Sustainable Adsorption of Textile Dyes Using Agricultural Waste

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Project Overview

Water pollution from textile dye discharge remains an environmental challenge, particularly in developing nations such as Bangladesh, where untreated industrial wastewater contaminates freshwater sources. Synthetic dyes such as methylene blue are widely used in textile manufacturing and are resistant to natural degradation, posing ecological and health risks. This study explores a sustainable, low-cost solution by turning agricultural waste into functional adsorbents for dye removal. Two adsorbents were engineered and compared: raw powder and magnetized heat-treated biochar. The heat-treated version was synthesized by pyrolysis and depositing Fe_3O_4 nanoparticles onto the biochar surface to enable magnetic separation. Batch adsorption experiments were conducted using methylene blue solutions, and removal efficiency was quantified using UV–Vis spectrophotometry. This research demonstrated how agricultural byproducts can be converted into effective environmental remediation materials.

Research Question

Does thermal heat-treatment with magnetization improve the adsorption efficiency of agricultural byproducts for removing methylene blue dye from water?

Background Information

Industrial Textile Dye Pollution

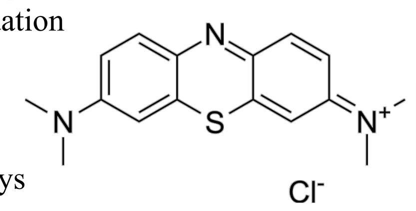
Industrial dye pollution is one of the largest sources of water contamination worldwide. The textile industry alone uses more than 10,000 different dyes, and it is estimated that 10–20% of dyes used in textile production are lost to wastewater during the dyeing process. In many rapidly industrializing countries, wastewater treatment infrastructure is limited. As a result, untreated dye effluent is often discharged directly into rivers, lakes, and groundwater systems.

Methylene Blue (MB) Dye

Methylene blue is a synthetic heterocyclic aromatic compound widely used in textile dyeing. It is classified as a cationic dye, meaning that it carries a positive electrical charge when dissolved in water. Because many natural materials have negatively charged surfaces, methylene blue readily interacts with adsorbent materials. Despite its widespread use, methylene blue poses several environmental risks when present in high concentrations. Exposure to methylene blue contamination can cause several harmful effects.

Aquatic Ecosystem Impacts

- ➢ Blocks sunlight penetration in water, preventing photosynthesis
- ➢ Interferes with the growth of phytoplankton and aquatic plants
- ➢ Reduces oxygen levels in water due to microbial degradation



Toxicity to Organisms

- ➢ Can cause oxidative stress in aquatic organisms
- ➢ May damage cellular membranes and metabolic pathways

Human Health Concerns

- ➢ Nausea and gastrointestinal irritation
- ➢ Methemoglobinemia, a condition that reduces oxygen delivery in blood
- ➢ Central nervous system distress

Agricultural Byproducts as Adsorbents

Agricultural byproducts are non-primary goods produced from farming operations, often viewed as waste or leftovers. The United States generates approximately 350 million tons of agricultural waste. Common agricultural byproducts include:

- ➢ *Banana peels*
- ➢ *Rice husks*
- ➢ *Coconut shells*
- ➢ *Corn cobs*

These materials contain natural polymers such as cellulose, hemicellulose, and lignin. Compounds containing functional groups such as hydroxyl (–OH), carboxyl (–COOH), and phenolic groups can interact with pollutants in water.

Because of these chemical properties, agricultural residues can act as adsorbents, meaning that they can bind and remove contaminants from water through surface interactions.

Advantages of using agricultural waste as adsorbents include:

- ➢ Low cost and wide availability and renewability
- ➢ Reduction of agricultural waste disposal
- ➢ Minimal environmental impact compared to synthetic materials

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Results: Raw Powder

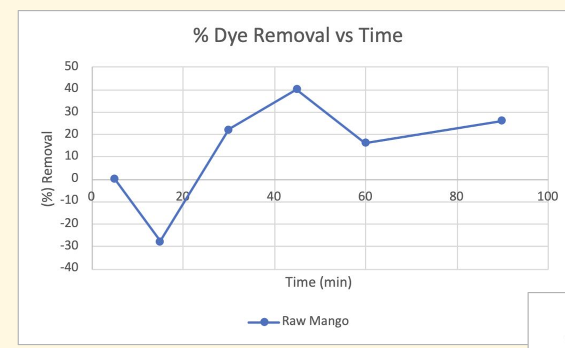
Raw Mango

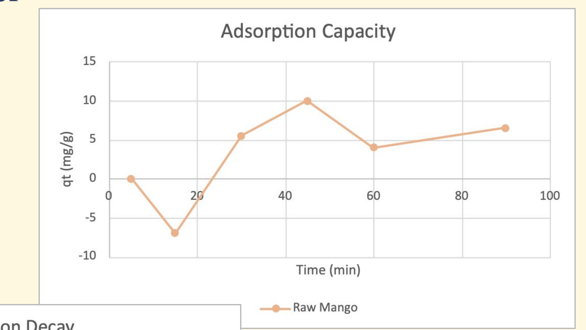
- ➢ Within the first 15 minutes, an unconventional increase in C_t from its initial level (from 50 to 64 mg/L) was observed, resulting in a negative adsorption capacity (q_t =−7 mg/g)
  - ○ This suggests the release of inherent organic matter
  - ○ However, subsequent recovery was observed post-15 minutes
- ➢ Between 15 and 45 minutes, C_t reached its minimum of **30 mg/L** and the maximum adsorption capacity (q_{max}) of **10 mg/g** was achieved with a maximum removal efficiency of **40%**
- ➢ Beyond 45 minutes, the system exhibited fluctuations, with Ct rising slightly to 37 mg/L. This behavior indicates a weak physical bond (physisorption)

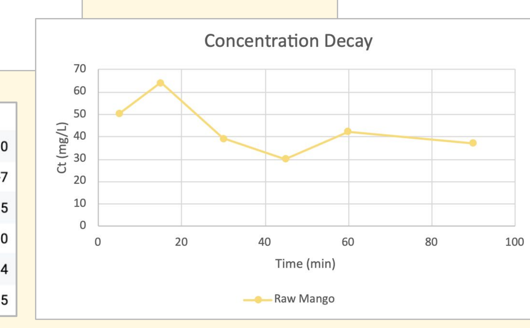
Raw Banana

- ➢ Within 15 minutes, the powder achieved a robust uptake, reaching a q_t of **13.25 mg/g**
- ➢ The final adsorption capacity of **14.15 mg/g** achieved at 90 minutes represents a relatively high affinity for the target pollutant
  - ○ After the first 15 minutes, removal rate hovered around **50%**, suggesting that the raw banana matrix has a higher density of accessible active sites
- ➢ The concentration profile for the banana powder dropped from **50 mg/L to 23.5 mg/L** almost immediately
- ➢ The q_t exhibited some fluctuations, achieving a maximum absorbance of 14.15 mg/g
- ➢ Unlike the mango powder, the banana powder showed little evidence of leaching.

Raw Mango Powder

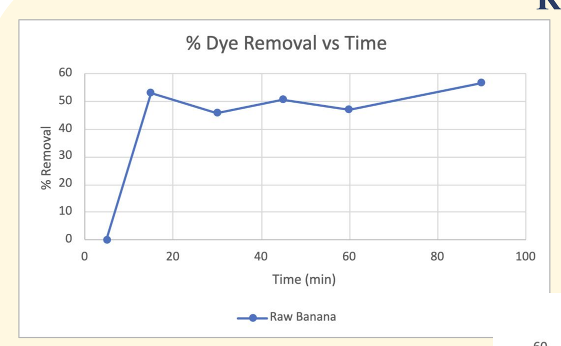


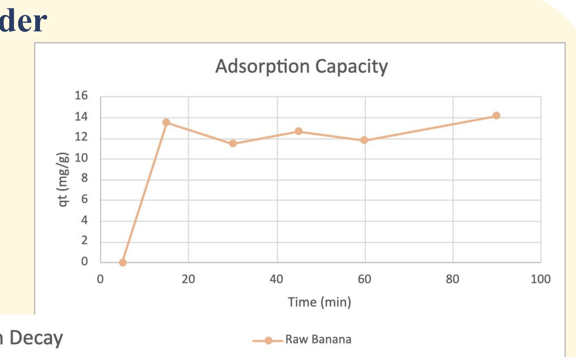


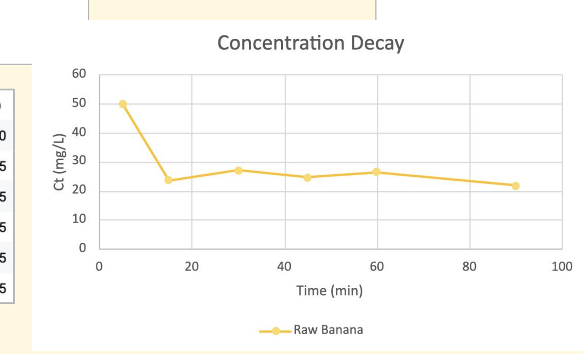


Time (min)	Absorbance (665 nm)	C_t (mg/L)	q_t (mg/g)
5	0.05	50	0
15	0.064	64	-7
30	0.039	39	5.5
45	0.03	30	10
60	0.042	42	4
90	0.037	37	6.5

Raw Banana Powder



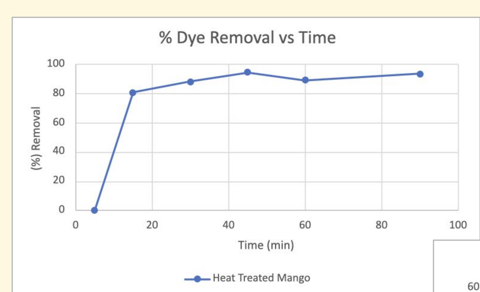


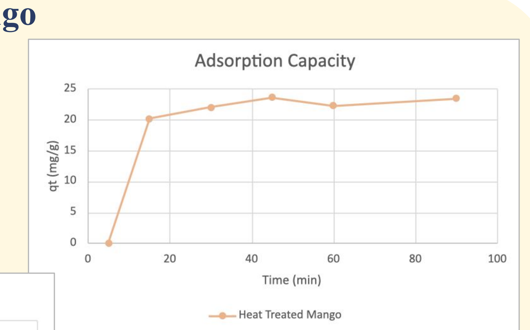


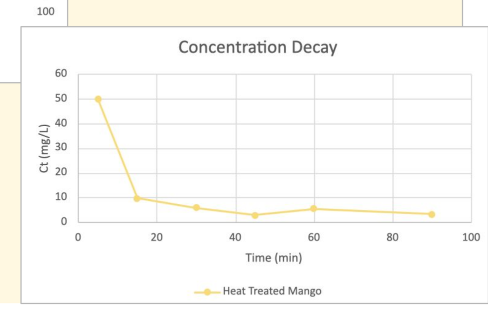
Time (min)	Absorbance (665 nm)	C_t (mg/L)	q_t (mg/g)
5	0.083	50	0
15	0.039	23.5	13.25
30	0.045	27.1	11.45
45	0.041	24.7	12.65
60	0.044	26.5	11.75
90	0.036	21.7	14.15

Results: Heat-Treated Biochar

Heat Treated Mango

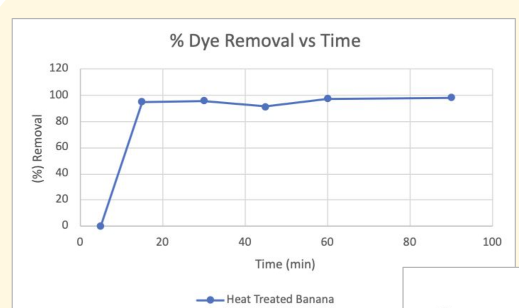


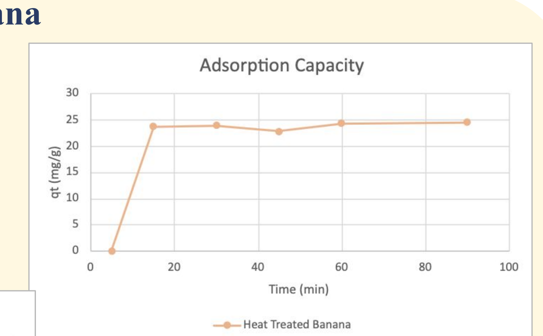


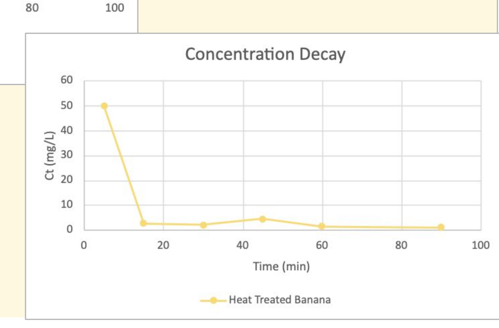


Time (min)	Absorbance (665 nm)	C_t (mg/L)	q_t (mg/g)
5	0.109	50	0
15	0.021	9.63	20.19
30	0.013	5.96	22.02
45	0.006	2.75	23.63
60	0.012	5.5	22.25
90	0.007	3.21	23.4

Heat Treated Banana







Time (min)	Absorbance (665 nm)	C_t (mg/L)	q_t (mg/g)
5	0.258	50	0
15	0.014	2.71	23.65
30	0.011	2.13	23.94
45	0.023	4.46	22.77
60	0.007	1.36	24.32
90	0.005	0.97	24.52

Heat Treated Mango

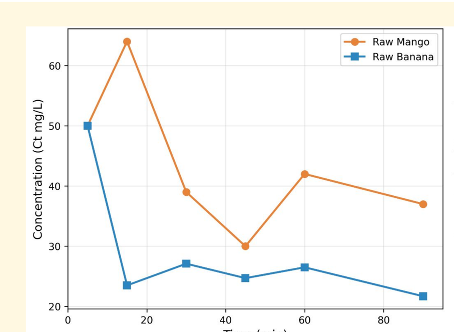
- ➢ Within the first 15 minutes, approximately 85% of the contaminant was removed, and ultimately reaching a peak removal efficiency of ~94% by the end of the 90-minute trial
  - ○ No leaching behavior was observed, indicating availability of active adsorption sites
- ➢ The adsorption capacity (q_t) exhibited a sharp initial increase, reaching 22.5 mg/g within 20 minutes, before gradually approaching a maximum capacity (qmax) of 23.5 mg/g
- ➢ The concentration profile showed a rapid decline from an initial 50 mg/L to below 10 mg/L within 20 minutes, eventually stabilizing at approximately 3 mg/L

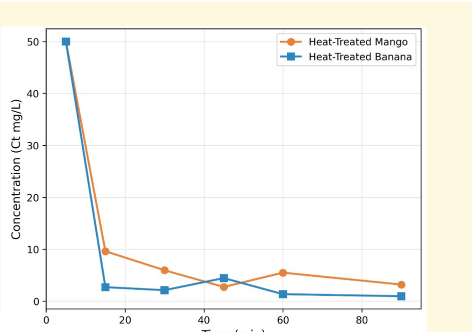
Heat Treated Banana

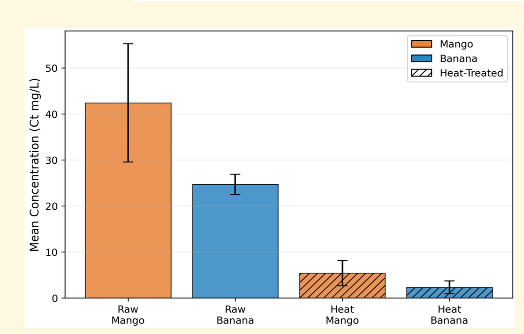
- ➢ Heat-treated banana powder demonstrated the highest removal efficiency among all tested materials
- ➢ Within the initial phase of the experiment, removal efficiency quickly stabilized in the 95–98% range
- ➢ Residual concentration (Ct) stayed below 5 mg/L for most of the experiment
- ➢ The adsorption behavior showed minimal fluctuation, suggesting stable surface interactions and a high density of active sites generated through thermal treatment

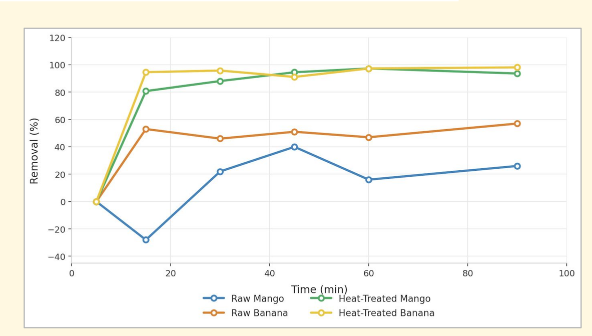
Results: Comparative Analysis and Statistical Significance

- ➢ A two-way ANOVA (Fruit×Treatment, n = 5 per group) was performed using Ct as the primary dependent variable
- ➢ The analyses revealed that **heat treatment was the dominant factor influencing adsorption efficiency** ($F(1,16) = 98.14$, $p < 0.001$), with heat-treated samples retaining significantly less dye (mango: 5.41 ± 2.74; banana: 2.33 ± 1.37 mg/L) compared to raw samples (mango: 42.40 ± 12.86; banana: 24.70 ± 2.20 mg/L)
- ➢ Fruit type was also significant ($F(1,16) = 12.03$, $p = 0.003$), with banana achieving lower residual concentrations
- ➢ A significant interaction ($F(1,16) = 5.95$, $p = 0.027$) indicated unequal treatment effects across fruit types
  - ○ Tukey HSD, however, confirmed no significant difference between the two heat-treated groups ($p = 0.885$), suggesting **thermal processing elevated both biosorbents to comparably high efficiency**
- ➢ Time (15–90 min) was not significant ($p = 0.278$), indicating rapid equilibrium.









Methodology

Materials

Agricultural Byproducts

Tropical agricultural waste, specifically banana and mango peels, were selected as feedstock due to their high lignocellulosic content, which provides an abundance of functional groups (hydroxyl and carboxyl) essential for binding cationic pollutants. These materials further represent abundant, low-cost resources found in regions such as Bangladesh where industrial textile pollution poses a significant environmental issue.

Contaminant Profile

Methylene Blue (MB) was selected as the model cationic dye to simulate textile runoff. A stock solution of 1000 mg/L was prepared and diluted to experimental concentrations of 50 mg/L to assess effectiveness of the engineered adsorbents.

Data Processing

Concentration data was gathered using a UV-Vis Spectrophotometer at a wavelength of 665 nm, the peak absorbance for the MB monomer.

Adsorbent Engineering

Synthesis Models

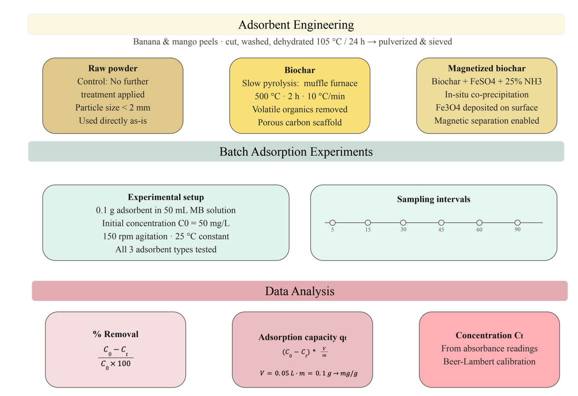
To determine the most effective treatment method, two adsorbents were created for each biomass type:

- ➢ Raw Powder (Control): Peels were cut and washed, dehydrated at 105°C for 24 hours, and were pulverized and sieved to a particle size of < 2 mm.
- ➢ Magnetized Heat-Treated Biochar: Produced via slow pyrolysis in a muffle furnace at 500°C for 2 hours (heating rate: 10°C/min). This thermal treatment induces the loss of volatile organic compounds, leaving behind a highly stable, porous carbon scaffold. Since these biochars are designed to remove pollutants from water, the resulting powders were magnetized to facilitate their removal from the treated water. The magnetization of the biochar was achieved by depositing Fe_3O_4 (magnetite) nanoparticles onto its surface via in-situ co-precipitation using iron salts ($FeSO_4$) and 25% concentration ammonia.

Measuring Adsorption Capacity

The biochar's adsorption capacity was measured using the following procedure: 0.1 g (100 mg) of adsorbent was added to 50 mL of MB solution (50 mg/L). The mixture was agitated at 150 rpm at a constant temperature of 25 °C. Samples were extracted at intervals (5, 15, 30, 45, 60, and 90 minutes) to monitor the "forward pass" of the adsorption process.

Data Collection



To determine the residual concentration of (Ct), the absorbance (A) of each sample was measured at λ_{max}=665 nm. According to the Beer-Lambert Law, absorbance is directly proportional to concentration allowing us to quantify the unknown concentration of a solute in a solution by measuring how much light it absorbs.

The percentage of dye removed from the aqueous solution was calculated using the following mass balance equation in the diagram in which C_0: Initial concentration (50 mg/L) and C_t: Final concentration at sampling time t.

The amount of MB adsorbed per unit mass of the banana/mango peel biochar (mg/g) was determined to compare the performance of raw vs. heat-treated samples using the equation shown in the diagram in which q_t: Adsorption capacity at time t (mg/g), V: Volume of the MB solution (0.05 L), m: Mass used (0.1 g).

Symbol	Definition	Value/Unit
C0	Initial Dye Concentration	50 mg/L
Ct	Residual Concentration	Measured (mg/L)
V	Solution Volume	0.05 L
m	Adsorbent Mass	0.1 g
qt	Adsorption Capacity	mg of dye / g

Conclusions

- ➢ As evidenced from the experimental data, the lignocellulosic matrix of banana and mango serves as a highly effective precursor for the sequestering of synthetic dyes from aqueous solutions
- ➢ The comparative analysis confirms that upcycling tropical agricultural waste into functional adsorbents can mitigate the ecological damage caused by industrial textile discharge
- ➢ This project is novel in conducting a comparative analysis of specific tropical byproducts for the synthesis of engineered biochar for water quality restoration
- ➢ Better optimization of low-cost, bio-based adsorbents will help prepare for sustainable water management in developing regions like Bangladesh

Future Outlook

- ➢ **Broader applications**
  - ○ Implementing these adsorbents into industrial stages to remove recalcitrant dyes like Methylene Blue that standard primary treatments fail to capture
- ➢ **Data enhancement**
  - ○ Expand the experimental matrix to test the efficiency of the engineered biochar against heavy metals commonly found in textile wastewater
- ➢ **Sustainable practices**
  - ○ Investigate the desorption capacity of the spent biochar using mild chemical washes to enable multiple reuse cycles and decrease the overall cost per liter of purified water