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Synthesis and Characterization of Water Hyacinth-Based Activated Carbon for the Removal of Dyes from Textile Effluents

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Abstract

This study investigates the synthesis of activated carbon from water hyacinth (*Eichhornia crassipes*) via sodium hydroxide (NaOH) activation for the treatment of textile dye wastewater. The preparation process involved chemical activation of dried biomass with varying NaOH concentrations (0.1 M, 0.25 M, 0.5 M, 0.75 M, and 1.0 M) for 2 hours, followed by carbonization at 350°C for 1 hour. The adsorption efficiency was evaluated using 0.2 g of the synthesized adsorbent in 100 ml of dye effluent across contact times ranging from 15 minutes to 3 hours.

Experimental results indicate that the concentration of the activating agent significantly influences the morphological structure and adsorption capacity of the carbon. The optimal performance was achieved using 0.1 M NaOH-activated carbon. Under these optimized conditions specifically a 30-minute contact time the material demonstrated a decolorization efficiency of 78% – 79%, yielding a transparent effluent with no visible residual dye. Furthermore, the treated water maintained a neutral pH of 7 and exhibited a significant reduction in Total Dissolved Solids (TDS). These findings suggest that water hyacinth-derived activated carbon is a highly effective, low-cost, and sustainable adsorbent for industrial wastewater remediation, with potential extensions into air purification and medical applications.

Keywords: Water Hyacinth, Activated Carbon, NaOH Activation, Textile Dye Adsorption, Wastewater Treatment

1. Introduction

Currently, the rapid proliferation of water hyacinth (Eichhornia crassipes) has emerged as a critical environmental challenge in natural water bodies (Gunnarsson & Petersen, 2007) [3]. As a highly resilient photosynthetic organism, water hyacinth thrives in sunlit environments, leading to excessive biomass growth. This overgrowth triggers a process known as eutrophication, where high levels of nutrients such as phosphorus accelerate the spread of aquatic weeds and algae (Villamagna & Murphy, 2010) [14]. This phenomenon significantly reduces dissolved oxygen (DO) levels, adversely affecting aquatic ecosystems and biodiversity (Mironga *et al*., 2011) [7]. Furthermore, the decay of excess biomass degrades water quality, causing unpleasant odors and deteriorating the aesthetic value of water resources.

To address the infestation of water hyacinth, various methods, including physical, chemical, and biological controls, have been employed. However, converting this invasive biomass into value-added products, such as activated carbon, presents a sustainable and multifaceted solution (Ahmed, 2016) [1]. Activated carbon is a highly porous carbonaceous material processed through physical or chemical activation. This process creates an extensive network of micropores, significantly increasing the surface area and enhancing the material's adsorption capacity for various molecular pollutants (Marsh & Rodriguez-Reinoso, 2006) [6]. Water hyacinth is an ideal precursor for activated carbon production due to its abundance, rapid growth rate, and naturally porous spongy structure (Murithi *et al*., 2014). Utilizing this invasive species not only helps mitigate its negative environmental impacts but also provides a cost-effective adsorbent for industrial applications (Mane *et al*., 2007) [5].

In the context of the textile industry, particularly in artisanal or household-scale dyeing, untreated wastewater containing

synthetic dyes is frequently discharged directly into natural water systems (Rafatullah *et al*., 2010) [12]. These effluents contain complex chemical structures that are resistant to natural degradation, leading to water pollution, loss of aesthetic appeal, and potential health hazards (Al-Qodah *et al*., 2017) [2].

Therefore, this research focuses on the synthesis of activated carbon from water hyacinth as an efficient adsorbent for treating textile dyeing wastewater. By transforming an environmental nuisance into a functional material for water purification, this study aims to contribute to sustainable environmental management and provide a viable pathway for improving water quality in the future.

2. Research Objective

1. To synthesize activated carbon from water hyacinth (*Eichhornia crassipes*) via chemical activation using varying concentrations of sodium hydroxide (NaOH).
2. To determine the optimal adsorption conditions, including contact time and adsorbent dosage, for maximum dye removal efficiency.
3. To evaluate the decolorization performance and physicochemical properties (pH and TDS) of the synthesized activated carbon in treating textile industry effluents.

3. Materials and Methods

3.1 Raw Materials

The primary raw material used for the production of activated carbon in this study was dried water hyacinth (Collected from Pak Ou District, Luang Prabang Province) and Sodium hydroxide (NaOH) Pellets 99% AR. grade, New Zealand was utilized as the chemical activating agent to enhance the porosity of the adsorbent.

3.2 Mix Proportions

The chemical activation technique involved immersing 20 g of dried water hyacinth biomass in sodium hydroxide (NaOH) solutions. To systematically assess the effect of activating agent concentration, five experimental groups (designated as Samples A–E) were generated with various NaOH molarities: 0.1 M, 0.25 M, 0.5 M, 0.75 M, and 1.0 M, respectively. To ensure adequate chemical interaction with the precursor's lignocellulosic matrix, all samples were impregnated for a consistent time of 2 hours each. This homogeneous impregnation stage is critical for starting the internal pore network formation before heat treatment. The carbonization process was then carried out at a pyrolytic temperature of 350°C for a dwell duration of 1 hour, as shown in Table 1.

Table 1: Experimental design and activation conditions for water hyacinth-based activated carbon

Sample ID	Precursor Weight (g)	NaOH Concentration (M)	Activation Time (h)	Activation Temperature (°C/h)
A	20	0.1	2	350/1
B	20	0.25	2	350/1
C	20	0.5	2	350/1
D	20	0.75	2	350/1
E	20	1	2	350/1

Adsorption Efficiency Study: To evaluate the adsorption performance of the synthesized activated carbon, a batch adsorption experiment was conducted. In this study, a fixed dosage of 0.2 g of activated carbon was added to 100 ml of textile dye wastewater for each experimental group (Samples A to E).

The effect of contact time on the dye removal efficiency was systematically investigated at four different intervals: 15 minutes, 30 minutes, 1 hour, and 3 hours. During these periods, the mixture was kept under constant conditions to allow the activated carbon to interact with the dye molecules. This experimental design aims to determine the optimum contact time required to achieve the maximum decolorization percentage and to understand the adsorption kinetics of the water hyacinth-derived activated carbon.

Table 2: Experimental parameters for dye adsorption study

Sample ID	Adsorbent Dosage (g)	Dye Wastewater Volume (ml)	Time Intervals
A - E	0.2	100	15 in, 30 min, 1 h, 3 h

3.3 Experimental Procedure

1. The production of activated carbon from water hyacinth

The production of activated carbon from water hyacinth using sodium hydroxide (NaOH) activation was conducted according to the following steps: 1) Sample Collection: Water hyacinth samples were collected from Ban Han, Hongsa District, Sayaboury Province. Only the stalk portions of the plants were selected for the experiment. 2) Pre-treatment: The collected stalks were thoroughly washed with distilled water to remove impurities and then manually cut into small pieces approximately 2 cm in length. 3) Initial Drying: The samples were dried in an electric oven at 100°C for 10 hours to eliminate moisture. 4) Chemical Activation: The dried water hyacinth was immersed in a Sodium Hydroxide (NaOH) solution for a duration of 2 hours to initiate the chemical activation process by using various concentrations (0.1 M, 0.25 M, 0.5 M, 0.75 M, and 1.0 M). 5) Secondary Drying: Following the activation stage, the samples were dried again at 80°C for 9 hours. 6) Carbonization: The treated samples were placed in ceramic crucibles and carbonized in a muffle furnace at 350°C for 1 hour. After the process, the samples were allowed to cool down to room temperature and subsequently stored in a desiccator to prevent moisture re-absorption. 7) Characterization: The internal morphology and pore structure of the synthesized activated carbon were analyzed using Scanning Electron Microscopy (SEM). This analysis was performed to compare the structural differences of the carbon before and after the activation process.

2. Application of Activated Carbon for Textile Dye Wastewater Treatment

The efficiency of the synthesized activated carbon in removing dyes from textile wastewater was evaluated through batch adsorption experiments. The systematic procedure is outlined below: 1) Adsorbent Dosage: A precise amount of 0.2 g of the prepared activated carbon was weighed using an analytical balance. 2) Preparation of Test Solution: The weighed adsorbent was added into a beaker containing 100 ml of textile dye wastewater. 3) Adsorption Process and Contact Time: The mixture was allowed to undergo the adsorption process under constant conditions. The contact time was monitored at specific intervals: 30 minutes, 1 hour, 3 hours, 6 hours, and 24 hours, to

determine the equilibrium point and adsorption kinetics. 4) Phase Separation: After each specified contact time, the treated wastewater was separated from the activated carbon using filtration (or centrifugation) to obtain a clear sample for further analysis. 5) Spectrophotometric Analysis: The concentration of the remaining dye in the wastewater was analyzed using a UV-Visible Spectrophotometer. The absorbance was measured at the maximum wavelength to calculate the percentage of dye removal and the adsorption capacity.

3.4 Testing Methods

3.4.1 Test Method for Microstructural Analysis

The Scanning Electron Microscopy (SEM) is a powerful imaging technique used to examine the surface topography and internal morphology of the synthesized activated carbon. The analysis focuses on two primary aspects: Surface Transformation and Pore Development. Before imaging, the activated carbon samples must be properly prepared to ensure high-resolution results: Dehydration: Samples are thoroughly dried to remove any residual moisture that could interfere with the vacuum chamber of the SEM. Conductive Coating: Since carbon materials can be semi-conductive or non-conductive, a thin layer of Gold (Au) is typically sputter-coated onto the sample surface. This prevents "charging" effects and enhances the emission of secondary electrons for clearer imaging.

The SEM allows for a comparative analysis between the raw water hyacinth and the NaOH-activated carbon: Pre-activation: The SEM images usually show a smooth, dense, and non-porous surface of the raw biomass, where the lignocellulosic fibers are tightly packed. Post-activation: After chemical activation with NaOH and carbonization at 350°C, the SEM reveals a dramatic transformation. The surface appears rugged and fractured, indicating the successful degradation of organic components.

The primary goal of using SEM in this study is to verify the existence of a porous network: Pore Distribution: SEM images provide visual evidence of various pore sizes, including macropores and mesopores, which are created during the dehydration and volatile evolution stages of carbonization. Effect of NaOH: The chemical action of NaOH acts as an "etching agent." It reacts with the carbon framework to create deep cavities and channels. These pores are crucial for the adsorption process, as they provide the necessary surface area for dye molecules to be trapped.

SEM was conducted using a COXEM EM-30AX+ microscope (COXEM Co., Ltd., Daejeon, Republic of Korea) with a magnification of 2000×

3.4.2 Test Method for absorbance measuring

To quantify the effectiveness of the adsorption process, the concentration of residual dye in the wastewater was determined using a UV-Visible Spectrophotometer. This method relies on Beer-Lambert's Law, which states that the absorbance of a solution is directly proportional to the concentration of the absorbing species. Before analyzing the samples, a scan of the dye solution was performed across the visible spectrum (typically 400–700 nm) to identify the λ_{max}. This is the specific wavelength where the dye molecule exhibits its peak light absorption. Measuring at λ_{max} ensures maximum sensitivity and accuracy in detecting even small changes in dye concentration.

The data obtained from the spectrophotometer was used to calculate two critical performance indicators:

1. Dye Removal Efficiency (R%):

This indicates the percentage of dye removed from the solution.

$$R\% = \frac{(C_0 - C_e)}{C_0} \times 100$$

Where C_0 is the initial concentration and C_e is the final concentration at equilibrium.

2. Adsorption Capacity (q_e):

This measures the amount of dye adsorbed per unit mass of the activated carbon (mg/g).

$$q_e = \frac{(C_0 - C_e)V}{m}$$

Where V is the volume of the solution in Liters and m is the mass of the adsorbent in grams.

4. Result and Discussion

4.1 Activated Carbon Production and Adsorption Efficiency

The production of activated carbon from water hyacinth, activated with varying concentrations of sodium hydroxide (NaOH) (0.1 M, 0.25 M, 0.5 M, 0.75 M, and 1.0 M) and carbonized at 350°C for 1 hour, demonstrated that the concentration of the activating agent significantly influences the adsorption capacity of the resulting material.

In the adsorption efficiency study, 0.2 g of the synthesized activated carbon was applied to 100 ml of textile dye wastewater. The results indicated that the activated carbon prepared with 0.1 M NaOH exhibited the highest adsorption performance. Within a contact time of 30 minutes, the adsorbent successfully removed the dye molecules from the solution, resulting in a completely clear aqueous phase with no visible residual color. These findings suggest that the 0.1 M NaOH activation, combined with a 30-minute contact time, represents the optimal conditions for the effective treatment of textile dyeing effluents using water hyacinth-derived activated carbon.

Fig 1: Physical appearance of activated carbon produced from water hyacinth

Weight Loss Percentage (%)

Based on the data presented in Figure 2, it is observed that as the NaOH concentration increases from Sample A to

Sample E, the weight loss percentage conversely decreases from 81.64% to 58.55%. To effectively illustrate this inverse relationship between the chemical concentration and mass reduction, a Line Graph is recommended. This graphical representation will provide a clear visualization of the trend, highlighting how higher concentrations of the activating agent influence the yield and thermal stability of the water hyacinth-derived activated carbon.

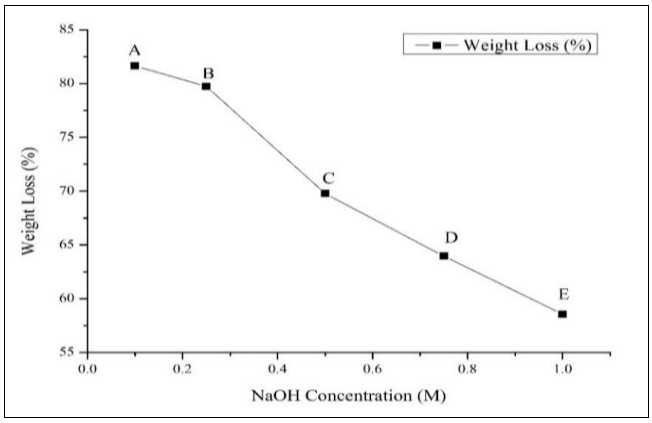

Fig 2: Relationship between NaOH concentration and the weight loss percentage of water hyacinth-based activated carbon during the carbonization process

4.2 Adsorption Efficiency

The efficacy of NaOH-activated carbon for treating textile dye wastewater was evaluated using a constant adsorbent dosage of 0.2 g per 100 ml of effluent. The adsorption process was monitored across four distinct contact time intervals: 15 minutes, 30 minutes, 1 hour, and 3 hours.

The experimental results indicated that a 30-minute contact time was the optimal duration for maximum dye removal, as evidenced by significant decolorization. Furthermore, the water quality analysis post-treatment yielded the following results: pH Value: The treated water maintained a neutral pH of 7, which complies with standard water quality requirements. TDS (Total Dissolved Solids): A notable reduction in TDS levels was observed compared to the pre-treatment stage. This reduction effectively decreased the turbidity of the wastewater, resulting in a clearer and highly transparent aqueous phase.

The visual observation in Figure 3: demonstrates the significant decolorization efficiency of the activated carbon. The initial dark purple color of the raw dye wastewater (O) was effectively removed, resulting in a clear aqueous phase starting from a 30-minute contact time (A2). No visible differences were observed between the 30-minute (A2), 1-hour (A3), and 3-hour (A4) intervals, suggesting that equilibrium was reached rapidly.

Label Descriptions: O: Raw dye wastewater (Control). Groups A – E: Samples treated with activated carbon synthesized using varying NaOH concentrations: A: 0.1 M NaOH, B: 0.25 M NaOH, C: 0.5 M NaOH, D: 0.75 M NaOH, E: 1.0 M NaOH, Subscripts 1 – 4: Represent different adsorption contact times: 1: 15 minutes, 2: 30 minutes, 3: 1 hour, 4: 3 hours.

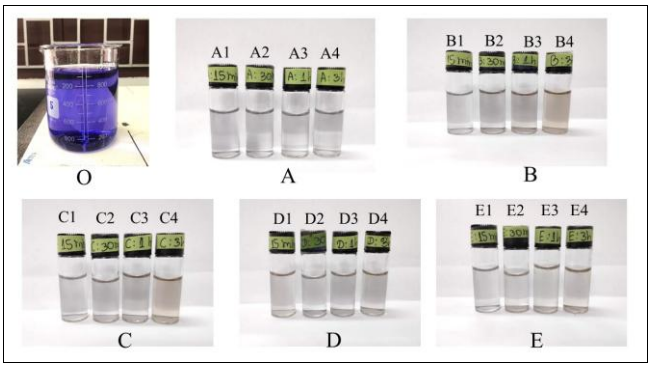

Fig 3: Visual comparison of decolorization efficiency between raw dye wastewater and treated effluents under various activation conditions and contact times

The visual evidence in the provided figures illustrates the impact of both NaOH activation concentration and contact time on the decolorization process. Group A (0.1 M NaOH activation) demonstrated the most effective adsorption performance, yielding a clear and colorless aqueous phase across all time intervals. Conversely, samples treated with higher NaOH concentrations (Groups B through E) exhibited a slight brownish tint or increased turbidity as the contact time progressed, particularly at the 3-hour mark (subscript 4). This suggests that the 0.1 M NaOH activation provides the optimal pore structure for dye molecule entrapment without causing secondary discoloration of the effluent.

pH Value

The pH values of the dye wastewater before and after treatment with activated carbon are summarized in the provided table. Initially, the raw dye wastewater exhibited a neutral pH of 7. Following the adsorption process, the pH levels of the treated effluents showed a direct correlation with the NaOH concentration used during the carbon activation stage.

Specifically, Sample A (0.1 M NaOH) maintained a stable neutral pH of 7 across all contact time intervals (15 min to 3 h). In contrast, increasing the activation concentration led to a progressive rise in alkalinity, with Sample E (1.0 M NaOH) reaching a pH of 10. Notably, the pH levels remained constant over time for each respective sample. These results indicate that Sample A is the most suitable adsorbent for maintaining water quality standards without requiring additional pH adjustment post-treatment.

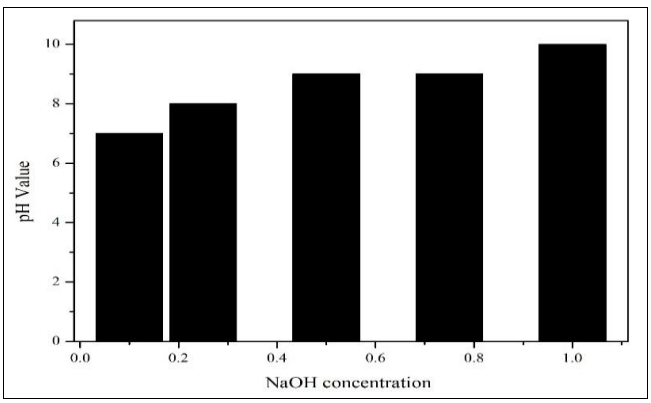

Fig 4: Analysis of pH Variation in Dye Wastewater Post-Treatment

4.3 TDS Value

The experimental results regarding the Total Dissolved Solids (TDS) concentration in dye wastewater before and after treatment are detailed in the provided table. The initial TDS level of the raw wastewater was measured at 667 ppm. Upon treatment with various activated carbon samples (A-E), a significant reduction in TDS was observed across all conditions.

Sample A (0.1 M NaOH activation) demonstrated the highest performance, consistently reducing the TDS concentration over time to a minimum of 104 ppm at the 3-hour mark. In contrast, while Samples B through E initially lowered TDS levels within the first 30 minutes, a gradual increase in TDS was noted during the extended contact periods (1–3 hours). This phenomenon may be attributed to the leaching of residual activating agents at higher concentrations. Consequently, Sample A is identified as the most effective and stable adsorbent for improving water quality by reducing dissolved solid content.

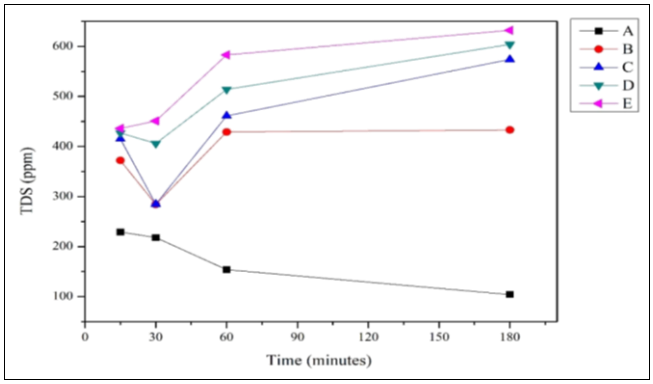

Fig 5: Analysis of Total Dissolved Solids (TDS) Reduction in Dye Wastewater

4.4 Microstructure Analysis

The surface morphology of the synthesized activated carbon was characterized using Scanning Electron Microscopy (SEM). As shown in (Figure 6. O), the non-activated carbon exhibited a dense and relatively non-porous structure. In contrast, chemical activation with NaOH (Figures 6. A–E) led to the formation of a well-defined porous network. The results indicate that increasing the NaOH concentration significantly enhanced the etching effect on the carbon matrix, resulting in a honeycomb-like structure with a high density of macropores and mesopores. These structural developments are crucial for increasing the effective surface area, thereby improving the dye adsorption capacity of the activated carbon.

Although the SEM micrographs reveal that samples C–E possess larger pore structures, Sample A (0.1 M NaOH) exhibited superior adsorption performance. This can be attributed to the optimal pore size distribution provided by the lower activation concentration, which more effectively matches the molecular dimensions of the dye used.

In samples with higher NaOH concentrations (C–E), 'over-etching' of the carbon matrix likely occurred, leading to the collapse of pore walls and the formation of excessively large macropores. While these pores appear prominent under SEM, they often result in a reduction of the overall effective surface area and a loss of high-affinity active sites. In contrast, the micro- and mesoporous network in Sample A provides a higher surface-area-to-volume ratio, facilitating stronger molecular interactions and more efficient entrapment of dye molecules within the carbon framework.

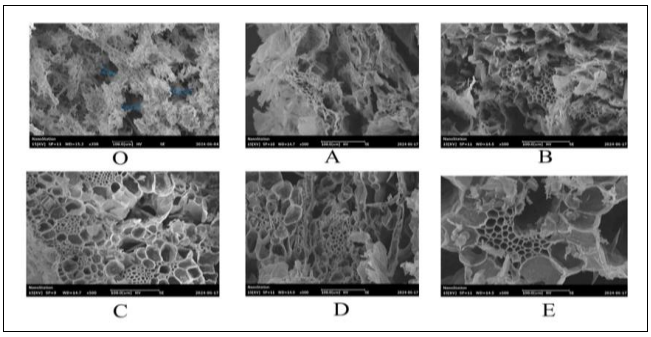

Fig 6: SEM micrographs of water hyacinth-derived carbon surfaces at different sodium hydroxide (NaOH) activation concentrations **(O):** Non-activated carbon (Control sample), **(A):** Activated carbon treated with 0.1 M NaOH, **(B):** Activated carbon treated with 0.25 M NaOH, **(C):** Activated carbon treated with 0.5 M NaOH, **(D):** Activated carbon treated with 0.75 M NaOH, **(E):** Activated carbon treated with 1.0 M NaOH

4.5 Spectrophotometric Analysis

The adsorption efficiency of water hyacinth-derived activated carbon was evaluated using UV-Visible spectrophotometry. The experiments involved treating 100 ml of 10 ppm dye solution with 0.2 g of activated carbon, prepared at varying NaOH concentrations (0.1 M to 1.0 M).

As illustrated in Figure 7. Sample A (0.1 M NaOH) exhibited rapid and stable adsorption, achieving a removal efficiency of 78%–79% within the first 15 minutes and maintaining this performance throughout the 3-hour period. For Samples B through E, while high adsorption efficiencies (78%–79%) were initially observed between 15 and 30 minutes, a subsequent increase in absorbance was noted at the 1-hour and 3-hour intervals. This rise in absorbance values, which corresponds to a decrease in removal efficiency to approximately 67%–68%, suggests a partial desorption process or increased turbidity in the aqueous phase. These findings confirm that a 30-minute contact time with 0.1 M NaOH-activated carbon represents the optimal conditions for maximum dye removal.

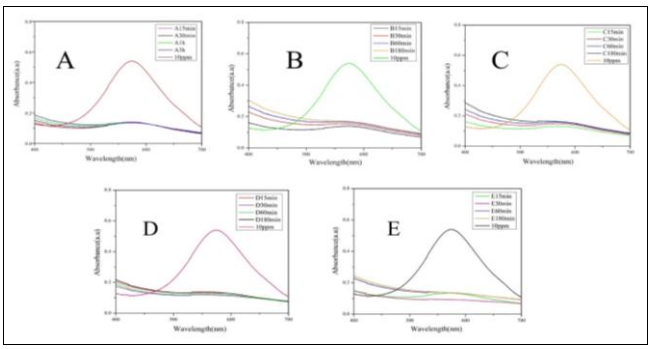

Fig 7: Spectrophotometric Analysis of Dye Adsorption Efficiency (A): 0.1 M NaOH, (B): 0.25 M NaOH, (C): 0.5 M NaOH, (D): 0.75 M NaOH, (E): 1.0 M NaOH

5. Discussion

The synthesis of activated carbon from water hyacinth using NaOH activation revealed that the 0.1 M concentration (Sample A) represents the optimal chemical environment for dye adsorption. Although SEM analysis indicated that higher concentrations (Samples A3–A5) produced more

pronounced macropores, these structural changes did not translate to higher adsorption efficiency. Instead, a decline in removal rates and subsequent desorption were observed over extended contact times. This phenomenon can be interpreted through the following comparative perspectives: Pore Structure and Over-activation: The degradation of adsorption performance at higher NaOH concentrations is likely due to "over-etching" of the carbon framework. As noted by Sahu *et al*. (2018) [13], excessive chemical activation can cause the collapse of micropore walls, merging them into larger voids and thereby reducing the total effective surface area. This aligns with our SEM observations where E showed large but potentially less active pores compared to the finer network in A. Adsorption Mechanism and Equilibrium: The high removal efficiency (78%–79%) achieved by Sample A within 30 minutes suggests a rapid attainment of adsorption equilibrium. According to Al-Qodah *et al*. (2017) [2], the presence of optimal microporosity is crucial for trapping organic dye molecules, as pores that are too large (as seen in C-E) may facilitate easier desorption of the adsorbate back into the solution. Water Quality and Chemical Stability: Sample A maintained a neutral pH of 7 and achieved the lowest TDS (104 ppm). This stability is critical; as highlighted by Zhu *et al*. (2020) [15], adsorbents that shift the effluent pH to extreme alkalinity (as seen in our 1.0 M samples) require costly post-treatment neutralization, making low-concentration activation more economically viable. Comparative Performance with Other Biomass: The dye removal percentage observed in this study is comparable to other aquatic weed-based carbons. Mane *et al*. (2007) [5] reported similar trends where the adsorption capacity of water hyacinth carbon is highly dependent on the initial concentration and contact time, further validating our finding that 30 minutes is the optimal threshold for this specific precursor. TDS Reduction Efficiency: The significant drop in TDS from 667 ppm to 104 ppm in Sample A suggests that the carbon possesses functional groups capable of ion exchange or inorganic salt entrapment, a characteristic also discussed by Hadi *et al*. (2015) in their study on modified biochar for wastewater purification.

6. Conclusion

This study successfully demonstrated the synthesis of activated carbon from water hyacinth (*Eichhornia crassipes*) via NaOH activation for the removal of textile dyes from wastewater. The experimental findings conclude that the concentration of the activating agent plays a critical role in determining the pore structure and adsorption performance. Optimal Activation: The activated carbon synthesized with 0.1 M NaOH exhibited the highest efficiency and stability. Adsorption Performance: Under optimal conditions (0.2 g dosage and 30-minute contact time), a decolorization efficiency of 78%–79% was achieved, yielding a clear effluent. Water Quality Improvement: The treated wastewater maintained a neutral pH of 7 and showed a significant reduction in Total Dissolved Solids (TDS), decreasing from 667 ppm to 104 ppm. Stability: Lower activation concentrations prevented the desorption of dye molecules and avoided excessive alkalinity in the treated water, unlike higher concentration samples (0.25 M – 1.0 M). In conclusion, water hyacinth-derived activated carbon prepared with 0.1 M NaOH is a highly effective, low-cost, and sustainable adsorbent, offering a viable solution for industrial wastewater remediation and environmental management.

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