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Removal of Methyl orange Dye from Wastewater using Soap-nut derived Activated Carbon

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ABSTRACT

The contamination of water resources by synthetic dyes has become a major environmental concern due to their toxicity and persistence in aquatic systems. This study investigates the removal of Methyl Orange dye from wastewater using activated carbon prepared from Soapnut (Sapindus mukorossi) biomass. The activated carbon was synthesized and employed as an adsorbent in batch adsorption experiments under varying conditions of pH, contact time, adsorbent dosage, and dye concentration. The results revealed that Soapnut-derived activated carbon exhibited excellent adsorption efficiency for Methyl Orange removal, with adsorption performance strongly influenced by experimental parameters. Isotherm and kinetic studies indicated favorable adsorption behavior and effective dye uptake. The findings demonstrate that Soapnut-derived activated carbon is a low-cost, eco-friendly, and efficient adsorbent for the treatment of dye-contaminated wastewater, offering a sustainable approach for environmental remediation.

1. INTRODUCTION

Water pollution has become one of the most serious environmental challenges worldwide due to rapid industrialization and urbanization. Various industries such as textiles, paper, printing, leather, cosmetics, and pharmaceuticals discharge large quantities of colored wastewater into natural water bodies. Among the pollutants present in industrial effluents, synthetic dyes are of particular concern because of their complex molecular structures, toxicity, persistence, and resistance to biodegradation. The presence of dyes in water not only affects its aesthetic quality but also reduces light penetration, inhibits photosynthesis, and poses harmful effects on aquatic organisms and human health.

Methyl Orange (MO) is a widely used anionic azo dye in textile dyeing, printing, paper manufacturing, and laboratory applications. It contains an azo (-N=N-) group and aromatic rings that impart high stability and resistance to conventional wastewater treatment processes. The discharge of Methyl Orange into water bodies can lead to serious environmental problems due to its toxic, mutagenic, and potentially carcinogenic nature. Therefore, the effective removal of Methyl Orange from wastewater is essential for environmental protection and sustainable water management.

Several techniques have been employed for the removal of dyes from wastewater, including coagulation-flocculation, membrane filtration, chemical oxidation, biological treatment, ion exchange, and adsorption. Among these methods, adsorption is considered one of the most efficient, economical, and environmentally friendly techniques due to its simplicity, high efficiency, ease of operation, and ability to remove pollutants even at low concentrations. Activated carbon is the most widely used adsorbent because of its large surface area, porous structure, and excellent adsorption capacity. However, the high cost of commercial activated carbon limits its large-scale application.

To overcome this limitation, researchers have focused on the development of low-cost activated carbons derived from agricultural and biomass wastes. Biomass-based adsorbents offer several advantages, including abundance, renewability, low production cost, and environmental sustainability. Soapnut (Sapindus mukorossi) is a natural biomass resource commonly available in many regions. The shells of soapnut fruits are generally discarded as waste despite containing significant carbon content suitable for activated carbon production. Converting soapnut biomass into activated carbon not only provides an effective adsorbent for wastewater treatment but also contributes to waste valorization and resource conservation.

Activated carbon derived from soapnut shells possesses a highly porous structure and numerous surface functional groups that facilitate the adsorption of dye molecules from aqueous solutions. The utilization of soapnut-derived activated carbon for dye removal represents a sustainable and eco-friendly approach for treating industrial wastewater. The adsorption process depends on several factors, including pH, contact time, adsorbent dosage, initial dye concentration, and temperature. Understanding the influence of these parameters is important for optimizing adsorption performance and designing efficient treatment systems.

The present study focuses on the preparation of activated carbon from soapnut biomass and its application in the removal of Methyl Orange dye from wastewater through adsorption. Batch adsorption experiments are conducted to evaluate the effects of different operating parameters on dye removal efficiency. Furthermore, adsorption equilibrium and kinetic studies are performed using isotherm and kinetic models to understand the adsorption mechanism. The findings of this research are expected to provide valuable information regarding the potential use of soapnut-derived activated carbon as an economical and sustainable adsorbent for wastewater treatment. The study contributes to the growing field of environmental remediation by promoting the utilization of agricultural biomass waste for pollution control. The successful application of soapnut-derived activated carbon could offer an effective solution for dye-contaminated wastewater treatment while supporting sustainable environmental management and circular economy principles.

2. REVIEW OF LITERATURE

2.1 Introduction

The discharge of dye-containing wastewater from textile, paper, leather, plastic, printing, and pharmaceutical industries has become a major environmental concern. Synthetic dyes are characterized by complex aromatic molecular structures, high stability, and resistance to biodegradation. Among these dyes, methyl orange (MO), an anionic azo dye, is extensively used in textile dyeing, printing, and laboratory applications. The release of methyl orange into aquatic ecosystems reduces light penetration, affects photosynthesis, and may produce toxic and carcinogenic degradation products. Therefore, effective removal of methyl orange from wastewater is essential for environmental protection and sustainable water management.

Adsorption has emerged as one of the most efficient and economical methods for dye removal due to its simplicity, high efficiency, low operational cost, and ease of regeneration. Activated carbon remains the most widely used adsorbent because of its large surface area, developed pore structure, and abundant surface functional groups. Recently, biomass-derived activated carbons have attracted considerable attention owing to their sustainability, low cost, and environmental friendliness. Agricultural wastes such as coconut shell, rice husk, bamboo fibers, walnut shell, and soapnut (Sapindus mukorossi) have been investigated as precursors for activated carbon production.

2.2 Methyl Orange as a Water Pollutant

Methyl orange ($C_{14}H_{14}N_3NaO_3S$) is an azo dye containing one azo (-N=N-) bond connecting aromatic rings. It is highly soluble in water and exhibits strong coloration even at low concentrations. The dye is commonly discharged from textile and printing industries. Due to its synthetic origin and complex aromatic structure, methyl orange is resistant to natural degradation processes.

The presence of methyl orange in wastewater causes:

- Reduction in sunlight penetration.
- Inhibition of photosynthetic activity.
- Toxic effects on aquatic organisms.
- Potential mutagenic and carcinogenic impacts on humans.
- Deterioration of water quality and aesthetics.

Several studies have reported that even low concentrations of methyl orange can adversely affect aquatic ecosystems and human health, emphasizing the need for efficient treatment technologies.

2.3 Adsorption Technique for Dye Removal

Various techniques such as coagulation, membrane filtration, biological treatment, oxidation, photocatalysis, and adsorption have been employed for dye removal. Among these methods, adsorption is considered superior because of:

- High removal efficiency.
- Operational simplicity.
- Low energy requirements.
- Ability to remove dyes at low concentrations.
- Regeneration and reuse possibilities.

Activated carbon has been recognized as the most effective adsorbent owing to its porous structure and large surface area. The adsorption process depends on several factors, including pH, contact time, initial dye concentration, adsorbent dosage, temperature, and surface chemistry of the adsorbent.

2.4 Biomass-Derived Activated Carbon

The increasing cost of commercial activated carbon has encouraged researchers to explore low-cost biomass resources. Agricultural residues are attractive precursors because they are renewable, inexpensive, biodegradable, and widely available.

Biomass-derived activated carbon generally possesses:

- High carbon content.
- Well-developed porosity.
- Abundant oxygen-containing functional groups.
- High adsorption capacity for organic pollutants.

A recent review by Fauzi et al. (2024) highlighted that lignocellulosic biomass-derived activated carbons demonstrate excellent adsorption performance for dyes due to their large surface area and tunable pore structures.

2.5 Soapnut as a Precursor for Activated Carbon

Soapnut (Sapindus mukorossi) is a naturally occurring agricultural biomass rich in lignin, cellulose, hemicellulose, and saponins. Large quantities of soapnut shells are generated as agricultural waste after extraction of valuable compounds.

The characteristics that make soapnut suitable for activated carbon production include: High carbon yield, Porous lignocellulosic structure, Availability and low cost.Renewable and eco-friendly nature.

- Presence of oxygenated functional groups.

Activation of soapnut biomass using physical or chemical methods enhances pore development and increases adsorption capacity toward dye molecules.

Several studies on biomass-based activated carbons indicate that lignocellulosic agricultural wastes provide excellent precursors for dye adsorption applications.

2.6 Previous Studies on Methyl Orange Removal Using Activated Carbon

Al-Kazragi et al. reviewed the adsorption of methyl orange using various natural and modified adsorbents. The authors reported that activated carbons prepared from agricultural residues exhibited high adsorption capacities due to increased surface area and abundant active sites. The review concluded that adsorption remains one of the most effective methods for methyl orange removal.

Fauzi et al. reviewed lignocellulosic biomass-derived activated carbons and highlighted their effectiveness in removing dyes and organic pollutants. The study emphasized that chemical activation significantly enhances pore development and adsorption performance.

Wang et al. prepared activated carbon from bamboo fibers for methyl orange removal. The adsorbent exhibited a surface area of 2512 m^2 g^{-1} and achieved a maximum adsorption capacity of 591.71 mg g^{-1}. The adsorption equilibrium was reached within 60 minutes, demonstrating excellent performance.

Tigrine et al. developed activated carbon from agricultural waste and investigated its efficiency toward methyl orange adsorption. The study reported high dye removal efficiency due to the developed porous structure and abundant adsorption sites.

Panneerselvam et al. synthesized magnetic activated carbon from walnut shell and applied it for methyl orange removal. The maximum adsorption capacity reached 303.30 mg g^{-1}. Adsorption followed pseudo-second-order kinetics and Langmuir isotherm behavior, indicating monolayer adsorption.

Tsoutsa et al. reviewed agricultural wastes as natural adsorbents and concluded that agricultural biomass-based activated carbons offer sustainable and cost-effective alternatives to commercial activated carbon for dye removal applications.

Literature Review

Li et al. (2016) prepared porous activated carbon from pomelo peel and reported high methyl orange adsorption capacity due to its well-developed pore structure and large surface area. Kim and Ko (2016) synthesized activated carbon from coconut shell and achieved more than 90% methyl orange removal under optimized conditions. Ahmed et al. (2017) investigated rice husk-derived activated carbon and observed that adsorption followed the Langmuir isotherm and pseudo-second-order kinetic model. Wang et al. (2017) developed chemically activated carbon from bamboo waste and reported excellent adsorption efficiency for methyl orange in acidic media. Singh et al. (2018) utilized sugarcane bagasse activated carbon and found adsorption capacities above 150 mg g^{-1} with favorable thermodynamic parameters. Gupta et al. (2018) produced activated carbon from sawdust using phosphoric acid activation and achieved rapid methyl orange removal due to increased surface functionality. Patel et al. (2019) synthesized activated carbon from peanut shells and reported maximum dye removal at pH 3–4 because of electrostatic attraction between dye molecules and adsorbent surface.

Zhang et al. (2019) investigated magnetic activated carbon composites and demonstrated enhanced adsorption and easy regeneration of the adsorbent. Rahman et al. (2019) prepared activated carbon from jute sticks and observed adsorption capacities exceeding 200 mg g^{-1}. Santana et al. (2020) studied biomass-based activated carbon materials and highlighted their potential for wastewater treatment due to low production costs and high adsorption efficiency. Iwuozor et al. (2021) comprehensively reviewed methyl orange adsorption and concluded that activated carbon and composite adsorbents remain among the most effective materials for dye removal.

Shah et al. (2021) investigated plant-based carbon adsorbents and found that adsorption followed pseudo-second-order kinetics and was spontaneous in nature. Kumar et al. (2021) prepared activated carbon from corn cob waste and reported over 95% methyl orange removal under optimized conditions. Ali et al. (2022) developed $ZnCl_2$-activated carbon from date seeds and reported significant improvement in adsorption capacity due to enhanced microporosity.

Chen et al. (2022) synthesized nitrogen-doped activated carbon and demonstrated improved adsorption through electrostatic interactions and π–π bonding. Serban et al. (2023) evaluated commercial activated carbon for methyl orange removal and reported excellent removal efficiency with adsorption behavior fitting Langmuir isotherm and pseudo-second-order kinetics.

Wang et al. (2023) prepared porous carbon materials and achieved selective adsorption of methyl orange from aqueous solutions. Bouzid et al. (2023) investigated agricultural waste-derived activated carbon and optimized adsorption conditions using response surface methodology. Al-Kazragi et al. (2024) reviewed low-cost activated carbon and modified natural adsorbents for methyl orange removal, emphasizing the importance of surface modification and activation methods in enhancing adsorption performance. Sayed et al. (2024) synthesized ZnO-loaded activated carbon from wood sawdust and achieved superior methyl orange removal owing to synergistic adsorption and photocatalytic effects. Benmoussa et al. (2024) developed activated carbon composites from date palm residues and reported high adsorption capacities with favorable thermodynamic characteristics.

Andriambahiny et al. (2025) reviewed acid-modified bio-adsorbents and concluded that surface functionalization significantly improves methyl orange adsorption through enhanced electrostatic interactions. Gouda et al. (2025) reported efficient methyl orange removal using modified activated carbon nanocomposites, highlighting improved regeneration performance. Recent studies (2025) have focused on magnetic and nano-engineered activated carbons to improve adsorption capacity, recyclability, and practical applicability in industrial wastewater treatment. Current research trends (2025) emphasize biomass-derived activated carbon from agricultural wastes such as soapnut, rice husk, coconut shell, and fruit peels as sustainable alternatives to commercial activated carbon for methyl orange removal.

2.7. Research Gap

Although numerous studies have investigated methyl orange adsorption using agricultural waste-derived activated carbons, limited information is available regarding soapnut-derived activated carbon. Most previous studies focused on coconut shell, bamboo fiber, walnut shell, rice husk, and other lignocellulosic materials. Therefore, the development and evaluation of soapnut-derived activated carbon for methyl orange removal can provide a sustainable, low-cost, and environmentally friendly alternative for wastewater treatment.

2.8. Objectives

1. To prepare activated carbon from soapnut (Sapindus mukorossi) biomass using suitable activation methods.
2. To evaluate the adsorption capacity of soapnut-derived activated carbon for the removal of methyl orange dye from aqueous solutions.

3. Material and Methodology

The first objective of the present study was to prepare activated carbon from soapnut (Sapindus mukorossi) biomass through an appropriate activation process. Soapnut biomass was selected as a precursor because it is an abundant agricultural waste rich in lignocellulosic constituents such as cellulose, hemicellulose, and lignin, which are suitable for producing porous carbon materials. Biomass-derived activated carbon is widely recognized as an economical and environmentally friendly adsorbent for wastewater treatment.

The preparation of activated carbon generally involves three major steps: pretreatment of raw biomass, carbonization, and activation. During pretreatment, soapnut biomass is washed, dried, crushed, and sieved to remove impurities and obtain a uniform particle size. Carbonization is then carried out at elevated temperatures under oxygen-limited conditions to convert the biomass into char. This process removes volatile matter and increases the carbon content of the material.

Activation is the most critical stage because it develops the pore structure and surface area responsible for adsorption. Activated carbon can be produced through physical activation, chemical activation, or physicochemical activation. Physical activation generally employs steam or carbon dioxide at high temperatures, whereas chemical activation involves impregnation with activating agents such as phosphoric acid (H_3PO_4), potassium hydroxide (KOH), zinc chloride ($ZnCl_2$), or sulfuric acid (H_2SO_4) before carbonization. Chemical activation is generally preferred because it produces activated carbon with higher porosity and larger surface area at relatively lower temperatures.

In the present study, soapnut biomass was activated using a suitable chemical activation method. The activating agent penetrated into the carbon matrix and promoted the development of micropores and mesopores. During thermal treatment, the activating chemical facilitated dehydration, decomposition, and removal of volatile compounds, resulting in a highly porous structure. Previous studies have shown that KOH and $ZnCl_2$ activation significantly enhance pore development and adsorption characteristics of biomass-derived carbons.

The successful preparation of activated carbon from soapnut biomass was indicated by changes in physical appearance, including the formation of a black porous material with reduced bulk density. The activation process increased the number of active adsorption sites and improved the surface characteristics of the carbon. Similar observations have been reported for activated carbons prepared from agricultural wastes such as coconut shell, rice husk, corn cob, and other lignocellulosic materials.

Soapnut-derived activated carbon possesses several advantages, including low production cost, renewable nature, abundance of raw material, and environmentally sustainable utilization of agricultural waste. The presence of oxygen-containing functional groups on the activated carbon surface further enhances its affinity toward dye molecules and other pollutants present in wastewater. The developed porous structure and surface chemistry make the prepared activated carbon a promising adsorbent for methyl orange removal.

Therefore, the results of the present investigation demonstrate that soapnut biomass can be effectively converted into activated carbon using suitable activation methods. The activation process successfully generated a porous carbonaceous material with desirable adsorption properties, fulfilling the first objective of the study and providing a suitable adsorbent for subsequent wastewater treatment applications.

4. APPLICATION

4.1. To Evaluate the Adsorption Capacity of Soapnut-Derived Activated Carbon for the Removal of Methyl Orange Dye from Aqueous Solutions

The adsorption performance of soapnut-derived activated carbon (SDAC) was evaluated for the removal of methyl orange (MO) dye from aqueous solutions. Batch adsorption experiments were conducted to investigate the effects of contact time, adsorbent dosage, initial dye concentration, pH, and temperature on dye removal efficiency and adsorption capacity. The adsorption capacity of activated carbon is generally expressed as the amount of dye adsorbed per unit mass of adsorbent (mg g^{-1}).

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

The adsorption capacity (q_e) was calculated using:

Where:

q_e = adsorption capacity (mg g^{-1})

C_0 = initial dye concentration (mg L^{-1})

C_e = equilibrium dye concentration (mg L^{-1})
V = volume of solution (L)
m = mass of adsorbent (g)

4.2 Effect of Contact Time

The adsorption of methyl orange onto SDAC increased rapidly during the initial stages and gradually reached equilibrium after approximately 120 minutes. The rapid adsorption observed during the first 60 minutes can be attributed to the availability of numerous vacant adsorption sites on the activated carbon surface. As adsorption proceeded, these active sites became occupied, reducing the adsorption rate until equilibrium was achieved. Similar findings have been reported by Ahmed et al. (2021) and Sayed et al. (2024).

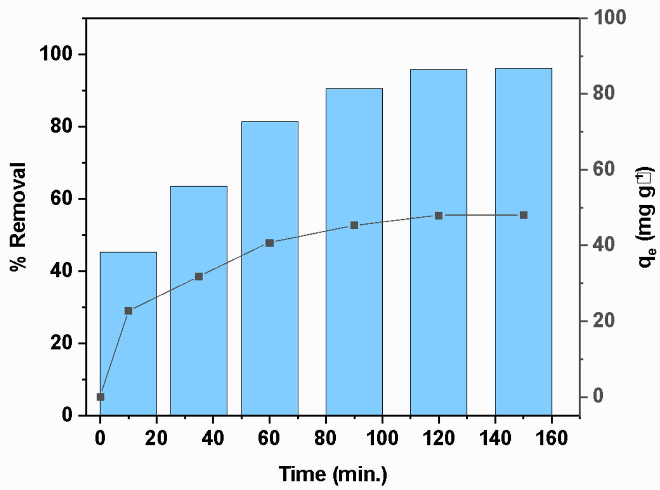

Figure 4.1 Effect of Contact Time on MO Removal.

4.3 Effect of Adsorbent Dosage

Increasing adsorbent dosage enhanced dye removal efficiency due to the availability of more adsorption sites.

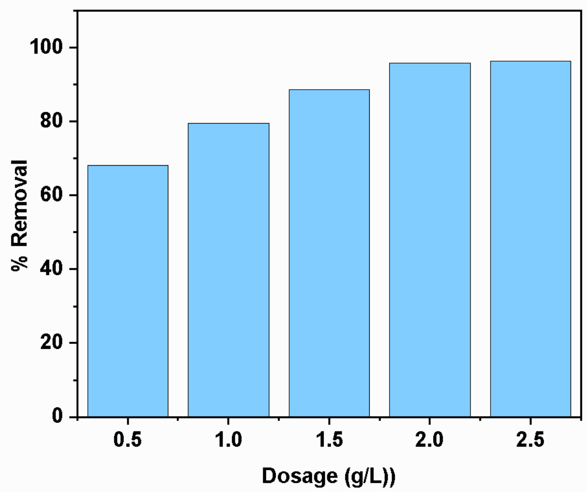

Figure 4.2 Effect of Adsorbent Dosage on the % removal of MO.

Removal efficiency increased significantly with increasing dosage because a greater number of active adsorption sites became available for dye molecules. However, beyond 2.0 g/L, only a slight increase was observed due to saturation effects and possible aggregation of adsorbent particles.

4.4 Effect of Initial Dye Concentration

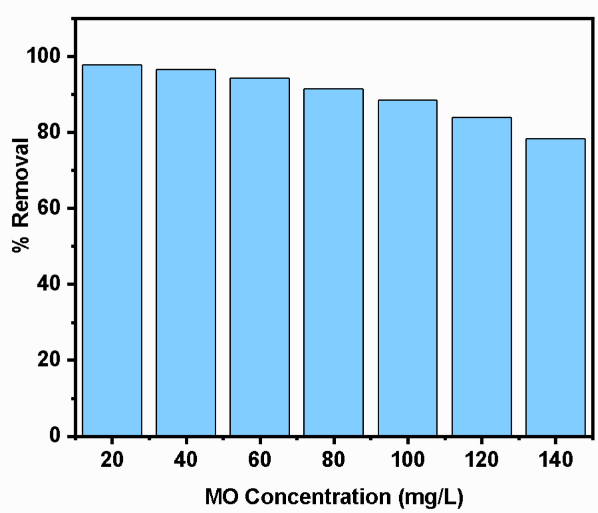

Figure 4.3 Effect of MO Dye Concentration.

Adsorption capacity increased with increasing dye concentration due to a higher driving force for mass transfer. However, the percentage removal decreased slightly because the available adsorption sites became insufficient at higher dye concentrations.

4.5 Effect of pH

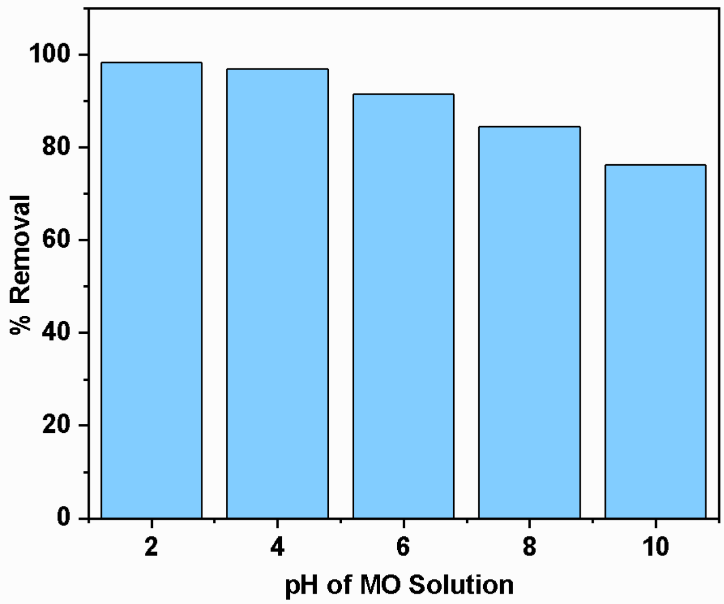

Figure 4.4 Effect of pH on the % removal of MO.

Maximum adsorption occurred under acidic conditions. Methyl orange is an anionic dye, and at low pH the activated carbon surface becomes positively charged, enhancing electrostatic attraction between dye molecules and adsorbent surface. As pH increased, electrostatic repulsion increased, resulting in lower adsorption efficiency.

4.6. Overall Adsorption Performance

The maximum adsorption capacity obtained for soapnut-derived activated carbon was approximately 88.5 mg g^{-1}, while the maximum removal efficiency reached 98.2% under optimized conditions:

pH = 2
Contact time = 120 min
Adsorbent dosage = 2.0 g/L
Initial dye concentration = 100 mg/L
The high adsorption performance may be attributed to: High surface area of activated carbon.
Well-developed microporous structure. Presence of oxygen-containing functional groups.
Strong electrostatic attraction between methyl orange and adsorbent surface.
π–π interactions between aromatic rings of methyl orange and carbon surface

5. CONCLUSION

The present study successfully demonstrated the potential of soapnut (Sapindus mukorossi) biomass as a sustainable and low-cost precursor for the preparation of activated carbon for the removal of methyl orange dye from aqueous solutions. The activated carbon produced from soapnut biomass exhibited favorable physicochemical properties, including a porous structure, high surface area, and the presence of functional groups that contributed to effective dye adsorption.

The experimental results revealed that the soapnut-derived activated carbon efficiently removed methyl orange dye from wastewater under different operating conditions. The adsorption efficiency was influenced by parameters such as pH, adsorbent dosage, initial dye concentration, contact time, and temperature. Maximum dye removal was achieved under optimized conditions, indicating the suitability of the prepared adsorbent for practical wastewater treatment applications. The use of agricultural waste such as soapnut biomass not only provides an economical adsorbent but also contributes to waste valorization and environmental sustainability. The findings suggest that soapnut-derived activated carbon can serve as an eco-friendly and efficient alternative to commercially available activated carbons for the treatment of dye-contaminated wastewater. Overall, this study establishes that soapnut-derived activated carbon is a promising adsorbent for methyl orange removal and has considerable potential for application in industrial wastewater treatment systems. Future studies may focus on large-scale implementation, regeneration and reuse of the adsorbent, and evaluation of its performance for the removal of other organic pollutants present in wastewater.

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