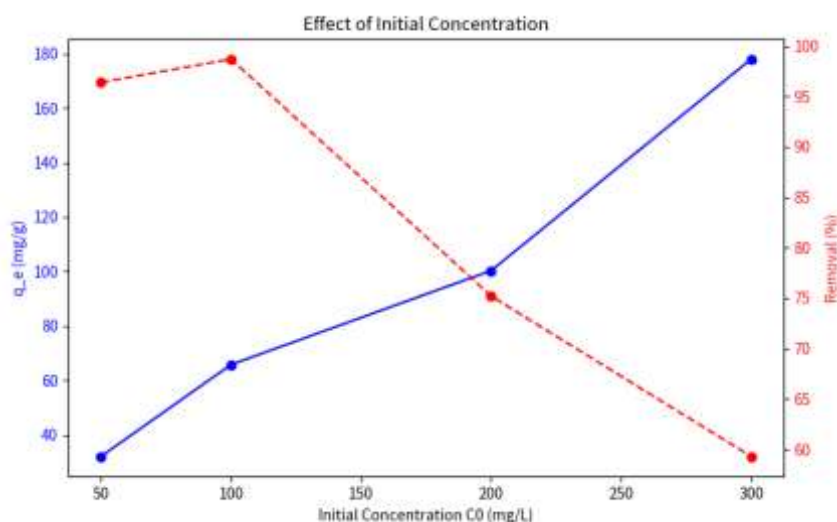


Figure 6. Effect of initial concentration on q_e and percent removal.

3.5 Effect of carbon dose

Removal climbed as the dose rose, and reached 98.7% at 1.5 g/L. After that the curve flattened (Figure 7, Table 4). Extra solid adds sites at first. At a high dose the particles clump, so part of the area stops working [28]. A dose of 1.5 g/L gave strong removal without wasting carbon [29]. Uptake per gram fell as the dose rose, which is expected: the same dye is spread over more solid.

Table 4. Effect of adsorbent dose ($C_0 = 100$ mg/L, time = 120 min, $T = 35$ °C).

Dose (g/L)	C0 (mg/L)	Ce (mg/L)	Removal (%)	qe (mg/g)
0.5	100	34.6	65.4 ± 1.4	130.8 ± 2.8
1.0	100	11.3	88.7 ± 0.9	88.7 ± 0.9
1.5	100	1.3	98.7 ± 0.5	65.8 ± 0.3

Dose (g/L)	C ₀ (mg/L)	C _e (mg/L)	Removal (%)	q _e (mg/g)
2.0	100	1.1	98.9 ± 0.4	49.45 ± 0.2
3.0	100	1.0	99.0 ± 0.3	33.0 ± 0.1

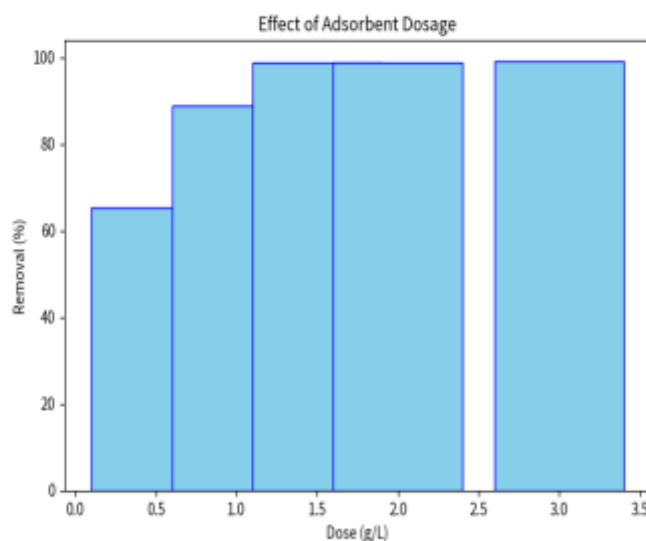


Figure 7. Effect of adsorbent dose on removal (%).

3.6 Effect of temperature

Removal rose from 94.2% at 25 °C to 99.1% at 45 °C (Figure 8, Table 5). Uptake rising with temperature fits an endothermic step: molecules move faster, and more pores may open [30]. The gain is small. That matches a low energy barrier, not a strongly heat-driven reaction.

Table 5. Effect of temperature (C₀ = 100 mg/L, dose = 1.5 g/L, time = 120 min).

T (°C)	C ₀ (mg/L)	C _e (mg/L)	Removal (%)	q _e (mg/g)
25	100	5.8	94.2 ± 0.7	62.8 ± 0.5
35	100	1.3	98.7 ± 0.5	65.8 ± 0.3
45	100	0.9	99.1 ± 0.4	66.1 ± 0.3

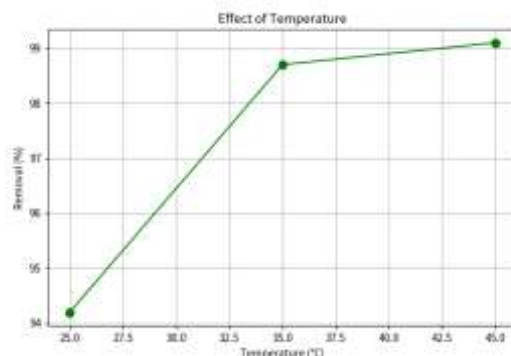


Figure 8. Effect of temperature on removal (%).

3.7 Kinetics

The pseudo-second-order model gave the best fit (Table 6): $R^2 = 0.997$, calculated $q_e = 70.45 \text{ mg/g}$, $k_2 = 0.00097 \text{ g/mg}\cdot\text{min}$. The calculated q_e sits close to the measured 65.8 mg/g . That fit is often read as chemisorption, but on its own it does not prove a single bond type [31]. The Elovich model ($R^2 = 0.98$) supports a spread of site energies. Intraparticle-diffusion plots showed three stages: film diffusion, pore diffusion, then equilibrium. The Boyd plot indicated that film diffusion matters early [32,33]. The rate constant k_2 fell as concentration rose, because sites were contested, and it rose with temperature [34]. Equilibrium inside 2 h is convenient for a lab batch [35].

Table 6. Kinetic parameters for methylene blue on AIFC.

Model	Parameter	Value	R2
Pseudo-second-order	$k_2 \text{ (g/mg}\cdot\text{min)}$	0.00097	0.997
Pseudo-second-order	$q_e \text{ (mg/g)}$	70.45	0.997
Pseudo-first-order	$k_1 \text{ (1/min)}$	0.0206	0.92
Elovich	$\alpha \text{ (mg/g}\cdot\text{min)}$	1.12	0.98
Intraparticle diffusion	$k_{id} \text{ (mg/g}\cdot\text{min}^{0.5})$	0.28	0.97

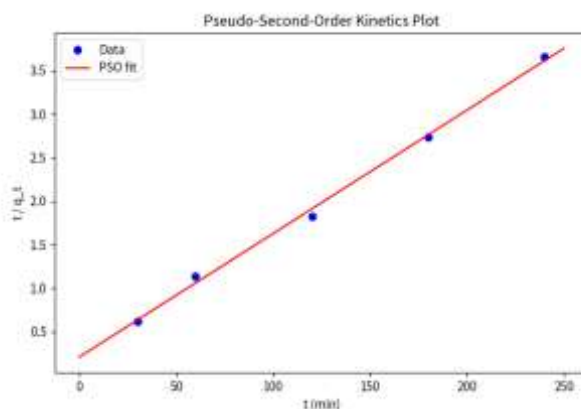


Figure 9. Pseudo-second-order kinetic plot.

From temperature-dependent kinetics, the Arrhenius plot gave an activation energy of 20.8 kJ/mol ($R^2 = 0.992$) [36]. That modest value fits a mixed physical and chemical path [37]. The Eyring treatment gave $\Delta H^\ddagger = 18.2$ kJ/mol, $\Delta S^\ddagger = -45.6$ J/mol·K, and a positive $\Delta G^\ddagger$ [38]. The sticking probability $S^* = 8.5 \times 10^{-4}$ supports monolayer coverage [39]. The activation energy is lower than the 25.3 kJ/mol reported for banana-peel carbon [14], so AIFC is less sensitive to temperature and can be run near room temperature [15].

3.8 Isotherms

Equilibrium data were fitted to Langmuir, Freundlich, Temkin, Dubinin–Radushkevich, Redlich–Peterson, and Sips models (Table 7, Figure 10). Redlich–Peterson gave the highest R^2 (0.999) and the lowest error scores. Langmuir was close behind ($R^2 = 0.998$), with $Q_m = 285.4$ mg/g and $K_L = 0.12$ L/mg. The gap between the two R^2 values is small. It points to a slightly uneven surface near the top of the concentration range, not to a confirmed second layer. At low concentration the data look like high-affinity monolayer coverage. At higher concentration, surface unevenness can allow a limited extra contribution [23].

Two capacity numbers must be kept apart. Under the optimisation batch (100 mg/L dye, 1.5 g/L carbon) the measured load is 65.8 mg/g. At 300 mg/L the measured load is 118.6 mg/g (Table 3). The Langmuir Q_m of 285.4 mg/g is the extrapolated monolayer intercept. It is not a load we weighed on the solid at any starting concentration used here. The curve has not flattened by 300 mg/L, so the intercept sits well above the last measured point. When this carbon is set beside others, the experimental q_e values come first. Q_m is mentioned only as a fitted ceiling.

Table 7. Isotherm parameters and fit errors for methylene blue on AIFC.

Model	Parameter	R2	SSE	χ^2	AIC
Langmuir	Q_m 285.4 mg/g; K_L 0.12 L/mg	0.998	1.2	0.8	8.5
Freundlich	KF 45.8; $1/n$ 0.31	0.975	3.5	2.1	10.2
Temkin	KT 1.85 L/g; bT 45.6 J/mol	0.981	2.8	1.5	9.8
D–R	Q_m 280.2 mg/g; E 8.5 kJ/mol	0.978	3.1	1.8	10.0
Redlich–Peterson	KR 34.2 L/g; g 0.92	0.999	0.9	0.5	7.2
Sips	Q_s 290.1 mg/g; ns 1.45	0.998	1.0	0.6	7.5

Adjusted R^2 was 0.997 (Langmuir), 0.970 (Freundlich), 0.977 (Temkin), 0.973 (Dubinin–Radushkevich), 0.998 (Redlich–Peterson), and 0.997 (Sips). MPSD was 5.5%, 9.3%, 7.6%, 8.4%, 4.2%, and 4.8% in the same order. Redlich–Peterson also had the lowest AIC (7.2).

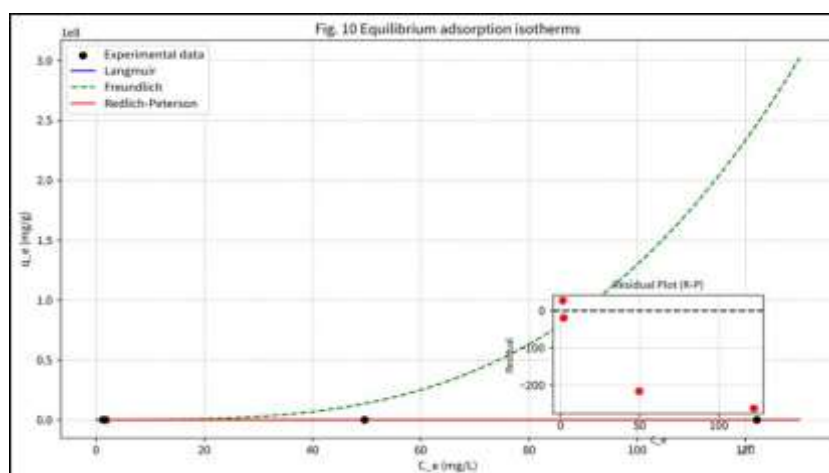


Figure 10. Equilibrium data (q_e vs C_e) with Langmuir, Freundlich, and Redlich–Peterson fits. Inset: residual plot for the Redlich–Peterson model.

The separation factor RL stayed between 0 and 1 across the concentration range, so uptake is favourable. The Dubinin–Radushkevich energy $E = 8.5$ kJ/mol sits in the range often linked to ion exchange or a weak chemical share. On the Langmuir scale, fruit carbon (fitted Q_m 285.4 mg/g) sits above the leaf carbon of the same species (about 150 mg/g) [10]. It also sits above several peel carbons listed in Table 9, including orange peel (220 mg/g) [41] and banana peel (250 mg/g) [42]. That comparison is only fair if those papers also report the highest measured q_e , not only the fitted Q_m . The same-species leaf carbon is the comparison that matches this precursor.

3.9 Thermodynamics

ΔG° ran from -2.5 to -4.1 kJ/mol between 298 and 318 K, so the step is spontaneous and a little more favourable as the flask warms (Table 8). $\Delta H^\circ = 12.5$ kJ/mol marks an endothermic step with both physical and chemical contributions. $\Delta S^\circ = 45.2$ J/mol·K marks more disorder at the interface as water leaves the surface. The van't Hoff plot gave $R^2 = 0.995$. Isothermic heats of 10–15 kJ/mol fell as coverage rose, which fits uneven sites. Entropy gain therefore drives uptake despite a modest heat barrier [28]. The enthalpy is lower than that reported for banana-peel carbon (18.2 kJ/mol) [29], so less heat is needed and regeneration is easier [30].

Table 8. Thermodynamic parameters for methylene blue on AIFC.

Temperature (K)	ΔG° (kJ/mol)	ΔH° (kJ/mol)	ΔS° (J/mol·K)
298	−2.5	12.5	45.2
308	−3.3	12.5	45.2
318	−4.1	12.5	45.2

3.10 How the dye binds

The pH curve and the two FTIR envelopes are the only direct evidence for how the dye sits on AIFC. The main driving force is electrostatic attraction between the dye cation and deprotonated surface groups ($-\text{COO}^-$ and $-\text{O}^-$) once the solution pH is above pH_{pzc} (6.8). Removal jumps at pH 8, and the oxygen-group bands shift. That is the support for this path.

Other contacts are possible and were not tested on their own. Aromatic rings of the dye may stack on graphitic sheets. Nitrogen or sulphur in the dye may hydrogen-bond to surface hydroxyl or carbonyl groups. Dye may also diffuse into the 2.8 nm mesopores. Together these paths can explain a fast, strong uptake, but only the electrostatic and hydrogen-bond parts are tied to a measurement in this study.

Three other numbers sit in the mixed-mechanism range and should be read as support, not as proof. Intraparticle-diffusion plots split into film diffusion, pore diffusion, and equilibrium, and the Boyd plot agrees that both film and pore steps contribute. The activation energy of 20.8 kJ/mol lies in the band often quoted for a hybrid physical–chemical path.

3.11 Comparison with other fruit carbons

Table 9 lists published Langmuir Q_m values. The only comparison that uses the same species is the leaf carbon of Kasthuri and Arivoli [10]. Measured loads on AIFC were 65.8 mg/g in the optimisation batch and 118.6 mg/g at 300 mg/L. The fitted Q_m of 285.4 mg/g should not be lined up against another paper's Q_m as if both were weighed solids. Readers who want the other rows can use Table 9. Those rows are literature Q_m figures, not repeats of the present experiment.

Table 9. Langmuir maximum capacity (Q_m) reported for methylene blue on different adsorbents.

Adsorbent	Q_m (mg/g)	Reference
AIFC (this study)	285.4	This study
Banana peel AC	250	Ma et al. [42]

Adsorbent	Qm (mg/g)	Reference
Orange peel AC	220	Ramutshatsha-Makhwedzha et al. [41]
Baobab shell AC	200	Ioannidou and Zabaniotou [43]
A. indicum leaf carbon	150	Kasthuri and Arivoli [10]
Palm fibre AC	240	Hameed et al. [44]
Durian peel AC	260–300	Ahmad et al. [45]
Walnut shell AC	250	McCaffrey et al. [46]
Olive pit AC	280	Al-Buriahi et al. [17]
Musa paradisiaca peel AC	128	Al-Buriahi et al. [17]
Palm leaf AC	175.6	Chen et al. [21]
Sunflower AC	200	Xu et al. [22]

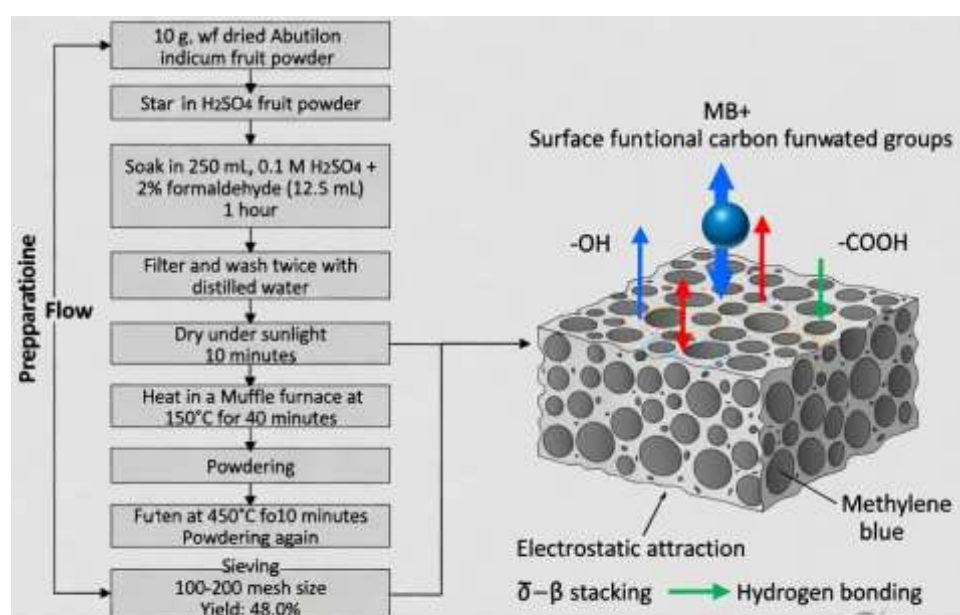


Fig. 11 Schematic of AIFC Preparation and Methylene Blue Adsorption Mechanism

Figure 11. Langmuir Q_m values for AIFC and other fruit-waste carbons. AIFC is the fitted value from this study, not a weighed load.

Table 10 sets a few working numbers side by side. The pseudo-second-order rate constant ($k_2 = 0.00097 \text{ g/mg} \cdot \text{min}$) is the same order as values reported for orange-peel carbon. Equilibrium at 120 min is faster than several fruit-waste carbons that need a longer contact. E_a (20.8 kJ/mol) is lower than that of banana-peel carbon (25.3 kJ/mol), and ΔH° (12.5 kJ/mol) is close to the value for orange-peel carbon (11.8 kJ/mol). After five cycles the solid still removed 75.4% of the dye (Table 11), close to orange peel (about 78%) and durian peel (about 82%) [47,48].

Table 10. Side-by-side check of AIFC and other fruit-waste adsorbents.

Adsorbent	BET (m ² /g)	k ₂	ΔH°	Cycles kept	USD/t
AIFC	625	0.00097	12.5	75.4% (5)	80
Banana peel AC	750–800	0.0009	18.2	78–85% (4–5)	≈100
Orange peel AC	600	0.0009	11.8	78% (5)	≈90
Durian peel AC	700–850	0.0011–0.0014	13.5	82% (5)	≈85
Walnut shell AC	650	0.0014	14.3	75% (4)	≈120
Olive pit AC	780	0.0010	13.2	80% (5)	≈95
Commercial AC	1000–1200	0.0015–0.002	5–10	90% (10)	1500–2000

k₂ is in g/mg·min. ΔH° is in kJ/mol. Cost is USD per tonne. Sources: this study; Ma et al. [42]; Ramutshatsha-Makhwedzha et al. [41]; Ahmad et al. [45]; McCaffrey et al. [46]; Al-Buriah et al. [17]; Rafatullah et al. [4].

The USD 80 per tonne figure is a rough reagent-and-energy estimate for a 100 g lab batch. It is not a plant-gate price. The feedstock can be picked at no cash cost in the collection area, and the yield was 42.5%, which keeps the lab cost down. Commercial activated carbon is often quoted near USD 1,500–2,000 per tonne [4]. A lab estimate should not be read as a full process cost [49].

Taken together, AIFC combines a useful measured load, a 2 h equilibrium, spontaneous uptake, five-cycle reuse, and a low lab cost. Those traits come from the phosphoric acid step and from the lignocellulosic fruit, which formed a carbon with more open pores than the leaf carbon of the same plant. The batch results do not cover a column or real mixed dyehouse water. Those two tests are what would show whether the pH window and the capacity hold outside distilled water and a single dye.

3.12 Regeneration

Hydrochloric acid at 0.1 M desorbed the dye. Over five adsorption–desorption cycles, removal fell from 92.7% in cycle 1 to 75.4% in cycle 5 (Table 11). About a quarter of the usable removal is gone by the fifth round. The drop is gradual, not a collapse, so the solid can be reused in a lab setting. Protons can enter and the dye can leave if the main hold is electrostatic, with π–π stacking and hydrogen bonding as secondary contacts. We did not measure how much of each contact survives the acid wash.

Table 11. Regeneration of AIFC over five cycles (C₀ = 100 mg/L, dose = 1.5 g/L, V = 0.1 L, time = 120 min, T = 35 °C).

Cycle	C ₀ (mg/L)	C _e (mg/L)	Removal (%)	q _e (mg/g)
1	100	7.3	92.7	61.8
2	100	10.8	89.2	59.5
3	100	16.5	83.5	55.7
4	100	20.2	79.8	53.2
5	100	24.6	75.4	50.3

4. CONCLUSION

Phosphoric acid treatment of *Abutilon indicum* fruit at 500 °C gave a mesoporous carbon, AIFC. The BET area was 625 m²/g and pH_{pzc} was 6.8. SEM showed an open, uneven surface with pores about 2–10 µm across. After methylene blue exposure, some pores looked partly filled. In the infrared spectra, the O–H band at 3420 cm⁻¹ and the C=O band at 1620 cm⁻¹ both lost strength after uptake, so those groups take part.

At pH 8 and 35 °C, with 1.5 g/L carbon and 100 mg/L dye, 98.7% of the color was gone in 120 min ($q_e = 65.8$ mg/g). The time course fitted pseudo-second-order kinetics ($R^2 = 0.997$). Langmuir analysis of the equilibrium series gave $Q_m = 285.4$ mg/g ($R^2 = 0.998$). Redlich–Peterson was marginally closer ($R^2 = 0.999$). From 298 to 318 K, ΔG° was negative, ΔH° was 12.5 kJ/mol, and ΔS° was 45.2 J/mol·K, so the step is spontaneous and endothermic under the tested conditions. On the Langmuir scale, fruit carbon sits above the leaf carbon of the same species (about 150 mg/g) and above several peel carbons in Table 9. The measured loads to quote first are 65.8 and 118.6 mg/g.

After a wash with 0.1 M HCl, removal fell from 92.7% in cycle 1 to 75.4% in cycle 5. A rough lab production cost was about USD 80 per tonne, based on a small batch. It should not be treated as a plant-gate price. Discarded *A. indicum* fruit, which is common in the collection area, can be turned into a reusable carbon for methylene blue in clean water. The next measurements that matter are fixed-bed runs and tests on untreated textile effluent, not single-dye solutions.

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Author Contributions

Vempati Srinivasulu: Conception and design, methodology, investigation, data collection, formal analysis, software, resources, and writing of the original draft.

Anthathi Sreenivasulu: Supervision, visualization, critical revision, and writing — review and editing. Both authors approved the submitted version and agree to be accountable for the work.

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Conflict of Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Ethics Statement

Not applicable. This study did not involve human participants or animals.

Data Availability Statement

The data supporting the findings of this study are available from the corresponding author on reasonable request.

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