

# THE EFFECT OF ACTIVATION TEMPERATURE ON PORE DIAMETER AND ADSORPTION CAPACITY OF ACTIVATED CARBON DERIVED FROM LIGNOCELLULOSIC BIOMASS: A REVIEW

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**Abstract:** Activated carbon derived from lignocellulosic biomass has attracted significant attention due to its potential application in wastewater treatment. This review examines the effect of activation temperature on pore structure development and methylene blue adsorption capacity of activated carbon produced from teak sawdust waste. Activation temperature plays a crucial role in determining pore size distribution, surface area, and adsorption performance. Based on previous studies, increasing activation temperature promotes the transformation of micropores into mesopores due to enhanced devolatilization and gasification reactions. This structural evolution improves the adsorption capacity for methylene blue, a large organic molecule commonly used as a model adsorbate. However, excessively high activation temperatures may lead to pore collapse and reduced adsorption efficiency. This review highlights the importance of optimizing activation temperature to achieve a balance between pore development and structural stability. The findings provide insights into the design of efficient biomass-based adsorbents for environmental applications.

**Keywords:** activated carbon, activation temperature, pore structure, methylene blue, teak sawdust, adsorption

## 1. INTRODUCTION

Industrial development has significantly increased the generation of wastewater containing hazardous pollutants, especially synthetic dyes. Among various treatment methods, adsorption using activated carbon is considered one of the most efficient and economical techniques due to its high adsorption capacity and operational simplicity (Babel & Kurniawan, 2003).

Activated carbon is widely recognized as an effective adsorbent because of its highly porous structure and large surface area. The adsorption performance of activated carbon strongly depends on its pore characteristics, including pore size distribution, pore volume, and surface functional groups (Marsh & Rodríguez-Reinoso, 2006).

Biomass-based activated carbon has become increasingly popular due to the abundance, renewability, and low cost of lignocellulosic waste materials. Among these materials, teak sawdust waste is a promising precursor because it contains high carbon and lignin contents, which are favorable for porous carbon formation.

One of the most important parameters in activated carbon production is activation temperature. Activation temperature controls devolatilization, carbon rearrangement, and gasification reactions, which directly influence pore development and adsorption behavior (Lua & Yang, 2004). Increasing activation temperature generally promotes pore widening and mesopore formation, thereby enhancing adsorption performance.

Methylene blue is commonly used as a model adsorbate for evaluating adsorption performance because of its relatively large molecular size (~1.43 nm), making it suitable for assessing mesoporous structures (Hameed et al., 2007). Therefore, understanding the relationship between activation temperature, pore diameter, and methylene blue adsorption capacity is essential for optimizing biomass-derived activated carbon.

This review aims to discuss the influence of activation temperature on pore structure evolution and methylene blue adsorption capacity of activated carbon derived from teak sawdust based on previous scientific studies.

## **2. MATERIALS AND METHODS**

### **2.1 Literature Search Strategy**

This review was conducted through a comprehensive literature study focusing on the effect of activation temperature on pore diameter and methylene blue adsorption capacity of activated carbon derived from biomass, particularly teak sawdust. Scientific articles were collected from several international databases, including Google Scholar, ScienceDirect, SpringerLink, MDPI, and Wiley Online Library.

The literature search was performed using combinations of keywords such as:

- “activated carbon”
- “activation temperature”
- “pore diameter”
- “methylene blue adsorption”
- “teak sawdust”
- “biomass-based adsorbent”

The selected references mainly consisted of peer-reviewed journal articles published between 2003 and 2025, with emphasis on recent studies from 2020 onward to ensure updated scientific perspectives.

### **2.2 Inclusion and Exclusion Criteria**

The reviewed articles were selected based on the following inclusion criteria:

1. Studies discussing activated carbon derived from biomass materials
2. Research focusing on the influence of activation temperature on pore structure
3. Studies evaluating methylene blue adsorption performance
4. Articles published in reputable international journals

Meanwhile, studies unrelated to adsorption properties, pore structure analysis, or activation processes were excluded from this review.

### **2.3 Data Analysis Method**

The collected literature was analyzed qualitatively by comparing the effects of different activation temperatures on pore development and adsorption performance. Particular attention was given to:

- Pore size distribution
- Surface area development
- Adsorption capacity trends
- Adsorption mechanisms

The findings from various studies were then synthesized to identify general trends, research gaps, and future research opportunities related to biomass-derived activated carbon.

3. RESULTS AND DISCUSSION

Table 1. Summary of Previous Studies on Activated Carbon for Methylene Blue Adsorption

No.	Raw Material / Precursor	Activation Temperature	Main Findings	Adsorption Capacity	Reference
1	Pistachio shell	600–900°C	Higher activation temperature increased pore development and mesopore formation; excessive temperature caused pore collapse	Increased significantly at optimum temperature	Lua & Yang (2004)
2	Agricultural residues	500–900°C	Activation temperature strongly influenced pore structure and surface area of activated carbon	Improved dye adsorption performance	Ioannidou & Zabaniotou (2007)
3	Palm oil waste	700°C	Mesoporous activated carbon showed better methylene blue adsorption due to improved diffusion pathways	High adsorption efficiency	Hameed et al. (2007)
4	Biomass-based activated carbon	600–800°C	Adsorption followed pseudo-second-order kinetics and Freundlich isotherm model	Effective methylene blue removal	El Jery et al. (2024)
5	Peanut shell activated carbon	700–900°C	Increased activation temperature enhanced surface area and pore volume, but excessive activation reduced stability	High dye adsorption capacity	Hashem et al. (2024)
6	Rice husk activated carbon	600–800°C	Mesopore development significantly improved adsorption performance toward dye molecules	Enhanced methylene blue adsorption	Wazir et al. (2023)
7	Banana peel activated carbon	700°C	Surface functional groups contributed to electrostatic interaction with dye molecules	Efficient dye removal performance	Ramutshatsha-Makhwedzha et al. (2024)
8	Biomass-derived activated carbon	700–800°C	Surface area exceeded 800 m <sup>2</sup> /g with well-developed mesoporous structure	>300 mg/g methylene blue adsorption	Zhang et al. (2024)
9	Modified biochar	600–850°C	Hydroxyl and carboxyl functional groups improved adsorption mechanisms through $\pi$ - $\pi$ interaction	Improved adsorption kinetics	Yu et al. (2024)
10	Various lignocellulosic wastes	500–900°C	Balanced micro–mesopore structures produced superior adsorption performance	Effective dye adsorption	Fito et al. (2023)

**Interpretation of Previous Studies**

Based on the reviewed studies, activation temperature has a significant influence on pore structure evolution and adsorption performance of activated carbon. Most studies reported that increasing activation temperature promotes the transition from micropores to mesopores, resulting in improved adsorption of methylene blue molecules.

The optimum activation temperature generally ranges between 700°C and 800°C, where balanced pore development and structural stability can be achieved. At excessively high temperatures, structural degradation and pore collapse may occur, leading to decreased adsorption performance.

In addition, several recent studies emphasized that adsorption efficiency is not only affected by pore diameter but also by surface functional groups such as hydroxyl and carboxyl groups, which enhance electrostatic and  $\pi$ - $\pi$  interactions between activated carbon and dye molecules.

The reviewed literature indicates that teak sawdust has strong potential as a precursor for activated carbon production due to its lignocellulosic composition and carbon content. However, studies specifically focusing on teak sawdust remain limited, indicating opportunities for further research.

### **3.1 Effect of Activation Temperature on Pore Development**

Based on the reviewed literature, activation temperature significantly affects the pore structure of activated carbon derived from biomass materials. Most studies reported that increasing activation temperature enhances pore development due to intensified devolatilization and gasification reactions.

At lower temperatures (500–600°C), activated carbon structures are generally dominated by micropores because thermal decomposition remains incomplete. Several studies reported relatively limited pore accessibility and lower surface area under these conditions (Lua & Yang, 2004).

As activation temperature increases to approximately 700–800°C, pore widening becomes more pronounced, resulting in the formation of mesoporous structures. Zhang et al. (2024) reported that biomass-derived activated carbon activated at higher temperatures exhibited significantly larger pore volume and improved surface area, which contributed to better adsorption performance.

However, temperatures above 900°C may cause excessive burn-off and pore wall destruction, leading to structural collapse and reduced adsorption efficiency (Ioannidou & Zabaniotou, 2007). Similar findings were also observed in recent studies involving agricultural biomass and lignocellulosic waste materials (Hashem et al., 2024).

Overall, the reviewed studies indicate that activation temperature plays a crucial role in controlling pore diameter and determining the balance between micropore and mesopore formation.

### **3.2 Effect of Activation Temperature on Methylene Blue Adsorption**

The reviewed literature consistently shows that methylene blue adsorption capacity increases with increasing activation temperature up to an optimum level. This improvement is primarily attributed to the development of mesopores and increased surface area.

Recent studies demonstrated that activated carbon prepared at optimized temperatures could achieve adsorption capacities exceeding 300 mg/g for methylene blue adsorption (Zhang et al., 2024). Enhanced adsorption performance was associated with improved pore accessibility and higher availability of active adsorption sites.

El Jery et al. (2024) reported that methylene blue adsorption generally follows pseudo-second-order kinetics and Freundlich isotherm models, indicating multilayer adsorption on heterogeneous surfaces.

In addition to pore structure, surface functional groups also contribute significantly to adsorption mechanisms. Oxygen-containing functional groups such as hydroxyl and carboxyl groups improve electrostatic interactions between activated carbon surfaces and dye molecules (Yu et al., 2024).

Nevertheless, excessively high activation temperatures may negatively affect adsorption performance due to pore collapse and reduced surface stability. Therefore, optimization of activation temperature is essential to maximize adsorption efficiency.

**MECHANISM OF METHYLENE BLUE ADSORPTION ON ACTIVATED CARBON**

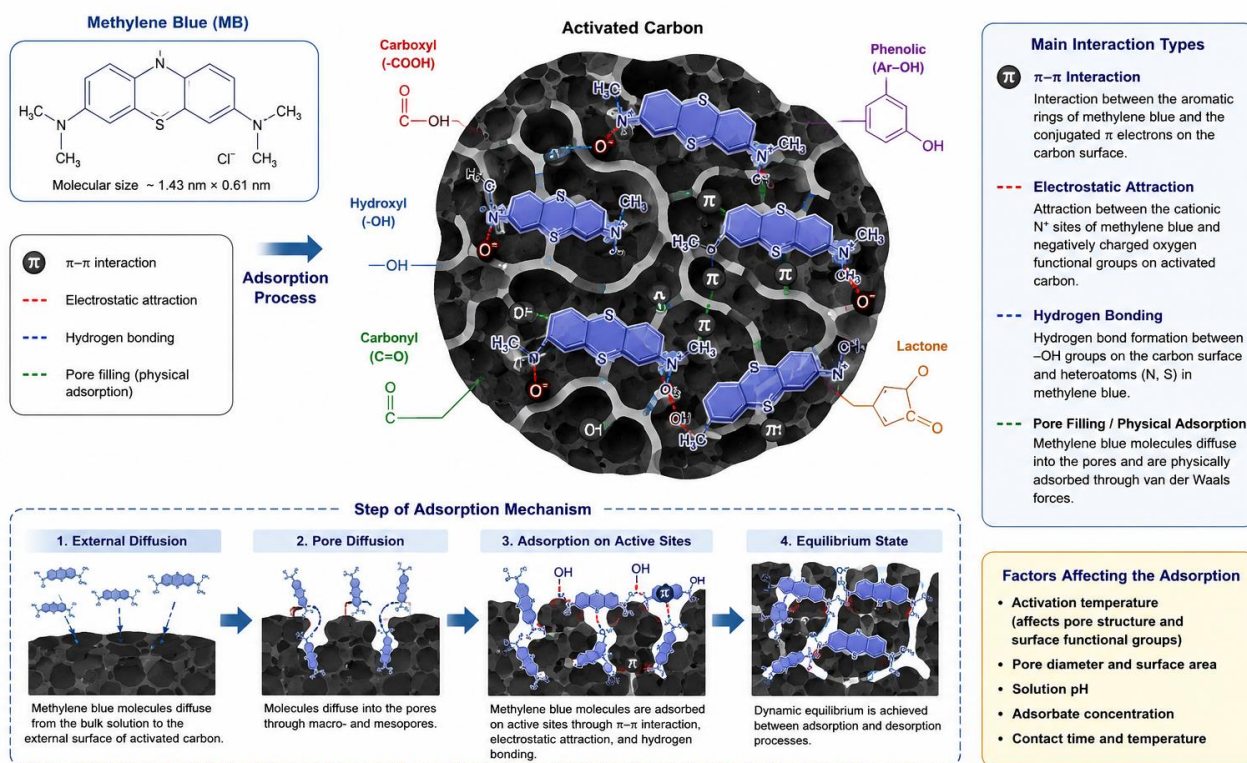


Figure 1. Proposed mechanism of methylene blue adsorption on activated carbon derived from biomass materials

**3.3 Relationship Between Pore Diameter and Adsorption Performance**

Pore diameter plays an important role in determining adsorption efficiency. Micropores mainly contribute to high surface area, whereas mesopores improve diffusion and adsorption of larger molecules such as methylene blue.

Studies showed that activated carbon containing balanced micro–mesoporous structures exhibited superior adsorption performance compared to purely microporous materials (Fito et al., 2023). Mesopores provide efficient transport pathways, enhancing adsorption kinetics and accessibility of dye molecules into the internal pore structure.

Additionally, compatibility between pore diameter and adsorbate molecular size strongly influences adsorption capacity. Since methylene blue molecules are relatively large, mesoporous activated carbon generally demonstrates better adsorption performance.

These findings suggest that controlling pore diameter through activation temperature adjustment is an effective strategy for developing high-performance biomass-based adsorbents.

**3.4 Proposed Mechanism of Methylene Blue Adsorption**

The adsorption mechanism of methylene blue onto activated carbon involves several interactions, including:

1. Physical adsorption through pore filling
2. Electrostatic attraction between dye molecules and oxygen-containing functional groups
3. Hydrogen bonding
4.  $\pi$ - $\pi$  interactions between aromatic structures of activated carbon and methylene blue molecules

Initially, methylene blue molecules diffuse from the bulk solution to the external surface of activated carbon. Subsequently, the molecules diffuse into the pore structure and occupy active adsorption sites until adsorption equilibrium is achieved.

Activation temperature significantly influences this mechanism because it determines pore accessibility, pore diameter, and surface functional groups.

## 5. RESEARCH GAP AND FUTURE PERSPECTIVES

Despite significant progress, several research gaps remain:

- Limited studies focusing specifically on teak sawdust as a precursor
- Lack of systematic optimization of activation temperature
- Limited understanding of pore evolution mechanisms at the molecular level

Recent studies suggest that combining experimental analysis with modeling approaches such as density functional theory (DFT) can provide deeper insight into adsorption mechanisms .

Future research should focus on:

- Advanced activation techniques
- Hybrid materials and nanocomposites
- Real wastewater applications
- Sustainable and scalable production methods

## 6. CONCLUSION

Activation temperature is one of the most important parameters affecting pore structure and methylene blue adsorption capacity of activated carbon derived from teak sawdust. Increasing activation temperature promotes pore development and transformation from micropores to mesopores, resulting in improved adsorption performance.

However, excessively high activation temperatures may lead to pore collapse and structural degradation, reducing adsorption efficiency. In addition to pore structure, surface functional groups also contribute significantly to adsorption mechanisms.

Overall, optimization of activation temperature is essential to achieve balanced pore development, structural stability, and high adsorption performance. Teak sawdust demonstrates strong potential as a sustainable precursor for activated carbon production in environmental remediation applications.

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