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Characterization of Activated Carbon from Sorghum Bagasse Using Double Activation (Chemical Activation and Physical Activation) for Methylene Blue Adsorption

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A B S T R A C T

This research aims to evaluate the adsorption performance of activated carbon derived from sorghum bagasse through a two-step activation process involving both chemical and physical activation. The sorghum bagasse precursor was first chemically activated using potassium carbonate (K_2CO_3) as the activating agent, followed by physical activation at 800 °C under an inert atmosphere. The resulting activated carbon was characterized using Scanning Electron Microscopy (SEM) to examine its surface morphology. Adsorption experiments were subsequently conducted employing methylene blue as a model dye at various initial concentrations to determine the adsorption efficiency. The results revealed that the K_2CO_3-activated sorghum bagasse carbon exhibited excellent adsorption capability, achieving a removal rate of up to 99% for methylene blue. Overall, these findings demonstrate that sorghum bagasse has considerable potential as a sustainable and cost-effective precursor for producing high-quality activated carbon with outstanding dye adsorption performance.

Contribution to Sustainable Development Goals (SDGs):
SDG 6: Clean Water and Sanitation
SDG 12: Responsible Consumption and Production
SDG 13: Climate Action

1. INTRODUCTION

1.1. Research Background

Sweet sorghum (Sorghum bicolor L. Moench) is a cereal crop that can be cultivated in both high-rainfall and arid regions [1]. The plant consists of seeds, stems, and leaves, each of which holds distinct utilization potential. In Indonesia, the use of sorghum as a food source remains limited due to the presence of tannins, antinutritional compounds that impart a bitter or astringent taste. The stems of sweet sorghum, however, contain juice that can be processed into liquid sugar or sorghum syrup [2]. The average yield of sorghum stems reaches approximately 23.06 tons per hectare, while the residual bagasse accounts for about 4.89 tons per hectare [3]. Once the juice is extracted, the remaining fibrous material is referred to as sorghum bagasse. This by-product is typically used as animal feed, while a substantial portion is discarded or burned, leading to potential environmental pollution.

Despite its limited current use, sorghum bagasse contains high amounts of lignocellulosic components. Thus, sorghum bagasse has significant potential for use as a raw material in the production of activated carbon. Activated carbon derived from sorghum bagasse can serve as an effective adsorbent for methylene blue, a synthetic dye commonly employed in the textile industry. When released untreated into aquatic environments, methylene blue can persist for extended periods, causing chemical pollution that degrades water quality, disrupts aquatic ecosystems, and poses risks to human health [4]. Therefore, the synthesis of activated carbon from sorghum bagasse not only enhances the economic value of this agricultural by-product but also offers an environmentally friendly solution for mitigating dye pollution from textile effluents.

1.2. Literature Review

Activated carbon is synthesized from organic compounds containing carbon elements that are specially processed to produce a porous structure. It is highly effective in adsorbing organic compounds and can be produced in powdered or granular form, characterized by a large specific surface area due to the abundance of fine pores (micropores) within its structure. As one of the most efficient adsorbents in adsorption processes, activated carbon exhibits optimal adsorption capacity. The quality of activated carbon is determined by its pore capacity, which directly contributes to enhanced adsorption performance [5]

The raw materials commonly used for the production of activated carbon are biomass sources, as biomass contains cellulose with strong potential for carbon material synthesis [6]. One such biomass is sorghum bagasse, which possesses a relatively high lignocellulosic content, including 16.73% cellulose, 17.45% hemicellulose, 3.94% lignin, and 61.88% other compounds [7]. The high cellulose and hemicellulose content in sorghum bagasse makes it an ideal precursor for producing activated carbon with a significant specific surface area. The synthesis of activated carbon can be achieved through the activation of biomass using either chemical or physical activation methods.

Fig. 1. Bagasse Sorgum

1.2.1. Activation

The activation process aims to enhance the adsorption capacity and surface area of activated carbon. This stage plays a crucial role in converting low-adsorptive biomass into carbon materials with high adsorption capacity. Accordingly, activation is conducted to expand the pore surface and increase the adsorptive properties of the resulting carbon. The activation method is generally categorized into two types [8] :

1. Chemical Activation

Chemical activation involves the introduction of activating agents that influence the pyrolysis process. The fundamental principle of this method is the impregnation of carbonised biomass with chemical compounds, including KOH, H_2SO_4, H_3PO_4, K_2CO_3, and $ZnCl_2$. Among the various chemical activators, this study employs potassium carbonate (K_2CO_3) as the activating agent. K_2CO_3 is selected due to its ability to enhance surface area and porosity through thermal decomposition into K_2O and CO_2, which subsequently react with carbon to form open-pore structures that promote high adsorption performance [9]. Furthermore, compared to stronger activators such as KOH which is more corrosive and generates more complex waste K_2CO_3 provides safer handling characteristics and greater recyclability potential during activated carbon production [10]. The activation mechanism of K_2CO_3 is particularly suitable for lignocellulosic biomass such as sorghum bagasse, as the interaction between alkaline agents and the cellulose–hemicellulose matrix accelerates the development of micro- and mesopores, resulting in activated carbon with an optimal pore texture for adsorbing dye molecules such as methylene blue [11].

2. Physical Activation

This stage is carried out through a high-temperature gas oxidation process that removes most of the volatile components. The carbon activation phase is then followed by carbonization at temperatures ranging from 800°C to 1000°C, using activating agents such as CO_2, O_2, or steam. In this study, a carbonization temperature of 800°C was applied. In this research, a physical activation temperature of 800 °C for two hours was selected to optimise pore development and surface area without excessive burn-off. Within the 800–1000 °C range, partial gasification reactions between char and oxidising gases (CO_2 or steam) efficiently create micro- and mesopores, with 800 °C providing the optimal balance between porosity and carbon yield [12]. At higher temperatures, oxidation becomes too intense, causing pore collapse and reducing the surface area [11]. A two-hour holding time allows sufficient gasification for the chemically activated precursor (e.g., with K_2CO_3) to develop interconnected pores, while longer durations may increase burn-off [13]. Studies on alkali-activated biomass have confirmed that combined chemical and physical activation at 800 °C yields activated carbon with high surface area and well-distributed pores suitable for dye adsorption such as methylene [14]

1.2.2. Adsorption

Adsorption is a physicochemical process in which molecules, ions, or particles of a substance (adsorbate) adhere to the surface of another material (adsorbent) due to intermolecular attractive forces. Unlike absorption, which involves penetration into the bulk of the material, adsorption occurs only on the surface. This process is widely applied in various industrial and environmental fields. In water and wastewater treatment, activated carbon serves as an adsorbent to remove contaminants. In the pharmaceutical industry, adsorption is used for drug purification, while in petrochemical processes, zeolites are employed for gas separation and oil refining. Moreover, adsorption plays an important role in energy and air pollution control technologies, such as hydrogen storage and carbon dioxide or toxic gas removal [15]

1.3. Research Objective

This study aims to investigate the potential of sorghum bagasse-derived activated carbon, produced through a two-step activation process (chemical and physical activation), as an adsorbent for methylene blue.

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2. MATERIALS AND METHODS

The materials used in this study consisted of sorghum bagasse as the precursor, potassium carbonate (K_2CO_3) as the chemical activator, 37% hydrochloric acid (HCl) as the neutralising agent, and methylene blue as the adsorbate for testing purposes. The equipment used included a disk mill, blender, hydrothermal reactor, 40-mesh and 100-mesh sieves, beaker glass, filter paper, glass funnel, vacuum pump, dropper pipette, oven, magnetic stirrer, and muffle furnace.

The initial process involved grinding the sorghum bagasse and standardizing its particle size to 100 mesh. The next step was activation to open the pores and form activated carbon in the precursor. The first stage involved chemical activation using K_2CO_3 as the activator, with a sorghum bagasse-to-activator weight ratio of 1:1. The K_2CO_3 activator was first dissolved in distilled water. Then the sorghum bagasse was added to the solution and stirred for 2 hours. The impregnated sample was then dried in an oven at 105°C for 24 hours. After drying, physical activation was performed using a furnace at 800°C for 2 hours. The resulting sample was neutralized using 37% HCl for 3 hours, followed by washing with distilled water until a neutral pH was achieved. The washed sample was again dried in an oven at 105°C for 24 hours. The activated carbon sample prepared using K_2CO_3 was then characterized using Scanning Electron Microscopy (SEM) to observe its surface morphology.

To evaluate the adsorption capacity of the activated carbon, methylene blue was used as the adsorbate in wastewater. The methylene blue solution was diluted to the desired concentrations ranging from 10 to 50 ppm with 10 ppm intervals. The prepared methylene blue solutions were then contacted with the activated carbon produced using K_2CO_3 as the activator. The adsorption contact times were varied between 20 and 100 minutes at 20-minute intervals. After the adsorption process, the mixture was filtered to obtain the filtrate, which was then analyzed using a UV-Vis spectrophotometer to determine the residual methylene blue concentration.

3. RESULT AND DISCUSSION

3.1. *Morphological Analysis (SEM Test)*

The synthesis of activated carbon using K_2CO_3 as the chemical activator produced a lighter carbon material with a broader pore distribution. Activation with K_2CO_3 predominantly generates mesopores rather than micropores, as the release of CO_2 during the physical activation process leads to the formation of larger cavities. This was confirmed by the SEM analysis results, which showed large and uniformly distributed pores. The presence of open pores indicates that the activated carbon is suitable for use in adsorption processes.

3.2. *Methylene Blue Adsorption Test (UV-Vis*

3.2.1. *Spectrophotometry)*

To determine the adsorption capacity of the synthesized activated carbon, the residual concentration of methylene blue after the adsorption process was analyzed using UV-Vis spectrophotometry at 664 nm. The results are presented in Table 1.

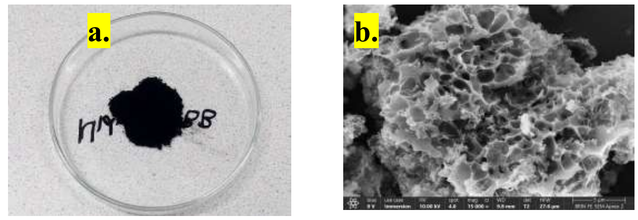
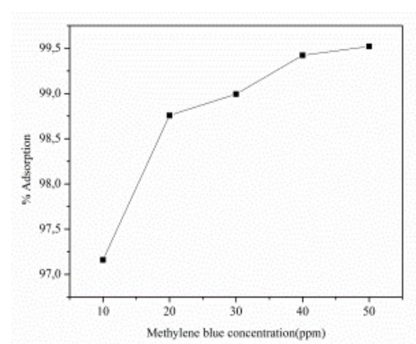


Fig.2 (a) Activated carbon obtained after activation; (b) SEM image showing the surface morphology of activated carbon at 15,000× magnification

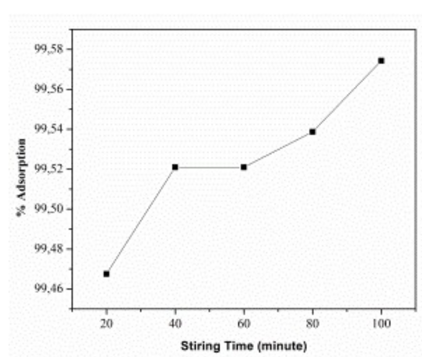
Table 1. Methylene Blue Adsorption by K_2CO_3 Activated Carbon

K2CO3 Concentration (Co)	% Adsorption	Time	% Adsorption
10	97.1593	20	99.4674
20	98.7577	40	99.5209
30	98.9937	60	99.5219
40	99.4234	80	99.5387
50	99.5209	100	99.5743

From Table 1, graphs were constructed to determine the relationship between methylene blue concentration and adsorption percentage, as well as the relationship between methylene blue concentration and stirring time.



(a)



(b)

Fig.3 (a) Relationship between methylene blue concentration (ppm) and adsorption percentage; (b) Relationship between stirring time (minutes) and adsorption percentage

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In the graph above, activated carbon prepared using K_2CO_3 as the activating agent reached adsorption equilibrium at a methylene blue concentration of 50 ppm and 100 minutes of stirring, achieving an adsorption percentage of 99.57%. This phenomenon is influenced by a greater driving force, where a higher methylene blue concentration enhances the diffusion rate of dye molecules into the pores of the activated carbon. As a result, a larger amount of methylene blue is adsorbed compared to that at lower concentrations. Moreover, higher methylene blue concentrations enable the adsorption process to operate more efficiently, thereby improving overall adsorption performance relative to lower concentration levels. Adsorption occurs rapidly at the initial contact time because adsorbate molecules can easily locate and occupy the vacant pores of the adsorbent. Once equilibrium is reached, excessive stirring may cause some methylene blue molecules to detach (desorption), resulting in a decrease in adsorption percentage [16]. Additionally, longer contact time with only a slight increase in adsorption efficiency can be attributed to certain adsorbent particles having smaller surface areas, which limits the number of adsorbate molecules that can be attracted and retained within their pores.

4. CONCLUSION

Based on the adsorption test results using activated carbon produced with K_2CO_3 at a methylene blue concentration of 50 ppm, the material achieved an adsorption efficiency of 99.5743% within 100 minutes of stirring. Therefore, the activated carbon derived from K_2CO_3 activation can be considered highly effective in removing methylene blue dye from solution.

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