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Investigation of Adsorption Kinetics, Thermodynamics, and Regeneration Efficiency of Activated Carbon Derived from Fruit Seed Waste for Dye Removal

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Abstract--- Disposal of artificial dyes into water sources creates many environmental issues due to the characteristics of stability, retention of color, and the non-degradable nature of such dyes. In this research, the use of activated carbon prepared from waste seeds of mangoes for the elimination of methylene blue dye has been investigated with a focus on kinetic, thermodynamic and recyclability aspects of the adsorbent. Waste mango seeds were converted to porous activated carbon by the process of carbonization along with chemical activation with potassium hydroxide. The adsorbent was studied using BET analysis, scanning electron microscopy (SEM), and FTIR spectroscopy. Several factors such as pH of the solution, dosage of adsorbent, concentration of the dye, contact time, and temperature have been considered in determining the adsorption behavior of the adsorbent. The specific surface area, average pore size, and pore volume of activated carbon were determined to be 842.60 m^2/g, 2.48 nm, and 0.52 cm^3/g, respectively. Process kinetics have shown that the pseudo-second-order model describes the process better. Thermodynamic analysis has revealed the endothermic nature of the adsorption process, with enthalpy and entropy changes of +18.60 kJ/mol and +0.086 kJ/mol·K, respectively. Results from the regeneration studies have shown that the adsorption capacity decreases from 47.55 mg/g to 36.80 mg/g, thus showing 77.39% capacity retention in five cycles. Desorption efficiency reduces to 84% from 92%. From the above results, it can be concluded that the activated carbon derived from mango seeds shows good adsorption behavior and retains good dye adsorption capacity even after several regenerations.

Keywords--- Mango Seed Waste, Activated Carbon, Methylene Blue, Adsorption Kinetics, Adsorption Thermodynamics, Regeneration Efficiency, Wastewater Treatment.

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I. Introduction

Environmental Implications of Synthetic Dye Contamination

The discharge of colored industrial effluents into the environment has become a significant environmental problem, particularly in the case of industries such as the textile processing industry, paper making, leather tanning, and dye industries. Dyeing using synthetic dyes is a common practice in the aforementioned industries because of the chemical stability and compatibility with various industrial materials. However, the presence of colored dyes in the effluents causes numerous problems in treating the wastewater since the dyes are very complex, highly concentrated, and resistant to biological degradation processes. Even low concentrations of dyes may lead to changes in the optical qualities of the recipient waters and prevent photosynthesis due to insufficient light penetration.

Methylene blue (MB), being a cationic thiazine dye, is often used in laboratory as well as industrial wastewater studies owing to its wide usage and coloring properties. Its chemical stability and relatively complicated molecular structure make its removal from aqueous solutions a relevant area of research. Traditional wastewater treatment methods like coagulation, chemical oxidation, membrane filtration, and biological treatment offer some degree of dye removal but pose heavy operational costs, generation of secondary waste, etc.

It is for this reason that adsorption has been studied intensively as another treatment method owing to the operational simplicity and the adaptability associated with the method irrespective of the level of contamination. The choice of the right adsorbent is a key determinant of removal effectiveness and efficiency (Bharath Balji & Senthil Kumar, 2022).

Agricultural Fruit Seed Waste as a Sustainable Carbon Precursor

Agricultural processing produces vast amounts of residues derived from fruits in the form of seeds, peels, and fiber content. Such residues are usually discarded despite having carbon-based organic content that is capable of being used to create adsorbents. The use of agricultural residues in the form of fruit seed waste in the preparation of activated carbon opens up avenues for waste management in the process of wastewater treatment (Zaidi et al., 2023).

The use of mango seeds as biomass precursors is feasible due to their availability in fruit processing industries and carbon-based organic composition. By carrying out controlled carbonization and chemical activation, mango seed waste may be transformed into carbonaceous adsorbent material with certain surface properties that are favorable for dye adsorption (Raji et al., 2022). In addition, the use of potassium hydroxide for chemical activation of the material will allow for the development of pores and modification of surface properties.

The transformation of mango seed waste to activated carbon allows for the valorization of agricultural waste through its potential environmental application.

Activated Carbon-Based Adsorption for Methylene Blue Removal

Activated carbon finds much attention in research related to wastewater treatment due to its porous nature, availability of surface area, and surface functional groups. Methylene blue adsorption occurs through interactions of the dye molecules and the surface of the adsorbents that are dependent on porosity, surface chemistry, temperature, and pH of the solutions. Study of these parameters in detail is important for understanding the adsorption process and determining optimal conditions for methylene blue removal.

Research Objectives and Technical Contributions

The study will evaluate the feasibility of the reuse of activated carbon residues, which are used in the removal of colors in water. This study uses an experimental design to test the effects of the properties of the adsorbent on the performance of the process.

The specific goals of this study include:

1. To synthesize activated carbon from waste seeds of mangoes through carbonization and chemical activation using potassium hydroxide.
2. To assess the physicochemical characteristics and surface properties of the prepared activated carbon.
3. To assess adsorption kinetics and equilibrium using existing mathematical models.
4. To assess thermodynamic parameters of the adsorption process.

All these techniques, biomass, adsorption modeling, thermodynamic evaluation, and adsorbent regeneration, have been used in this study.

II. Literature Review

Development of Biomass-Derived Activated Carbon for Dye Adsorption

Biomass-based activated carbon has become a research interest as an alternative material to commercialized adsorbents for wastewater treatment. Biomass precursors such as coconut shells, rice husks, fruit peels, nutshells, and seeds consist of carbonaceous components that can be transformed into porous adsorbents under appropriate thermal and chemical treatments (Alsulaili et al., 2023). The choice of precursors depends on their availability, carbon content, composition, and suitability for activation. Fruit seed residues have great potential since they are formed as a by-product of food processing and are usually disposed of as organic waste. The transformation of such residues into activated carbon provides an opportunity not only to reduce agricultural waste but also to produce adsorbents from it. The carbon structure depends on precursor composition, carbonization temperature, heating time, and activation conditions. Adsorptive properties of biomass-derived carbon are related to pore distribution, accessible surface area and surface functional groups.

Micropores contribute to surface area formation, while bigger pores provide a pathway for moving dye molecules closer to adsorption centers (Al-Musawi & Al-Qaim, 2025). Interactions between the adsorbent and contaminant may be influenced by the presence of functional groups on the surface, which may contain oxygen. Hence, when designing an adsorbent from biomass, the choice of the precursor and activation process is essential (Mussa et al., 2023).

Influence of Activation Conditions on Adsorbent Surface Characteristics

Some of the physicochemical characteristics of the produced carbon are governed by the process of activation. Chemical activation requires the use of activators to create holes and modify the carbon, while physical activation involves oxidation that is induced by the introduction of certain gases (Al-Hyali et al., 2023). Potassium hydroxide has been known to be used in many instances to activate the carbon since it has the ability to create pores by reacting with carbon materials. The impregnation ratio, the activation temperature, the activation time, and the washing stage all play an important role in chemical activation. High levels of activation can affect the carbon's structure negatively, but low activation levels fail to form good pores (Sahu et al., 2020). For evaluation of the suitability of the material for dye absorption, more characterization needs to be done. Although SEM can provide information about the morphology of the material, FTIR can give information about the chemical groups present in the material.

Mechanisms of Dye Adsorption and Adsorption Kinetics Models

The rate at which dye molecules become adsorbed and transferred to the active sites of the adsorbent from aqueous media can be determined from the study of adsorption kinetics. Factors such as resistance to mass transport, dye concentration, adsorbent dosage, and accessibility of binding sites play an important part in determining the adsorption rate. Removal of dyes from porous activated carbon is achieved through first transferring them through the outer liquid boundary layer, followed by diffusion through pores and lastly bonding to accessible surface sites (Bazan-Wozniak & Pietrzak, 2023; Hashem et al., 2025). In addition to using the coefficient of determination, correlation coefficient, and statistical errors should be considered alongside the agreement of predicted and experimental values of adsorption capacity shows in Equation (1) Equation (2).

Thermodynamic Behavior of Adsorption Systems

Thermodynamic studies help in understanding the effect of temperature on the adsorption process and the energy changes. Free energy change ($\Delta G°$) is indicative of thermodynamic favorability, enthalpy change ($\Delta H°$) relates to heat transfer, and entropy change ($\Delta S°$) is associated with interface disorder changes. Parameters can be determined based on the equilibrium data at different temperatures (Al-Hazmi et al., 2024). Interpretation of these values along with kinetic and equilibrium data gives an understanding of methylene blue adsorption on biomass-based activated carbon.

Regeneration Strategies and Adsorbent Reusability

Moreover, the practical application of activated carbon would not only be contingent upon the efficiency of the adsorption process but also upon the ability of the carbon to preserve its adsorptive capacity for several adsorption-desorption cycles. Thus, for the purpose of desorption of methylene blue and evaluation of the feasibility of recycling of the adsorbent, this current experiment will examine the regeneration process utilizing ethanol as the desorbing agent.

Literature Search Strategy and Identification of Research Gaps

The literature review will be basically focused on the biomass-based activated carbon, dye adsorption, thermodynamic process characterization, adsorption kinetics modeling, and adsorbent regeneration. The use of combinations of keywords like biomass-based activated carbon, fruit seed adsorbent, methylene blue adsorption, adsorption kinetics, adsorption thermodynamics, and adsorbent regeneration will allow you to effectively search for scientific literature within the field using databases such as Scopus, Web of Science, ScienceDirect, and Google Scholar. The literature review will focus on prioritizing peer-reviewed experimental studies, which address the topic of selecting the precursors of carbon, chemical activation, physicochemical characterization, adsorption mechanism and regeneration efficiency. If there are articles where there are studies on different biomass precursors and dye systems, then the comparative analysis of those studies will help you to identify the difference in methodology and limitation. The gap identified above is related to the integration of fruit seeds-derived activated carbon on the issue of adsorption kinetics, equilibrium behavior, thermodynamic properties, and repeated regeneration performance. If individual study on these properties is done, then no conclusive results can be obtained.

III. Materials and Methodology

Selection and Preparation of Mango Seed Waste

The biomass residue that was used to prepare the activated carbon from the mango seeds was chosen owing to its high carbon content and abundance as agricultural waste. To begin with, the seeds of the mangoes were washed with distilled water to get rid of the pulp, soil particles, and other contaminants that could be present in them. The material obtained was then dried up to a constant weight to ensure that no moisture would affect the further treatment process. Thereafter, the dried mango seeds were ground to facilitate better heating and interaction of the activating agent.

Carbonization and Chemical Activation of Biomass Precursors

Carbonization of the biomass from prepared mango seeds was done through thermal treatment of the organic contents present in the biomass under oxygen-limited conditions to form a carbon-rich char. This involved releasing volatile components upon heating to create a carbon-rich material that would be used in the next stage of processing. Upon carbonization, the carbon-rich material formed was cooled and collected for chemical treatment. The KOH solution was chosen as the activating agent for creating pores in the carbon to increase its surface area. The char was treated with the KOH solution and subjected to activation using a heat treatment process. This will assist in the creation of the porous structure of the carbon through a chemical reaction between the activating agent and the carbon.

Preparation of Synthetic Dye Solutions and Experimental Conditions

The compound method used to determine the Carbon Methylene blue, which is used to dissolve the amount in distilled water. The concentration of the methylene blue was determined through the UV-Visible spectrophotometric method. Standard solutions having a certain concentration were prepared in order to obtain a calibration curve so that concentration of the remaining dye can be quantified after adsorption.

Batch Adsorption Experiments and Process Parameter Selection

The Batch adsorption should analyze the various characteristics related to mango seeds. This also defines the amount of the added dye related to the string conditions. The influence of time on dye adsorption was also studied. The temperature studies were conducted for finding out the effect of temperature on dye adsorption capacity. After a fixed time interval of dye adsorption, the adsorbent material was separated by filtration or centrifugation. The amount of methylene blue remaining in solution was determined spectrophotometrically. Dye adsorption capacity and percentage dye removal were calculated using equations (1) and (2), respectively.

$$q_t = \frac{(C_0 - C_t)V}{m} \tag{1}$$

$$R(\%) = \frac{C_0 - C_t}{C_0} \times 100 \tag{2}$$

Adsorption Kinetic Modeling and Equilibrium Analysis

Adsorption kinetics have been studied to examine the effect of contact time on methylene blue adsorption by activated carbon prepared from mango seeds. Pseudo first-order (PFO) and pseudo second-order (PSO) kinetic models have been used to study adsorption rate. Pseudo second-order kinetic model considers adsorption process as a function of residual adsorption capacity and is represented in equation (3):

$$q_t = \frac{k_2 q_e^2 t}{1 + k_2 q_e t} \tag{3}$$

Langmuir and Freundlich isotherm adsorption equilibria were studied to investigate interactions between dye and adsorbent. In Langmuir isotherm, adsorption takes place at equivalent surface sites forming a monolayer while Freundlich isotherm considers heterogeneous surface properties. Comparison of Langmuir and Freundlich isotherm gives information about adsorption capacity and surface heterogeneity, besides adsorbate affinity towards activated carbon.

Thermodynamic Parameter Determination

Thermodynamic study was carried out to investigate the energetics and thermal behaviour of methylene blue adsorption. The equilibrium data at various temperatures was analysed to determine the standard Gibbs

free energy change (ΔG^∘), enthalpy change (ΔH^∘) and entropy change (ΔS^∘) of the process. The standard Gibbs free energy change of the process was calculated from equation (4):

$$\Delta G^{\circ} = -RT \ln K^{\circ} \qquad (4)$$

These computed values were then employed for evaluating the thermodynamics of favorability, heat, and interfaces during dye adsorption. A dimensionless equilibrium constant had to be applied to ensure consistency in the calculations of thermodynamics.

Adsorbent Regeneration and Reusability Assessment

Regeneration efficiency of mango seed-based activated carbon was carried out by repeating adsorption-desorption process. After the adsorption of methylene blue on activated carbon, the loaded dye on the adsorbent was separated using a solid-liquid separation technique. In order to release dye molecules adsorbed on the carbon surface, ethanol was used as a desorption solvent. After desorption, the separated carbon was cleaned and dried and then reused. The regenerated carbon was again used to adsorb methylene blue dye under similar adsorption conditions. This process was repeated five times consecutively to study the stability of adsorption process.

Adsorption efficiency percentage of the adsorbent after each cycle was calculated in equation (5):

$$CR_n(\%) = \frac{q_n}{q_1} \times 100 \qquad (5)$$

Where CR_nrepresents the adsorption capacity retention during cycle n, $q_n$is the adsorption capacity obtained in the corresponding cycle (mg/g), and $q_1$denotes the adsorption capacity recorded during the first cycle.

Variation in adsorption capacity and desorption efficiency between cycles was considered to understand the possible effect of dye not being released completely, pore blockage, and alteration in the adsorbent's surface.

Experimental Workflow and Performance Evaluation

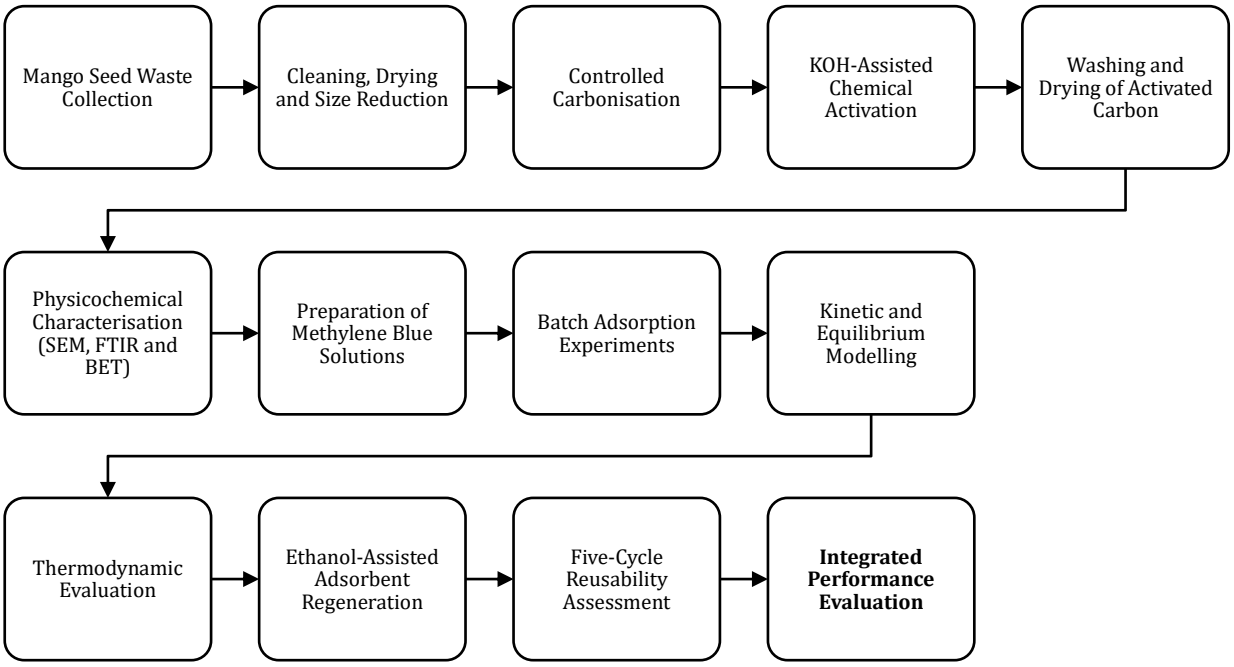


Figure 1: Experimental Workflow for Preparation, Characterisation, Adsorption Evaluation and Regeneration of Mango Seed-Derived Activated Carbon

The research was conducted according to a number of steps, which included biomass pretreatment, carbon production, material characterization, adsorption, kinetic, thermodynamic analysis and regeneration. First, residues of mango seeds were collected, washed, dried and carbonized to produce charcoal. This material was subjected to activation using KOH, washed and dried afterwards. Prepared activated carbon was analyzed through SEM, FTIR, and BET techniques to obtain information about its structure and surface properties.

Adsorption studies on methylene blue were conducted under different conditions to study the removal capability of the material. Experimental concentrations were utilized to calculate adsorption capacity and removal efficiency of the dye. Kinetics and isotherms were used to analyze data on adsorption of the dye, whereas experiments at different temperatures were conducted to conduct thermodynamic analysis. Desorption with ethanol and five regeneration cycles were applied to test adsorbent stability and adsorption capacity retention. Overall experimental scheme is shown in figure 1.

IV. Results and Discussion

Physicochemical Characteristics of Fruit Seed-Derived Activated Carbon

Physicochemical properties of the prepared activated carbon from mango seed were determined to evaluate its suitability for methylene blue adsorption. It can be seen from Table I that the produced carbon has highly developed porosity with specific surface area being equal to 842.60 m^2/g and total volume equal to 0.52 cm^3/g. The above parameters mean that there are pores which can accommodate dye molecules in case of their adsorption. From the point of average pore diameter equal to 2.48 nm, it can be concluded that the mesopores are present in the prepared carbon. They might favor the entrance of methylene blue molecules into the carbon inner structure. Irregular porous structure was determined by SEM analysis. FTIR analysis showed the presence of functional groups such as oxygen-containing (hydroxyl (–OH), carbonyl (C=O), and carbon–oxygen (C–O)). Depending on solution conditions, they might participate in adsorption process via electrostatic interactions, hydrogen bonds, and others. Moisture content and ash content were determined to be 4.25% and 6.80%, respectively.

Table I: Physicochemical Characteristics of Prepared Activated Carbon

Characteristic	Analytical Method	Value
Specific surface area (m^2/g)	BET analysis	842.60
Average pore diameter (nm)	BET analysis	2.48
Total pore volume (cm^3/g)	BET analysis	0.52
Surface functional groups	FTIR analysis	–OH, C=O, C–O
Surface morphology	SEM analysis	Irregular porous structure
Moisture content (%)	Proximate analysis	4.25
Ash content (%)	Proximate analysis	6.80

The adsorption pattern found through batch studies can be further explained by using the characteristics obtained from these techniques. The efficiency of adsorption could have been achieved if the activated carbon was provided with proper pore structure and a large available surface area. However, having a large surface area does not necessarily guarantee the success of the adsorption process.

Influence of Operating Parameters on Dye Adsorption Performance

The adsorption of methylene blue using activated carbon derived from mango seeds is affected by pH, dose of adsorbent, initial concentration of dye, contact time, and temperature. pH affects the surface charge and electrostatic interaction between dye molecules and the surface. More adsorbent increases the number of binding sites. An increase in the concentration of dye increases the driving force for mass transfer until saturation of adsorption sites is attained. The contact time affects the equilibrium state, while temperature affects the adsorption process thermodynamically.

Adsorption Kinetics and Equilibrium Model Evaluation

Methylene Blue adsorption kinetics were modeled based on pseudo-first order, pseudo-second order, and intraparticle diffusion approaches. The latter two models fit better to the data from experiments reported, though this does not prove chemisorption in any case. Intraparticle diffusion modeling was carried out in order to understand dye transfer within pores. Langmuir and Freundlich isotherms have been used for studying the equilibrium, capacity, and heterogeneity of surface properties.

Thermodynamic Behavior and Adsorption Feasibility

Methylene blue adsorption on activated carbon from mango seeds was examined using thermodynamic analysis. This is due to the endothermic nature of the reaction, as indicated by the positive value of enthalpy change (+18.60 kJ/mol), while the positive value of entropy change (+0.086 kJ/mol·K) shows increased disorder at the interface. The observed reduction in Gibbs free energy at high temperatures shows improved thermodynamic favorability. However, ΔG° values should be known for each temperature.

Regeneration Efficiency and Adsorbent Reusability

Five sequential adsorption-desorption cycles have been used for determining the regeneration efficacy of activated carbon prepared from mango seed. It can be seen from Table II that there is an increase in adsorption capacity as well as desorption efficiency as the cycles progress. Based on the cycle analysis got the result from the various ranges such as 47.55 mg/g.

Table 2: Regeneration Efficiency and Adsorption Capacity Retention Across Repeated Cycles

Regeneration Cycle	Adsorption Capacity (mg/g)	Capacity Retention (%)	Desorption Efficiency (%)
1	47.55	100.00	92.00
2	44.70	94.01	90.00
3	41.95	88.22	88.00
4	39.20	82.44	86.00
5	36.80	77.39	84.00

The total decrease in adsorption capability from the first to the fifth cycle was 10.75 mg/g, which translates to about 22.61%. On the other hand, the desorption rate decreased from 92% to 84%, meaning there was a drop of eight percentage points in the desorption process. The reduction could be attributed to either incomplete stripping of adsorbed dye, pore blockage, or alteration in surface properties.

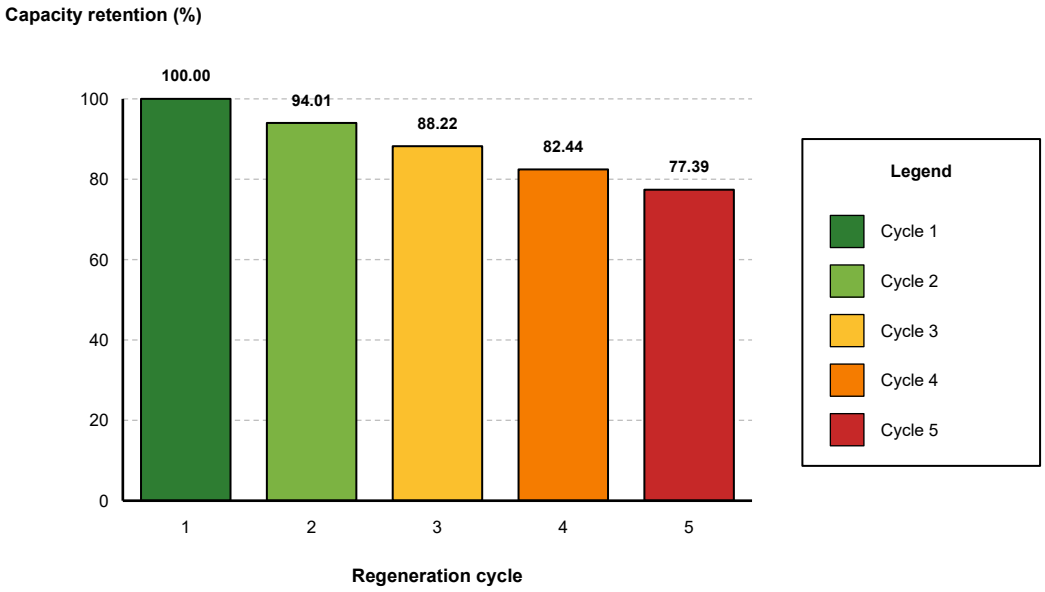


Figure 2: Comparative Adsorption Capacity Retention Across Five Regeneration Cycles

This is depicted in figure 2, which shows the decreasing retention of adsorption capacity through five consecutive cycles of adsorption and desorption. The decline in the retention level suggests that the repeated regeneration process influences the performance of the dye adsorption. Despite the decrease, however, the adsorbent retained 77.39% of the original adsorption capacity after the fifth cycle.

V. Conclusion

This research aims at assessing the potential of using the activated carbon from mango seed to treat methylene blue in water using the equilibrium model, thermodynamics assessment, regeneration tests, and kinetics of adsorption. The agricultural fruit seed waste can be used in the preparation of carbon material having surface properties suitable for dye removal by chemically activating carbon adsorbents with potassium hydroxide. One can examine the efficiency of the adsorbent with regard to methylene blue adsorption in light of the characteristics of the surface, functional groups, and porosity combined. Adsorption efficiency tests will be conducted under various pH, doses of the adsorbent, concentrations of the initial dye, contact times, and temperatures. The pseudo second-order kinetics model is going to be more appropriate for all the models. The benefits of this paper mainly focus on influencing the heat efficiency of the adsorption process. Both techniques

are used to improve efficiency; the ethanol desorption technique is used to activate the carbon from Mango seeds, benefiting from the biomass materials.

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