

REMOVAL OF METHYLENE BLUE FROM SYNTHETIC WASTEWATER USING BAMBOO LEAVES ASH

Rubel Ali^{*1}, Md. Hridoy Parvez², Md. Masud Rana³, Dr. Ganesh Chandra Saha⁴ and Md. Abul Hasanath⁵

¹ Graduate, Dhaka University of Engineering & Technology, Gazipur, e-mail: 201024@student.duet.ac.bd

² Graduate, Dhaka University of Engineering & Technology, Gazipur, e-mail: 201022@student.duet.ac.bd

³ Graduate, Dhaka University of Engineering & Technology, Gazipur, e-mail: 201014@student.duet.ac.bd

⁴ Professor, Dhaka University of Engineering & Technology, Gazipur, e-mail: ganesh@duet.ac.bd

⁵ Assistant Professor, Dhaka International University, e-mail: abulhasanath.civil@diu.ac

***Corresponding Author**

ABSTRACT

The removal of dyes in industrial wastes has become an issue of concern because of their toxic and persistent nature. Methylene blue (MB) is a dye that is extensively used and a significant pollutant that the textile industry releases. It is an evaluation and comparison study of the efficiency of cost-effective and environmental friendly adsorption materials used to remove the MB in synthetic wastewater. The Bamboo leaves ash was not subjected to any chemical treatment. To establish the optimum removal efficiency of Methylene Blue, experiments were carried under controlled lab conditions by changing the pH of the solution between 2 and 12, shaking rate between 25 and 225 rpm, adsorbent dose between 0.01 and 0.05 g/ 100 mL and initial dye concentration between 5 and 175 mg/ L. The FTIR result on the ash analysis of bamboo leaves displayed characteristic absorption peaks of functional groups of -OH, -COOH, -NH₂ and other oxygen and sulfur functional groups, which showed that the active sites conducive to MB adsorption existed. After adsorption, noticeable shifts and intensity changes in these peaks suggested strong interactions between MB dye molecules and the surface functional groups of the ash. The optimum conditions for Bamboo leaves ash were pH 9, shaking speed 225 RPM, adsorbent dose 0.05 g/100 mL, and initial dye concentration 25 ppm, resulting in a maximum removal efficiency of 88%. Adsorption data fitted well with Langmuir, Henry, and Freundlich isotherm models, with maximum Langmuir monolayer adsorption capacities of 33.08 mg/g for Bamboo leaves ash SEM analysis revealed porous and rough surface morphologies that favored adsorption. These findings confirm that MB removal primarily occurred through surface adsorption, with active functional groups playing a key role in dye binding. Overall, Bamboo leaves ash demonstrated strong adsorption potential, providing sustainable and low-cost solutions for dye-contaminated wastewater treatment.

Keywords: *Bamboo leaves ash; Methylene Blue; Adsorption; Textile Dye Removal; Eco-friendly Treatment*

1. INTRODUCTION

Bangladesh is another notable emerging economy in South Asia because of what has been experienced in the field of industrialization and urbanization both have contributed to huge economic growth. As a result, diversified manufacturing industries have been created in the country that include textiles, leather tanning and ceramics, which are industries that have historically been high in pollution and water-intensive, and chemical, pharmaceutical, cement, and pigment manufacturing. The growth of these sectors has significantly increased the national income and employment (Saha et al., 2022). The growth curve has been shadowed by an increase in the degree of environmental pollution, especially in the water sphere, which is due to the release of untreated industrial effluents (Auta & Hameed, 2012; Uddin et al., 2020; Uddin et al., 2023).

The textile sector plays the most dominant role in Bangladesh's economy while also being the largest contributor to industrial pollution. It accounts for approximately 85% of the country's export revenue, providing employment to millions of workers, both directly and indirectly (Mufti, 2024). The textile and dyeing technology places large demands on water, which is used in the form of fresh water for the actual dyeing, washing, and finishing. There are, however, around 1,866 small and large knit dyeing textile industries in the country (BTMA, 2025). The majority of these industries are known to directly discharge the dyed effluent into water bodies after a few primary treatments, thereby severely contaminating surface and underground drinking water sources (Azanaw et al., 2022).

The wastewater generated from textile industries contains a complex mixture of pollutants, including suspended solids, various organic compounds, inorganic salts, surfactants, and non-biodegradable synthetic dyes (Mostafa, 2015). The presence of these dyes, on the one hand, makes the water unsightly, and on the other, reduces sunlight penetration and decreases photosynthetic action in aquatic plants, thereby disrupting the entire ecosystem of aquatic plants. Among the various dyes used, Methylene blue (MB) is a cationic dye that has been widely employed in the textile industry for its bright color and high solubility in water. It is also used in paper, leather, and cosmetic manufacturing.

MB is a dark green powder that becomes blue when dissolved in water. It turns out to be an artificial, non-biodegradable molecule that is very stable in the environment. Prolonged discharge of MB-based effluents into watercourses leads to a persistent pollution, long-term impeding the development of aquatic life by modifying its oxygenation and influencing bio growth. At high levels, such as Methylene blue concentration, algal photosynthesis is inhibited, and fish and microorganisms are killed. Humans in close contact with or inhaling MB can experience irritation, nausea, vomiting, and skin rashes. Long-term exposure has been associated with respiratory and gastrointestinal diseases (Lellis et al., 2019).

In Bangladesh, very few textile factories effectively run effluent treatment plants (ETPs) (Hasan et al., 2022). A large number of small and medium-sized industries either lack an ETP facility or are non-operational due to the high cost and inefficiency of operation. Consequently, untreated dye-laden effluent is often released into the environment, mostly with a natural water body such as the Buriganga, Turag and Shitalakshya rivers, polluting to a large extent the water quality and ecosystem (Hasanath et al., 2020).

The textile industry is believed to be the largest dye polluter, responsible for about 54%, followed by that of dyeing (21%), paper and pulp (10%), tannery and paint (8%) and dye producers 7% (Yagub et al., 2014). These data clearly indicate that the textile and dyeing industries are the primary source of dyes entering aquatic systems in Bangladesh.

However, the conventional methods that are commonly used for treatment of dye-polluted wastewater (coagulation-flocculation, oxidation, and biological method) usually suffer from their high cost, energy consumption, and generation of a large amount of secondary sludge, which is not favorable in developing countries (Crini, 2006). On the other hand, adsorption has attracted attention as an effective, and simple approach in the dye removal process (Bhatnagar & Sillanpää, 2010). Many works that have demonstrated efficient dye adsorption with natural, low-cost and waste based adsorbents. For instance,

maximum uptake reported for banana leaves ash was 23.9 mg/g (Alam et al., 2022), Neem leaves 8.76 mg/g (Bhattacharyya & Sharma, 2005), Pine Cone Powder 32.65 mg/g (Dawood & Sen, 2012), and Grass Waste 457.64 mg/g (Hameed, 2009).

Nevertheless, there are very limited studies on the use of Bamboo leaves ash for Methylene Blue (MB) dye removal and its physicochemical characterization. Being a plentiful and renewable agricultural waste in Bangladesh, bamboo leaves are considered an excellent, low-cost, and environment-friendly adsorbent. Upon combustion, bamboo leaves produce an ash rich in metal oxides such as SiO_2 , CaO , K_2O , and MgO , which provides a high surface area and active adsorption sites for dye removal (Rocky & Thompson, 2021). Therefore, this study investigates the efficiency of Bamboo leaves ash in adsorbing Methylene Blue dye from synthetic wastewater while characterizing its surface features. By changing operational conditions, such as pH, shaking rate, contact time, dosage of adsorbent and initial dye concentration, the adsorption process is further optimized to obtain a complex knowledge of its adsorption behaviour as well as removal performance.

2. MATERIALS AND METHODOLOGY

2.1 Materials Collection and Adsorbent Preparation

Bamboo leaves were hand-picked from Bhurulia village, Gazipur district in Bangladesh, as they grow widely, rapidly, and are one of the most sustainable plants that do not use chemical fertilizers or pesticides. The leaves were air-dried to remove any surface water; then, a muffle furnace was used to heat treat the leaves at 600 °C for 15 minutes to manufacture bamboo leaves ashes. The obtained ash was ground into fine powder using a grinding machine and sieved through a 150 µm sieve to ensure uniform particle size. The larger retained ash powders were then reground and sieved to achieve the same size. The fine bamboo leaf ashes powders were collected, stored in an airtight container, and a dry place until use for the adsorption experiment was necessary.

2.2 Preparation of Synthetic Wastewater

The textile effluent was synthetically prepared in the laboratory by adding Methylene blue dye to synthetic wastewater. A 5 mg/L stock solution was then prepared by dissolving 5 mg of powdered Methylene blue in 1000 mL of fresh, distilled water. The solution was then swirled (in a magnetic stirrer) to mix the dye completely and uniformly in the medium. Synthetic wastewater during the experimentation of adsorption was carried out with stock solution. It was used to identify adsorption process of bamboo leaves ash under various conditions, such as pH, contact time, adsorbents dose, and dye concentration (Kuntari and Fajarwati, 2018).

2.3 Characterization of Adsorbents

A Fourier-transform infrared (FTIR) spectroscopic study was carried out to determine the chemical functional groups of the adsorber. Pellets of potassium bromide (KBr) adsorbent were ready and put in a Jasco FT/IR-6X/8X high-end spectrometer. There were no inertial components involved, and both electrically conducting and magnetic powders were utilised in the process. The sample was attached to a stage with a rectangular Alnico bar attached to it. Surface morphology and porosity were analysed by a Hitachi VP-SEM SU1510 scanning electron microscope. The samples were fixed on the carbon tape and gold-coated, and the samples were observed at different magnifications. A transmission electron microscope was used to observe the surface and the structure of the micropores of the adsorber.

2.4 Batch Adsorption

The performance of Methylene blue removal using Bamboo leaves ash as the adsorbent was determined using the batch adsorption method. MB at concentrations of 25 mg/L to 175 mg/L (100 mL volumes of MB) were set in 250 mL conical flasks. The dosage of experimental bamboo leaves ash ranged between 0.02 to 0.065 g. The conical flasks were turned on orbital shaker under controlled experimentation with

the following parameters; 25 to 250 rpm shaking speeds, 5 to 180 minutes of contact time, and 30 minutes of settling time. The concentration of the residual dye in the supernatant was measured with the help of a UV-Visible spectrophotometer at 665 nm. Critical parameters were optimized together; initial pH (4-12), contact time, shaking speed, MB concentration, and adsorbent dosage so that their intricate interplay could be considered in regard to adsorption efficiency. Under these optimized conditions, the best Methylene blue removal efficiency was determined and validated with the help of experiments.

2.5 Adsorption Isotherm Analyses

The Freundlich isotherm model and Henry and Langmuir were used to explain adsorption of Methylene blue on Bamboo leaves ash. The resulting linearized forms gave the respective constants, and determined the relationship between dye concentration and adsorption capacity, and the type of adsorption behaviour followed, monolayer, multilayer, or first-order.

2.6 Initial Dye Concentration Calculation

The percentage of dye removal was obtained using the formula below:

$$\text{Dye Removal (\%)} = \frac{C_o - C_e}{C_o} \times 100$$

q (mg/g) represents the amount of dye adsorbed on the adsorbent at time t, calculated using the following mass balance equation:

$$q_t = \frac{C_o - C_t}{m} \times V$$

Where C_o , C_t and C_e are the initial, time-dependent, and equilibrium dye concentrations (mg/L), respectively; q_t is the dye uptake (mg/g); V is the solution volume (L); and m is the adsorbent mass (g). Experimental uncertainty was within $\pm 10\%$.

3. RESULTS AND DISCUSSION

3.1 MB Removal under Different Conditions

Batch adsorption tests were carried out to identify the optimum conditions, using a contact time of 60 minutes and a shaking speed of 150 rpm, with an adsorbent dose of 0.05 g and a dye concentration of 5 mg/L at various solution pH (4-12). The effects of each factor were tested in separate curves, with all other factors held constant. From these studies, one could obtain information on the favourable conditions for better dye treatment and understand the adsorption behaviour of Bamboo leaves ash.

3.1.1 Optimum pH Determination

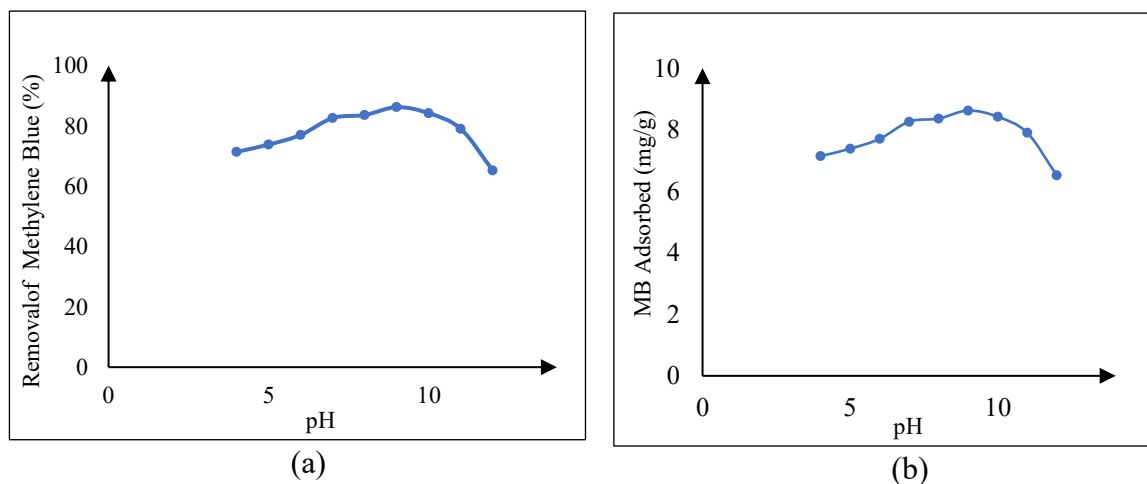


Figure 1: Effect of pH on (a) MB removal efficiency and (b) uptake capacity

By varying the pH from 4 to 12 and studying MB adsorption by Bamboo leaves ash in batch experiments at ambient temperature for 60 minutes, the impact of initial solution pH on MB adsorption was investigated. Either bamboo ash from leaves or phenol removal from leaves is quite effective. Although the removal efficiency of Bamboo leaves ash on MB decreased with increasing solution pH, at pH 7 it still reached 86.2%. The recorded maximum MB uptake was 8.62 mg/g, indicating that the increased surface negativity at higher pH enhances electrostatic attraction between cationic MB molecules and the adsorbent surface (Figure 1).

3.1.2 Optimum Shaking time Determination

MB was adsorbed using Bamboo leaves ash with an efficiency of 79.8% over 30 minutes, as shown in Figures 2(a) and 2(b), which indicates a maximum MB uptake of 7.98 mg of dye per gram of Bamboo leaves ash adsorbent. When the adsorption time was 30 min, the adsorption rate decreased sharply because most active sites were already occupied, and it eventually reached a balance. As such, 30 minutes was determined to be the optimal exposure time for Bamboo leaves ash.

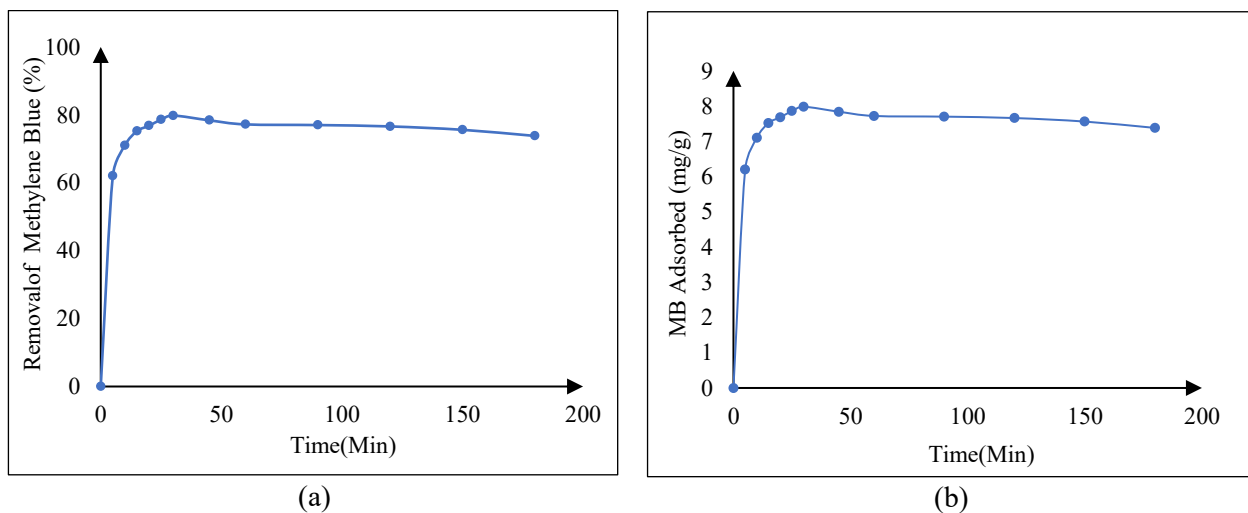


Figure 2: Effect of shaking time on (a) MB removal efficiency and (b) uptake capacity

3.1.3 Optimum Shaking Speed Determination

The percentage of dye removed by the Bamboo leaves ash grew steadily as the shaking level increased and reached its peak of 96.8 % percent at 225 RPM and maximum uptake 9.68 mg/g. At speeds higher than this, no significant advantage was found, so the speed of shaking at 225 RPM was considered optimal in this adsorbent. These results are presented in Figure 3(a) and Figure 3(b).

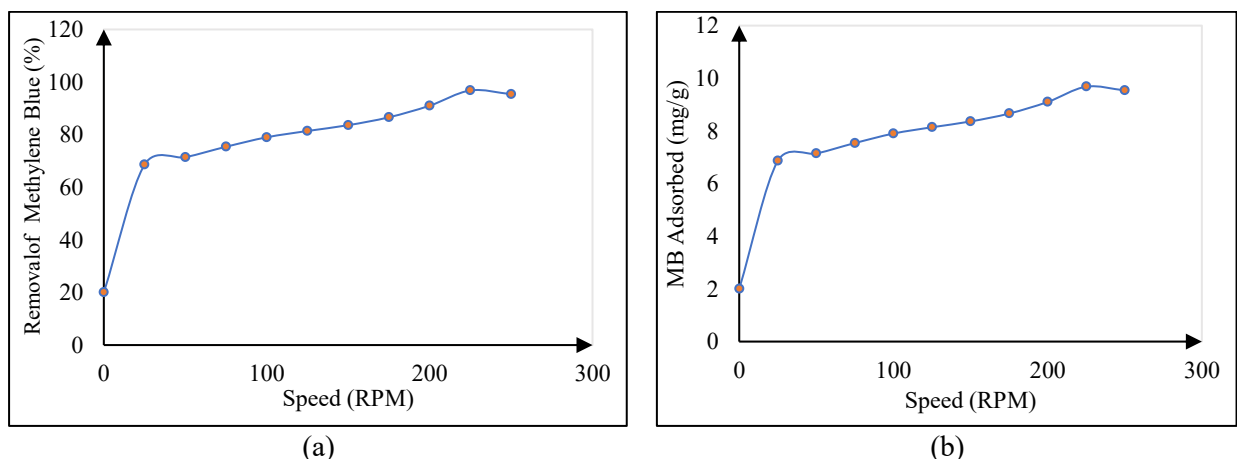


Figure 3: Effect of shaking speed on (a) MB removal efficiency and (b) uptake capacity

3.1.4 Optimum Adsorbent Dose Determination

With bamboo leaves ash, the doses were as follows: 0.020 g, 0.025 g, 0.030 g, 0.035 g, 0.040 g, 0.045 g, 0.050 g and 0.065 gm. The removal efficiency increased with dose, and maximum removal was 76.6 % at 0.050 g and uptake 7.66 mg/g. These results are presented in Figure 4(a) and Figure 4(b). After this, the efficiency could not be increased appreciably, meaning that 0.050 g is the optimal dose.

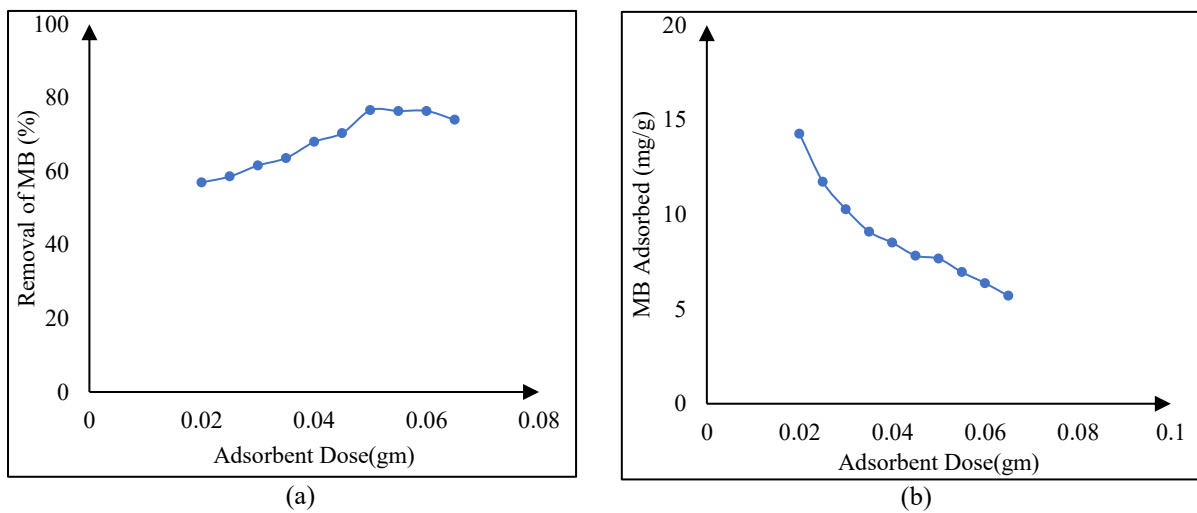


Figure 4: Effect of adsorbent dose on (a) MB removal efficiency and (b) uptake capacity

3.1.5 Optimum Initial Dye Concentration Determination

The presence of early methylene blue (MB) dye has intense effects on the adsorption performance of adsorbents, significantly influencing removal efficiency, capacity, equilibrium time, and interaction with surface functional groups, keeping all other experimental variables constant. In the current study, the experiment involved dye concentrations of 5, 10, 25, 50, 75, 100, 125, 150 and 175 ppm. An optimum 10 ppm was reached for the ash content of bamboo leaves with uptake 8.78 mg/g. This was at 87.84 % at Figure 5(a) and Figure 5(b), respectively.

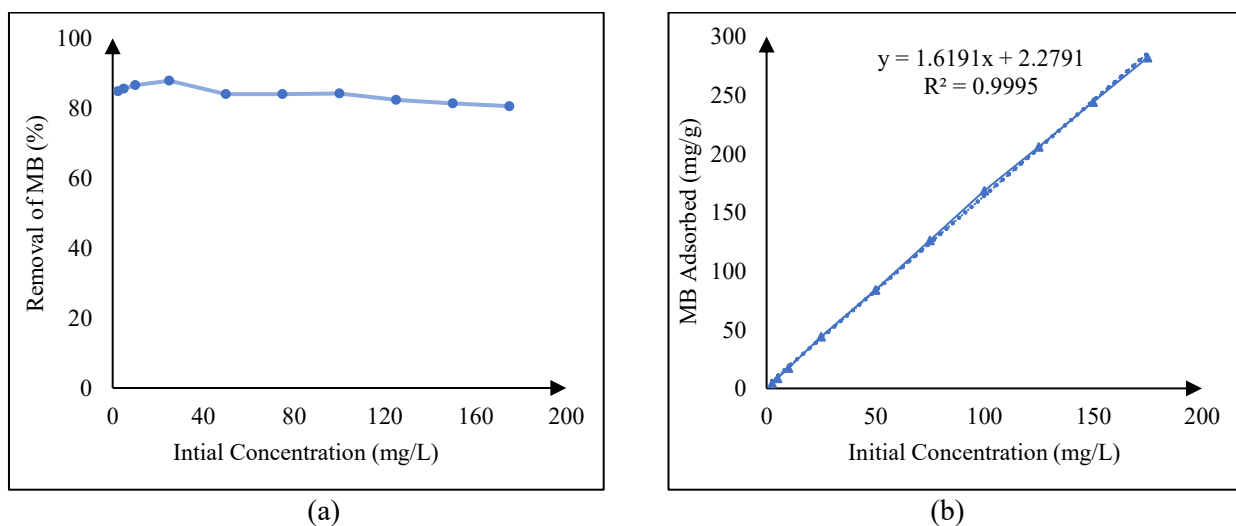


Figure 5: Effect of initial MB concentration on (a) removal efficiency and (b) uptake capacity

3.2 Characteristics of Adsorbents

Figure 6a shows the FTIR spectra of the bamboo leaves prior to and after being treated with Methylene blue adsorption of the substance, revealing some of the important functional groups during adsorption. A broad peak at 3676 cm⁻¹ that represents -OH groups and a peak at 2954.4 cm⁻¹ that indicates C-H bending vibrations are prominent before adsorption and observable changes and shifts in the intensities of peaks after adsorption respectively. The SEM images illustrate the surface morphology of Bamboo leaves ash before and after dye adsorption, showing an irregular, rugged, and highly porous surface before adsorption (Figure 6b), providing numerous active sites for dye binding. Following adsorption, the surface becomes relatively smoother with narrower pores, as in Figure 6(c), indicating that many pore spaces are now occupied by dye molecules, reflecting the physical adsorption of MB onto the porous ash surface.

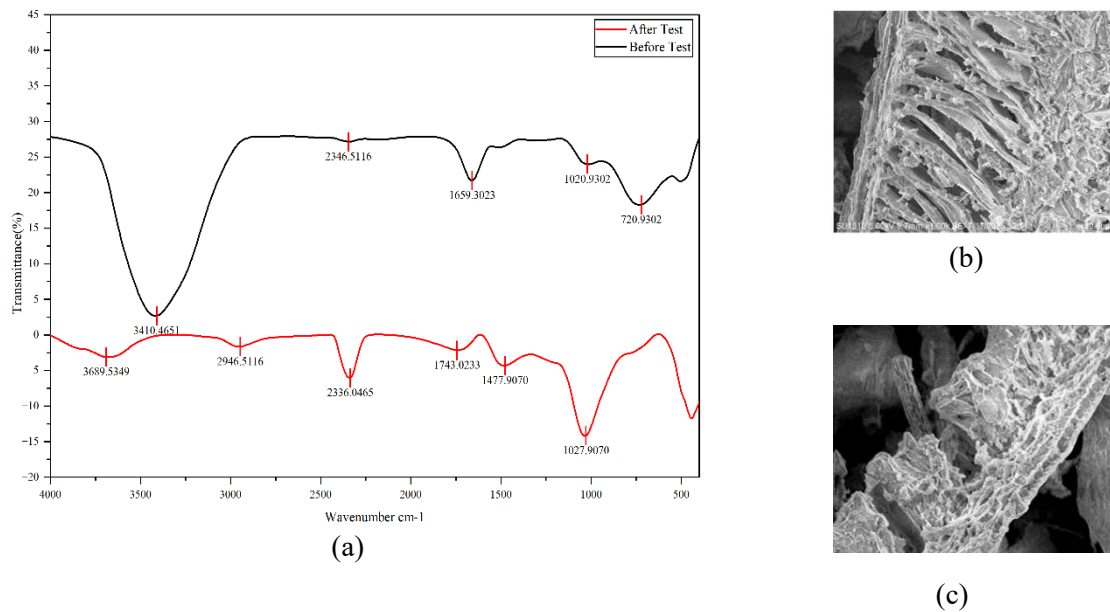


Figure 6: Characterization of surgical mask ash at optimum experimental condition, (a) FTIR analysis, (b) before experiment, (c) after experiment

3.3 Kinetic Studies of the Adsorption

The pseudo-second-order kinetic model for the adsorption of MB dye on Bamboo leaves ash is demonstrated in Figure 7. The data were well represented by a pseudo-second-order kinetic model, as reflected by a high correlation coefficient ($r^2 = 0.9998$). The obtained k^2 value best fitted with 0.0229 g/mg min⁻¹, and q_e was predicted to be 7.48 mg/g, respectively, indicating that the adsorption of MB onto Bamboo leaves ash is mainly controlled by chemisorption through the exchange or sharing of electrons between the dye molecules and active sites present on the surface of the adsorbent.

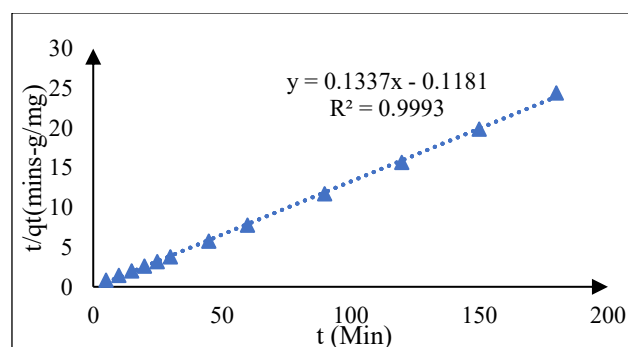


Figure 7: Pseudo-second-order kinetics of MB

3.4 Isotherms Adsorption Modelling

3.4.1 Langmuir Isotherm Model

The Langmuir isotherm fit Bamboo leaves ash data excellently ($R^2 = 0.9973$). The highest Methylene blue adsorption occurred at $K_L = 0.0136$ L/mg and $q_m = 833.33$ mg/g (Figure 8), similar to the maximum Langmuir uptake q of 33.08 mg/g, indicating strong monolayer chemisorption of the dye molecules onto the adsorbent surface. The results verified monolayer adsorption on a homogeneous surface, with chemisorption as the predominant process. Thus, the Bamboo leaves ash could be an efficient and economical adsorbent for the dye-contaminated wastewater.

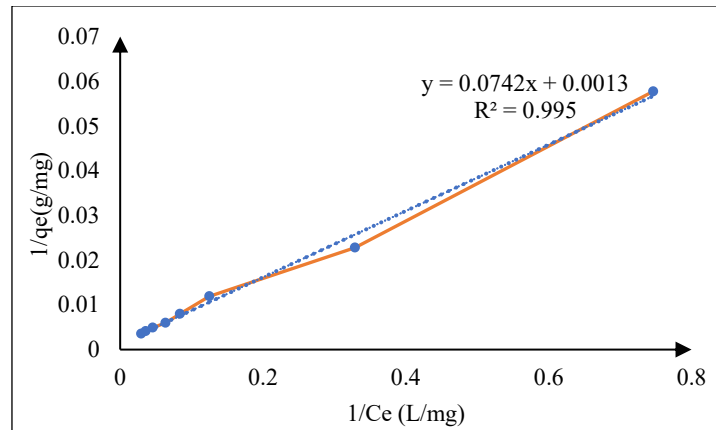


Figure 8: Langmuir isotherm for MB adsorption

3.4.2 Henry Isotherm Model

The Henry isotherm model was ingeniously used to investigate the adsorption of Methylene blue onto Bamboo leaves ash. The isotherm plot in its linear form (Figure 9) yielded an R^2 value of 0.9907, indicating strong adherence to the Henry model. A Henry constant (K) of 8.9730 L/mg achieved, suggesting that at low dye concentrations, the adsorption of MB onto Bamboo leaves ash follows a first-order dependence. As the concentration increases, the amount adsorbed rises linearly, illustrating a remarkable affinity.

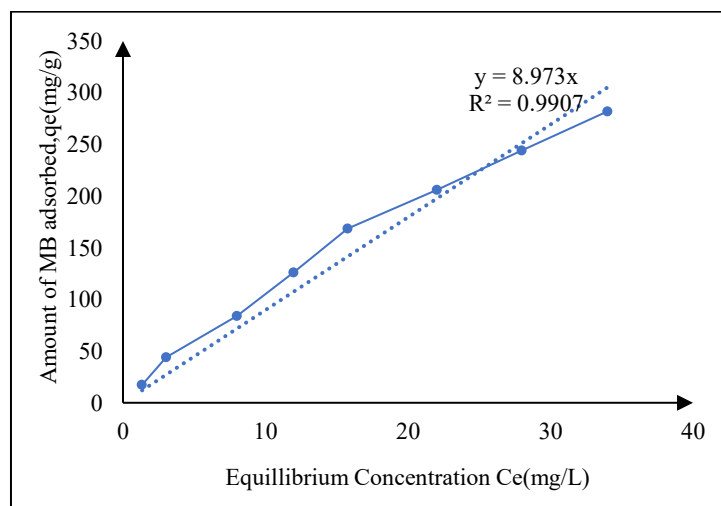


Figure 9: Henry isotherm for MB adsorption

This strong correlation implies that the adsorption process is dominated by physical interactions rather than chemical bonding. Hence, Bamboo leaves ash exhibits excellent potential as an efficient adsorbent for low-concentration dye removal in aqueous systems.

3.4.3 Freundlich Isotherm Model

The type of isotherm model that best fit with the Methylene blue adsorption uptake on Bamboo leaves ash was found to be Freundlich's. This modified model yield an R^2 value of 0.9936 (Figure 10) and we could conclude that the experimental data was fitted well by the linear fit. The K_f and n values of Freundlich constants were 511.09 mg/g, and 1.1801 indicating heterogeneous surface adsorption with sites possessing different energies causing the MB dye to attach as multilayers.

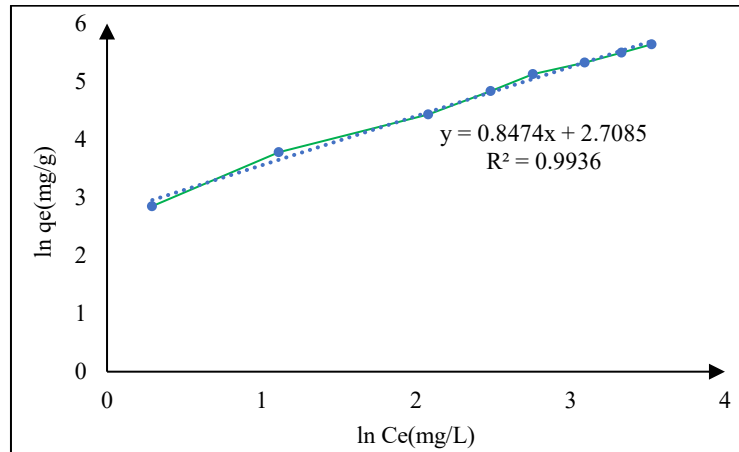


Figure 10: Freundlich isotherm for MB adsorption

From these findings, it can be deduced that the adsorption intensity increased with increase in dye concentration indicating the surface heterogeneity of the Bamboo leaves ash. Consequently, the Freundlich model validates its applicability to describing complex sorption mechanisms in wastewater treatment applications..

4. CONCLUSIONS

This study has demonstrated the potential of bamboo leaves ash (BLA) as a cheap, environmentally friendly bio-adsorbent for the removal of methylene blue (MB) from aqueous solution. From the adsorbent characterization, it was confirmed that BLA has a porous surface and active functional groups that support the adsorption of dye molecules. The results from the batch experiment indicated that MB removal % is significantly dependent on solution pH, dye concentration, shaking time, speed, and the adsorbent dose. The process at pH 9, 25 mg/L dye concentration, 30 min shaking, and 225 rpm shaking speed resulted in 88% MB removal at an adsorbent dose of 0.05 g/100 mL. The data were best fit by the Langmuir isotherm model, as indicated by $R^2= 0.9973$, suggesting monolayer adsorption of MB on a homogeneous surface, with a maximum adsorption capacity of 33 mg/g due to strong interactions between MB molecules and BLA. The suppression and valorisation of Bamboo leaves ash, using it as a dye-removal agent, are essential and low-cost initiatives. Recycling BLA on a sustainable dye solution is not limited to optimizing the crop process. It was confirmed in this study. However, only synthetic dye solutions have been tested in this study. Further research will focus on applying Bamboo leaves ash to real textile wastewater and testing its performance using simple setups such as a fixed-bed column, a dynamic flow column, and a continuous flow system to evaluate its practical use for the public.

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Declaration of Use of AI

The authors used an AI-based language tool to improve the clarity and grammar of the manuscript. No AI tools were used in data analysis, methodology, or interpretation of results.

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