Removal of Chemical Dye (DNB-106) by Adsorption Using Low-Cost Activated Carbon from *Jatropha curcas* Leaves

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Abstract Adsorption plays a pivotal role in the treatment of dye-contaminated industrial wastewater. In the textile industry, effluents contain synthetic dyes, heavy metals, and complex organic compounds that are resistant to conventional degradation. This study investigates the removal of Direct Navy Blue 106 (DNB-106), a widely used azo dye, using activated carbon prepared from *Jatropha curcas* (Kattamanakku) tree leaves (KTC) via acid carbonization. Batch adsorption experiments were conducted to evaluate the effects of pH, adsorbent dosage, contact time, and initial dye concentration. The KTC adsorbent exhibited a surface area of $467.38\,m^2\,g^{-1}$ and achieved 93% dye removal under optimal conditions: pH 7.5, 1.1 g adsorbent per 100 mL of $100\,mg\,L^{-1}$ dye solution, and 60 min contact time, with equilibration at 210 min. The equilibrium data fitted both the Langmuir and Freundlich isotherms, while kinetic studies confirmed first-order adsorption behaviour. The adsorption process was predominantly physical in nature, with initial rapid uptake attributed to the high available surface area. The study demonstrates that 1.1 g of KTC can purify approximately 62.93 L of wastewater, highlighting its potential as a cost-effective and reusable adsorbent for textile effluent treatment.

Keywords: Adsorption, Direct Navy Blue 106, Activated carbon, *Jatropha curcas*, Langmuir isotherm, Freundlich isotherm, First-order kinetics, Wastewater treatment.

I Introduction

Water pollution remains one of the most pressing global environmental challenges, necessitating continuous evaluation and revision of water resource policies at all levels. Industrial activities are among the largest contributors to water pollution, accounting for more than half of the total pollutant volume and introducing some of the most hazardous substances into aquatic ecosystems. The textile industry, in particular, is a major source of coloured wastewater, as it extensively uses synthetic organic dyes—including direct, reactive, and processing dyes—to meet market demands for vibrant and durable fabric shades [1]. The rapid industrialization and the consequent disposal of untreated or partially treated effluents have reached alarming levels, posing significant risks to ecosystems and human health. Elevated concentrations of toxicants in the environment can cause phytotoxicity, bioconcentration, and biomagnification through the food chain [1].

Heavy metals such as Cr^{6+}, V^{5+}, Mn^{6+}, Ti^{6+}, Zn^{2+}, Cd^{2+}, and Cu^{2+}, along with aromatic functional groups (e.g., CN, SO, NO) and inorganic oxides (AlO, SiO, GeO), contribute to the colour and toxicity of textile effluents. These pollutants are persistent and resistant to natural degradation, necessitating effective treatment methods before discharge. Various techniques have been employed for dye removal, including chemical coagulation, flocculation, biological treatment (both aerobic and anaerobic), membrane separation, ozonation, biosorption, and adsorption [2, 3, 4]. Among these, adsorption has emerged as a superior method due to its simplicity, high efficiency, low cost, and ability to treat a wide range of dyes [5].

Activated carbon is widely recognised as an effective adsorbent for removing organic pollutants from aqueous solutions, owing to its large surface area and porous structure [5, 6, 7]. However, the high

cost of commercially available activated carbon limits its widespread application. Consequently, there is growing interest in developing low-cost alternatives from agricultural and industrial waste materials. Numerous studies have explored the use of various adsorbents, including wood [8], lignite and sphagnum peat [9], fly ash [10], boiler bottom ash [11], rice husk [12], coal [13], resins [14], inorganic salts [15], and biomass [16]. Recent reviews have further highlighted the potential of sustainable mesoporous activated carbon and agro-waste-based adsorbents for efficient dye removal [17, 18].

Azo dyes, which constitute a significant proportion of commercially produced dyes, are particularly problematic due to their resistance to microbial degradation and stability under light and washing conditions [19]. Dye effluents may contain chemicals that are toxic, carcinogenic, mutagenic, or teratogenic to various organisms [20, 21]. Conventional treatment methods such as coagulation, flocculation, and reverse osmosis often prove economically unviable or insufficient for complete dye removal [2, 3, 4]. Adsorption on activated carbon has been demonstrated to be highly effective for removing colour from textile waste effluents [5, 22].

The present study aims to investigate the feasibility of using activated carbon prepared from the leaves of the Kattamanakku tree (*Jatropha curcas* L.; family: Euphorbiaceae) as a low-cost adsorbent for the removal of Direct Navy Blue 106 (DNB-106), a common azo dye used in the textile industry. The specific objectives include:

1. Optimisation of carbon characteristics.
2. Evaluation of the effects of pH, adsorbent dosage, and contact time on dye removal.
3. Analysis of adsorption isotherms (Langmuir and Freundlich).
4. Kinetic modelling of the adsorption process.

This study contributes to the development of sustainable and cost-effective wastewater treatment technologies by utilising locally available bio-waste materials.

II Experimental

II.a Materials

Direct Navy Blue 106 (DNB-106) dye (microscopic grade, Sigma-Aldrich) was used as the adsorbate without further purification. All solutions were prepared using double-distilled water. The chemical structure of DNB-106 is shown in Figure 1.

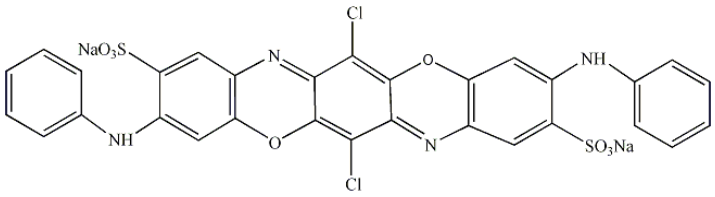

Figure 1: Chemical structure of Direct Navy Blue 106 (DNB-106) dye.

Mature Kattamanakku (*Jatropha curcas*) tree leaves were collected from local sources, mixed thoroughly, and washed repeatedly with water to remove dust and other impurities. The cleaned leaves were dried, ground, and subjected to acid carbonization to prepare activated carbon. The resulting carbon was sieved to 400 mesh size and stored in glass bottles for use as the adsorbent (designated KTC).

II.b Characterisation of Activated Carbon

The physicochemical characteristics of the prepared KTC were determined using standard procedures. The surface area was measured by the *p*-nitrophenol (PNP) adsorption method. The results are summarised in Table 1.

Table 1: Physicochemical characteristics of Kattamanakku tree leaf carbon (KTC).

Parameter	**Value**
Moisture content (%)	24.90
Ash content (%)	0.266
Bulk density ($g\,mL^{-1}$)	0.2527
pH	7.8
Decolourising power ($mg\,g^{-1}$)	73.5
Ion exchange capacity ($mEqg^{-1}$)	0.4866
Surface area ($m^2\,g^{-1}$)	467.38

II.c Adsorption Experiments

Batch adsorption experiments were conducted using aqueous solutions of DNB-106 dye. The effects of various parameters—adsorbent dosage, agitation time, pH, and initial dye concentration—were systematically investigated. In each experiment, a known amount of KTC was added to 100 mL of DNB-106 solution in a conical flask, and the mixture was agitated in a thermostatic mechanical shaker at 30 °C for 5 hours. The pH was adjusted using dilute HNO_3 or NaOH. After equilibration, the mixture was centrifuged (Remi Research Centrifuge), and the residual dye concentration in the supernatant was determined spectrophotometrically (Hitachi 3210) at the wavelength of maximum absorbance ($\lambda_{max} = 600\,nm$). Calibration curves were prepared using standard DNB-106 solutions, and the amount of dye adsorbed was calculated by mass balance.

III Results and Discussion

III.a Effect of pH

The pH of the solution is a critical parameter influencing dye adsorption, as it affects both the surface charge of the adsorbent and the ionization state of the dye molecules. The effect of initial pH on the adsorption of DNB-106 onto KTC was investigated over the pH range 2.0–10.0, with an initial dye concentration of $100\,mg\,L^{-1}$ at room temperature for a contact time of 5 hours. As shown in Figure 2, the percentage of dye removal increased from approximately 60% at pH 2.0 to 93% at pH 7.5–8.0, after which it remained relatively stable. The enhanced adsorption at near-neutral pH can be attributed to the increased electrostatic attraction between the negatively charged dye molecules and the positively charged surface of the carbon. The maximum removal was observed at pH 7.5, which was therefore selected as the optimum pH for subsequent experiments.

III.b Effect of Adsorbent Dosage

The effect of KTC dosage on dye removal was studied by varying the adsorbent amount from 0.1 to 1.4 g in 100 mL of $100\,mg\,L^{-1}$ dye solution, with a contact time of 5 hours. As depicted in Figure 3, the percentage of dye removal increased with increasing adsorbent dosage, reaching a maximum of approximately 93% at 1.1 g. Beyond this dosage, the increase in removal was marginal. The initial rapid increase is due to the greater availability of adsorption sites, while the plateau region indicates that the system has reached equilibrium. The amount of dye adsorbed per unit mass of carbon

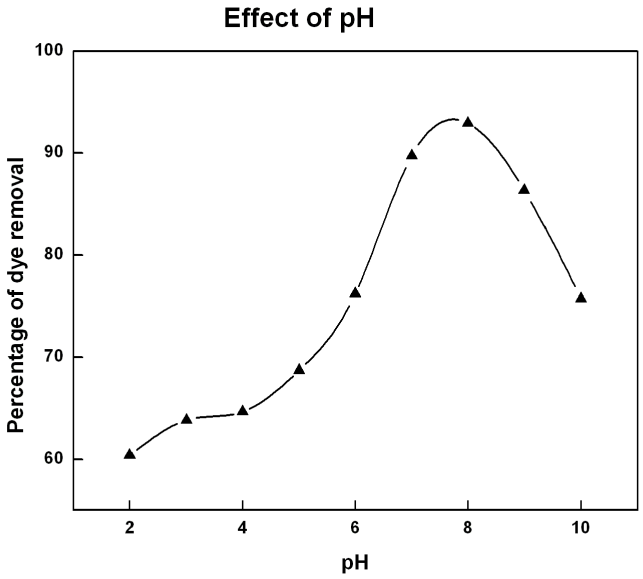

Figure 2: Effect of pH on the adsorption of DNB-106 onto KTC (initial dye concentration: 100 mg L^{-1}; contact time: 5 h; temperature: 30 °C).

(mg g^{-1}) decreased with increasing adsorbent dosage, which may be attributed to the aggregation of carbon particles at higher doses, reducing the effective surface area.

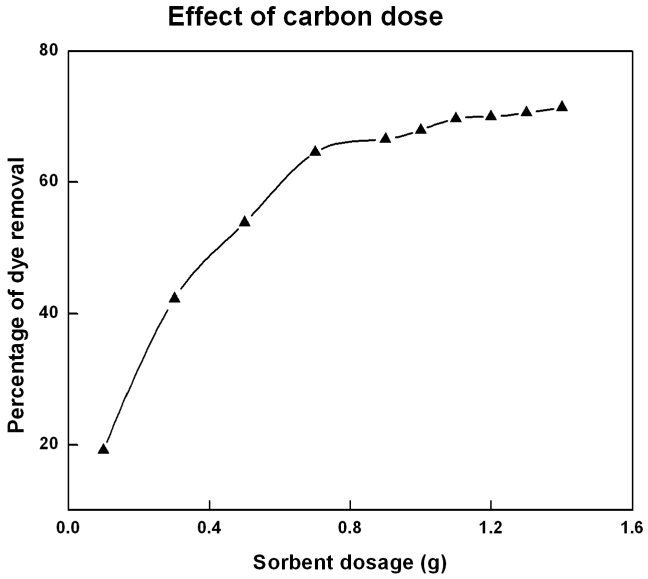

Figure 3: Effect of adsorbent dosage on the adsorption of DNB-106 onto KTC (initial dye concentration: 100 mg L^{-1}; contact time: 5 h; pH 7.5; temperature: 30 °C).

III.c Effect of Initial Dye Concentration and Contact Time

The influence of initial dye concentration on adsorption was examined at concentrations ranging from 15 to 90 $\mathrm{mg\,L^{-1}}$, with varying amounts of KTC (50–250 mg) at pH 7.0 and 27 °C for 5 hours. The results, presented in Table 2, indicate that the amount of dye adsorbed ($\mathrm{mg\,g^{-1}}$) increased with increasing initial dye concentration, while the equilibrium dye concentration (C_e) decreased with increasing adsorbent dosage. This trend suggests that higher initial concentrations provide a greater driving force for mass transfer, while higher adsorbent doses offer more surface area for adsorption.

Table 2: Adsorption of DNB-106 onto KTC at varying initial concentrations and adsorbent doses (pH 7.0; temperature 27 °C; contact time 5 h).

Initial dye concentration ($\mathrm{mg\,L^{-1}}$)	**KTC dosage (mg)**	**Amount adsorbed** ($\mathrm{mg\,g^{-1}}$)	**Equilibrium concentration** C_e ($\mathrm{mg\,L^{-1}}$)
15	50	2.99	5.98
30	100	3.98	3.98
50	150	4.92	3.28
70	200	5.78	2.89
90	250	6.86	2.74

III.d Adsorption Isotherms

Adsorption isotherms describe the equilibrium relationship between the amount of adsorbate adsorbed per unit mass of adsorbent and the equilibrium concentration of the adsorbate in solution. In this study, the experimental data were fitted to the Langmuir and Freundlich isotherm models.

III.d.1 Langmuir Isotherm

The Langmuir isotherm assumes monolayer adsorption on a homogeneous surface with finite identical sites. The linear form of the Langmuir equation is:

$$\frac{C_e}{x/m} = \frac{1}{ab} + \frac{1}{a}C_e \tag{1}$$

where x/m is the amount of dye adsorbed per unit mass of adsorbent ($\mathrm{mg\,g^{-1}}$), C_e is the equilibrium dye concentration ($\mathrm{mg\,L^{-1}}$), a is the adsorption capacity ($\mathrm{mg\,g^{-1}}$), and b is the Langmuir constant related to the energy of adsorption ($\mathrm{mg^{-1}\,L^{-1}}$). A plot of $C_e/(x/m)$ versus C_e (Figure 4) yielded a straight line, confirming that the adsorption follows the Langmuir model. The calculated Langmuir parameters are presented in Table 3. The separation factor $R_L = 1/(1 + bC_0)$ was found to be between 0 and 1, indicating favourable adsorption.

III.d.2 Freundlich Isotherm

The Freundlich isotherm is an empirical model applicable to heterogeneous surfaces and multilayer adsorption. Its linear form is:

$$\log\left(\frac{x}{m}\right) = \log k + \frac{1}{n}\log C_e \tag{2}$$

where k and n are Freundlich constants indicative of adsorption capacity and intensity, respectively. A plot of $\log(x/m)$ versus $\log C_e$ (Figure 5) gave a straight line, indicating that the Freundlich model also provides a good fit to the experimental data. The value of n (0.42–0.53) further confirms favourable adsorption.

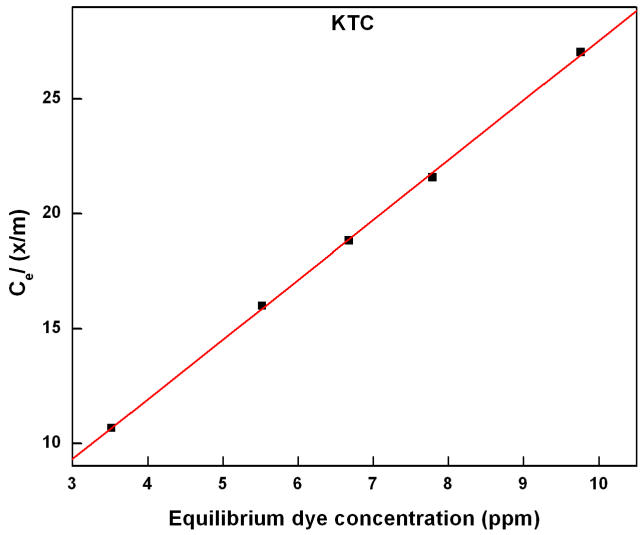

Figure 4: Langmuir adsorption isotherm for DNB-106 onto KTC.

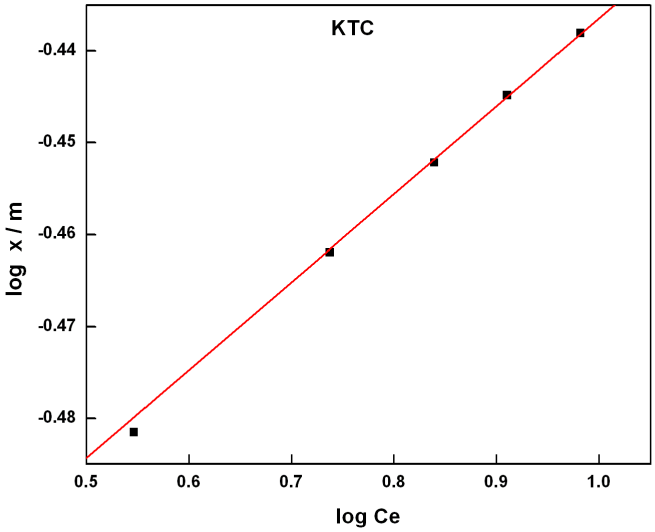

Figure 5: Freundlich adsorption isotherm for DNB-106 onto KTC.

III.e Kinetics of Adsorption

The kinetics of DNB-106 adsorption onto KTC were analysed using the Bhattacharya–Venkobachar equation, which is applicable to first-order reversible kinetics:

$$\log[1 - u(t)] = -\frac{k}{2.303}t \tag{3}$$

Table 3: Langmuir and Freundlich isotherm parameters for DNB-106 adsorption onto KTC.

Parameter	Value
Langmuir	
a ($\mathrm{mg\,g^{-1}}$)	0.321
b ($\mathrm{mg^{-1}\,L^{-1}}$)	0.9988–0.9995
R_L	0.9988–0.9995
Freundlich	
k	0.44
n	0.42–0.53
R^2	0.99

where $u(t) = (q_0 - q_t)/(q_t - q_e)$, with q_0, q_e, and q_t representing the dye concentrations at initial time, equilibrium, and time t (min), respectively, and k is the first-order rate constant ($\mathrm{min^{-1}}$). Plots of $\log[1 - u(t)]$ versus time (Figure 6) were linear for all dye concentrations studied, with correlation coefficients (r) ranging from 0.9876 to 0.9989, confirming that the adsorption process follows first-order kinetics. The initial rate of adsorption was high, attributed to the large available surface area of the carbon and the low initial dye concentration.

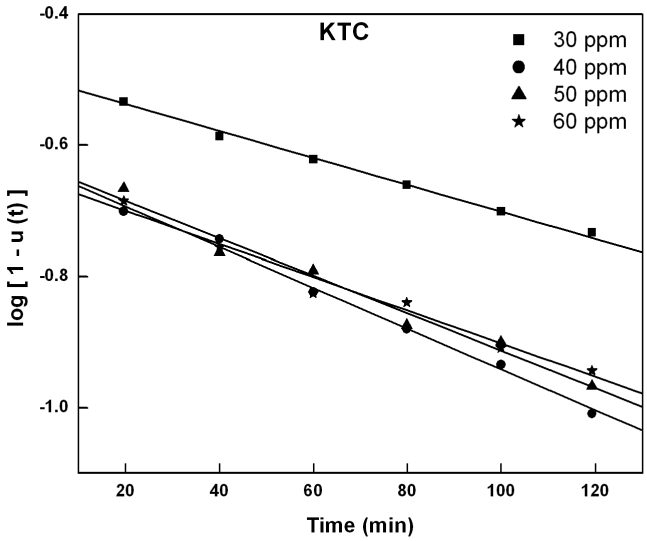

Figure 6: Bhattacharya–Venkobachar plots for the adsorption of DNB-106 onto KTC at various initial dye concentrations.

III.f Application to Textile Effluent

The applicability of KTC for the treatment of real textile wastewater was evaluated using effluent samples collected from dyeing factories in Tirupur, Tamil Nadu, India. The untreated samples were first subjected to coagulation with $FeSO_4$ and oxidation with $CaOCl_2$, followed by treatment with KTC. The physicochemical parameters of the untreated, chemically treated, and KTC-treated samples are presented in Table 4. The results demonstrate that KTC treatment significantly reduced the levels of

suspended solids, dissolved solids, total solids, and chemical oxygen demand (COD), bringing them closer to the permissible limits prescribed by the World Health Organization (WHO). The colour of the effluent was also substantially reduced, from dark black to light yellow.

Table 4: Characterisation of textile dyeing wastewater before and after treatment.

Parameter	**Untreated**	**Chemically treated**	**KTC-treated**	**WHO permissible limit**
pH	11.4	9.5	7.9	6.5–8.5
Suspended solids ($mg\,L^{-1}$)	1,500	920	520	200
Dissolved solids ($mg\,L^{-1}$)	2,500	1,200	700	500
Total solids ($mg\,L^{-1}$)	3,500	2,120	1,220	700
COD ($mg\,L^{-1}$)	1,000	600	350	250
Temperature (°C)	28	26	24.5	0–65.6
Colour (visual)	Dark black	Yellow	Light yellow	Colourless

IV Conclusion

This study demonstrates the potential of activated carbon prepared from *Jatropha curcas* (Kattamanakku) tree leaves (KTC) as an effective and low-cost adsorbent for the removal of Direct Navy Blue 106 (DNB-106) from aqueous solutions. The following conclusions can be drawn:

1. The adsorption of DNB-106 onto KTC is highly dependent on pH, adsorbent dosage, and contact time. Optimal removal (93%) was achieved at pH 7.5 with 1.1 g of KTC per 100 mL of $100\,mg\,L^{-1}$ dye solution.
2. The equilibrium data fitted both the Langmuir and Freundlich isotherm models, indicating monolayer coverage on a heterogeneous surface.
3. The adsorption kinetics followed a first-order model, with rapid initial uptake attributed to the high surface area of the carbon.
4. The adsorption process is predominantly physical (physisorption), with no evidence of chemisorption.
5. KTC was effective in treating real textile effluent, significantly reducing pollutant levels and colour.
6. The adsorbent can be reused for at least four cycles, highlighting its cost-effectiveness and sustainability.

The study confirms that KTC is a promising, eco-friendly, and economically viable alternative to commercial activated carbon for the treatment of dye-contaminated wastewater.

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Conflict of interest: The Authors have no conflicts of interest to declare that they are relevant to the content of this article.