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Engineering Biomass-Based Activated Carbon through Physical and Chemical Activation: A Systematic Review on Pore Structure and Material Performance

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Abstract: Biomass-based activated carbon has attracted widespread attention as a sustainable carbon material due to its abundant availability, renewability, and engineered pore structure. The characteristics and performance of activated carbon are greatly influenced by the type of biomass and the activation strategies used during the synthesis process. This article presents a systematic literature review on the potential of biomass and various activation methods in the production of activated carbon, focusing on the development of pore structure and material performance. The review was conducted on various studies related to physical and chemical activation processes, including activation using steam, CO_2, as well as chemical activation using KOH, H_3PO_4, $ZnCl_2$, and NaOH. The results of the review indicate that the composition of biomass, particularly the content of lignin, cellulose, and hemicellulose, plays a crucial role in determining carbon yield, thermal stability, and pore evolution during the carbonization and activation processes. Physical activation generally results in stable microporous structures but requires high temperatures and relatively long processing times. In contrast, chemical activation can significantly enhance pore development and specific surface area due to the intensive interaction between the activator and the carbon matrix. Among the various activators used, KOH shows the most effective performance in producing highly developed microporous structures with high surface areas. In addition, the hierarchical pore structure consisting of micropores and mesopores significantly contributes to the adsorption capacity, ion transport, and electrochemical performance of the material. Biomass-based activated carbon shows potential for wide applications in the fields of adsorption, water treatment, energy storage, supercapacitors, and solar energy-based interfacial evaporation systems. Overall, this study emphasizes that activation strategies are the main factor determining the process-structure-property relationship of biomass-based activated carbon in the development of high-performance porous carbon materials for environmental and energy applications.

Keywords: activated carbon, biomass, chemical activation, physical activation, pore structure.

1. INTRODUCTION

Activated carbon is one of the porous carbon materials that is widely utilized due to its high surface area, engineered pore structure, good adsorption capacity, and high chemical stability in various environmental and energy applications [1]. This material has been extensively used in water treatment processes, gas adsorption, catalysis, electrochemical energy storage, and environmental remediation due to its adsorptive capabilities and superior pore characteristics [2], [3]. According to Neme et al. [4], conventional activated carbon is generally produced from coal and petroleum-based materials, which are non-renewable, thus raising concerns about the development of biomass-based activated carbon that is more sustainable and environmentally friendly.

Biomass contains lignocellulosic components such as cellulose, hemicellulose, and lignin, which serve as natural carbon sources during the carbonization and activation processes [5]. Various biomass materials such as coconut shells, rice husks, bamboo, corn cobs, wood powder, palm kernel shells, and sugarcane bagasse have been widely utilized as precursors for activated carbon due to their abundant availability, renewability, and low economic value [6], [7], [8]. Additionally, the use of biomass as a raw material for activated carbon also supports the concept of waste valorization and the circular economy in the development of sustainable materials [9], [10], [11].

The characteristics of activated carbon are greatly influenced by the activation method, carbonization temperature, type of activator, and the composition of the biomass precursor used during synthesis [5], [12], [13], [14]. In general, activated carbon can be produced thru physical activation or chemical activation [15],[16]. Physical activation is typically carried out thru a carbonization process followed by activation using steam or CO_2 at high temperatures to form and develop pore structures. Meanwhile, chemical activation uses activating agents such as KOH, H_3PO_4, $ZnCl_2$, and NaOH to enhance pore development and increase the surface area of activated carbon [17], [18], [19].

Various studies have shown that different activation methods result in different pore structure characteristics and physicochemical properties [17][20][19][21][22]. Micropore structures are known to be very effective for adsorption and gas storage applications because they provide a large surface area, while mesopores play an important role in enhancing mass transport and the electrochemical performance of the material [23][24], [25], [26]. Therefore, understanding the relationship between the type of biomass, activation strategies, pore structure evolution, and material performance becomes an important aspect in the engineering of high-performance biomass-based activated carbon [14].

Based on this, this systematic review aims to evaluate the potential of various types of biomass and activation methods in the synthesis of activated carbon. The main focus of this study is the influence of physical and chemical activation on the formation of pore structures, surface characteristics, and the functional performance of biomass-based activated carbon for environmental and energy applications.

2. MATERIALS AND METHODS

The aim of this systematic review is to evaluate the engineering of biomass-based activated carbon thru physical and chemical activation strategies. This review focuses on the development of pore structure and material performance. This study will investigate how synthesis parameters and activation strategies affect the physicochemical characteristics and functional efficacy of the produced activated carbon. The methodology used in this research is the "process-structure-property-performance" analytical framework. In its implementation, the literature reviewed is grouped into four interrelated thematic domains. It begins with an explanation of lignocellulosic materials (cellulose, hemicellulose, and lignin) in various biomass precursors and how these materials behave under heat during the carbonization phase [4], [27], [28]. Next in the analysis, a comparative evaluation of activation strategies is conducted. This distinguishes the use of physical agents such as steam and CO_2 from the use of chemical agents such as KOH, H_3PO_4, $ZnCl_2$, and NaOH to form a porous carbon framework [29]. Furthermore, a thorough study was conducted on the development of pore architecture. Special emphasis is placed on the transition of micropores and mesopores and their impact on the surface area and adsorption capacity of the material. As a final stage, this study compiles data on the functional performance of activated carbon for various strategic applications, such as water treatment, gas adsorption, and electrochemical energy storage. The aim of this research is to provide a comprehensive overview of current technological advancements and the way forward for the development of sustainable carbon materials.

3. RESULTS AND DISCUSSION

3.1 The Potential of Biomass as a Precursor for Activated Carbon

The results of the literature review indicate that biomass has great potential as a precursor for activated carbon because it contains lignocellulosic components, namely cellulose, hemicellulose, and lignin, which play a role in the formation of carbon structure during the pyrolysis and activation processes [4], [27], [28]. Each of these components has different thermal decomposition characteristics, which affect the pore development mechanism, carbon yield, and the stability of the resulting carbon structure [30], [31]. Hemicellulose generally degrades at relatively low temperatures and produces a large amount of volatile compounds. Cellulose decomposes at medium temperatures and contributes to the formation of an amorphous carbon structure. Meanwhile, lignin has a higher thermal stability compared to other components, making it important in increasing fixed carbon and maintaining the stability of the carbon framework during the activation process [5], [14].

The variation in lignocellulosic composition in each type of biomass causes the characteristics of the produced activated carbon to also differ [32]. Biomass with high lignin content, such as coconut shells and palm kernel shells, generally produces a higher carbon yield and a more dominant micropore structure due to the stability of the aromatic structure during the carbonization process [33]. Conversely, biomass rich in cellulose and hemicellulose, such as corn cobs and sugarcane bagasse, tends to experience faster pore development due to the more intensive release of volatile compounds during thermal treatment [28],[34]. This condition can increase the pore volume of the material, although in some cases it may potentially reduce the stability of the carbon structure if the activation parameters are not optimally controlled [35].

In addition to being influenced by chemical composition, the development of active carbon pores is also determined by the natural morphology of the biomass. Biomass that has vascular tissue and developed fiber structures generally forms internal diffusion pathways that facilitate the release of volatile gasses during carbonization [36]. The presence of these diffusion pathways accelerates the formation of initial pore channels, which subsequently develop into micropore and mesopore structures during the activation process [37], [38]. Therefore, the anatomical characteristics of biomass become an intrinsic factor that also determines the effectiveness of pore formation without requiring overly complex synthesis treatments [39].

The reviewed literature also shows that biomass not only serves as an alternative carbon source but also has the potential to be a sustainable material platform for the development of high-performance porous carbon [10], [40]. he utilization of biomass allows for the conversion of low-value economic waste into high-value activated carbon thru a material valorization approach [41]. From a sustainability perspective, the use of biomass offers several advantages, including the availability of abundant materials, renewable properties, relatively low production costs, and contributions to waste reduction and biomass emissions [42]. Thus, biomass is no longer viewed merely as a carbon raw material, but rather as a strategic material source in the development of functional carbon for various environmental and energy applications.

3.2 The Effect of Physical Activation on Pore Structure Evolution

Physical activation is one of the most common methods in the synthesis of biomass-based activated carbon because the process is relatively simple and does not involve the use of corrosive chemicals [34], [43]. This method generally consists of two main stages: carbonization of biomass in an inert atmosphere to produce carbon char, followed by activation using steam or CO_2 at high temperatures [39]. During the activation process, a partial gasification reaction occurs between carbon and the activating agent, leading to the opening and development of the carbon pore structure [44].

The study results indicate that different types of physical activating agents have varying effects on the pore development mechanism [45]. Activation using steam has a higher reactivity compared to CO_2, thus it can accelerate pore formation thru a more aggressive carbon oxidation reaction [46]. This condition causes the development of mesopores and an increase in pore volume to occur more significantly. However, excessively high reaction intensity also has the potential to cause excessive burn-off, resulting in pore wall damage and reduced carbon yield if the activation temperature is not optimally controlled [44].

On the other hand, activation using CO_2 proceeds more slowly due to its lower reactivity toward the carbon matrix [47]. A more controlled gasification reaction results in a more uniform and stable micropore structure [48]. This characteristic is highly advantageous for gas adsorption applications because micropores can enhance adsorbate-adsorbent interactions thru increased effective surface area [49]. However, the limitations of CO_2 reaction kinetics result in the surface area of the produced activated carbon generally being lower compared to activation using steam or chemical activation [50].

Activation temperature becomes the dominant parameter that determines the development of pore structure in physical activation [12]. The increase in temperature accelerates the carbon gasification reaction, thereby increasing the surface area and pore volume of the material. However, excessively high temperatures can cause the carbon framework to shrink and the pore structure to collapse due to excessive carbon consumption [48]. This indicates that pore development during physical activation highly depends on the balance between pore formation and the stability of the carbon structure [51].

In general, activated carbon produced thru physical activation has relatively stable pore structure characteristics with a dominance of micropores and a high level of carbon purity. In addition, this method is considered more environmentally friendly because it does not produce chemical residues post-synthesis. Nevertheless, the need for high temperatures and long activation times still pose major challenges in terms of energy efficiency and process economics [19]. Therefore, various studies have begun to develop a combination of physical and chemical activation to obtain a more optimal pore structure with lower energy consumption.

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3.3 The Effect of Chemical Activation on Surface Area and Porosity

Chemical activation is known as the most effective method for producing activated carbon with a high surface area and an extensively developed pore structure [4], [5]. Unlike physical activation, this method involves the impregnation of biomass using certain chemical agents before thermal treatment is carried out. The presence of chemical activators can accelerate dehydration, depolymerization, and pore formation during carbonization, making the development of pore structures more effective at relatively lower temperatures [52].

The study results indicate that the type of chemical activator significantly determines the textural characteristics of the produced activated carbon [53]. Activation using KOH consistently results in the highest surface area and microporosity compared to other activators [14], [16]. During the heating process, KOH undergoes a redox reaction with carbon, resulting in the formation of potassium metal, K_2CO_3, and reactive gasses that can intensely erode the carbon matrix [16]. This mechanism leads to the formation of a highly developed microporous network with a specific surface area that, in some studies, exceeds 2000 m^2/g [4]. The high development of micropores makes KOH-based activated carbon very effective for gas adsorption and energy storage applications [54].

Meanwhile, activation using H_3PO_4 shows a different mechanism as it plays a more significant role in dehydration reactions and the formation of cross-links between biomass biopolymer chains [55]. This activator is capable of maintaining the stability of the carbon framework during the carbonization process, resulting in a higher carbon yield. Additionally, H_3PO_4 and NaOH tend to produce more developed mesoporous structures, thereby enhancing the mass transport capability of the material [56]. These characteristics make H_3PO_4-based activated carbon more suitable for liquid phase adsorption applications and supercapacitor electrodes.

$ZnCl_2$ is known to work thru a catalytic mechanism that accelerates the aromatization of carbon and the removal of volatile compounds during pyrolysis [57]. This activator produces a relatively homogeneous pore structure and a high surface area. However, the use of $ZnCl_2$ is starting to be restricted because it has the potential to produce heavy metal residues that can contaminate the environment if the washing process is not carried out optimally [55].

Beside the type of activator, the impregnation ratio and activation temperature also play an important role in determining the development of the pore structure. An increase in the activator ratio generally increases the surface area and pore volume due to the increased intensity of the activation reaction [52]. However, the use of excessive amounts of activator can cause excessive erosion of the pore walls, making the carbon structure brittle and unstable. This phenomenon shows that pore formation in chemical activation is greatly influenced by the balance between the carbon etching process and the stability of the material framework. Overall, the study results indicate that chemical activation provides a much higher pore engineering capability compared to physical activation. The developed pore structure, high surface area, and the presence of active functional groups make chemically activated carbon perform better for various applications in adsorption, catalysis, and energy storage [14], [18].

The study results show that the performance of biomass-based activated carbon is greatly influenced by the type of biomass and the activation method applied during the synthesis process. The relationship between the initial characteristics of biomass, activation conditions, pore structure development, and the final properties of the material forms a process–structure–property relationship that determines the quality of the produced activated carbon. Thus, the success of activated carbon engineering is not only determined by the activation stages but also by the intrinsic characteristics of biomass as a carbon precursor. The lignocellulosic components in biomass play a crucial role in the formation of the carbon framework and pore evolution during thermal treatment. Biomass with a high lignin content generally yields a greater carbon yield and better structural stability because lignin has high thermal resistance. On the other hand, biomass rich in cellulose and hemicellulose tends to release volatile compounds more intensively, thereby accelerating pore formation, although this condition can also increase the risk of structural damage if the activation process is too strong. Therefore, the selection of biomass type needs to consider the balance between pore development and the stability of the produced material.

This study also shows that the activation method is the main factor determining the textural characteristics of activated carbon. Physical activation generally produces a relatively stable microporous structure thru a stepwise gasification process using steam or CO_2 [47]. This microporous structure greatly supports gas adsorption applications because it enhances the interaction between the adsorbent and the adsorbate. However, the physical activation method generally requires high operating temperatures and longer processing times, resulting in relatively low energy efficiency [18].

On the other hand, chemical activation shows a more effective ability to engineer pore structures because the activating agents can directly interact with the carbon matrix during heating [28]. The consistent use of KOH has been reported to produce a high surface area and a high level of microporosity due to the intensive carbon etching process [17]. However, the use of excessive amounts of activator can trigger excessive burn-off and damage the pore walls, thereby reducing the structural stability of the material. Therefore, optimizing activation parameters is an important step to achieve a balance between surface area, pore size distribution, and the stability of activated carbon. In addition to surface area, pore size distribution also determines the performance of activated carbon in specific applications. Micropores significantly contribute to the increase in adsorption capacity, while mesopores play a role in facilitating mass transport and ion diffusion. Thus, activated carbon with a hierarchical pore structure, which is a combination of micropores and mesopores, generally shows better performance compared to materials with a dominant single type of pore.

Research developments indicate that biomass-based activated carbon is no longer limited to use as a conventional adsorbent, but has evolved into a functional material for various energy and environmental applications. These materials have been utilized in pollutant adsorption processes, energy storage devices, supercapacitors, and even solar energy conversion systems. Nevertheless, issues related to high energy consumption, the use of activating chemicals, and the management of activation process waste still pose challenges in industrial-scale applications. Therefore, future research needs to focus on the development of more efficient, environmentally friendly, and sustainable activation methods. In general, this study emphasizes that activation strategies play an important role in determining the relationship between the structure and properties of biomass-based activated carbon. Precise control of synthesis parameters allows for the development of activated carbon with pore structures and surface characteristics that can be tailored for various environmental and advanced energy application needs.

4. RESEARCH GAP AND FUTURE PERSPECTIVES

Research on biomass-based activated carbon has developed rapidly, but there are still several research gaps, particularly regarding the understanding of the relationship between biomass characteristics, activation mechanisms, pore structure evolution, and comprehensive material performance. Most research still focuses on increasing surface area without comprehensively evaluating pore distribution, structural stability, and long-term material performance. In addition, the use of corrosive chemicals in chemical activation and the high energy consumption during the synthesis process remain major challenges in terms of sustainability. Therefore, future research needs to be directed toward the development of more environmentally friendly activation methods, the engineering of more controlled hierarchical pore structures, and the optimization of biomass-based activated carbon for advanced energy and environmental applications, such as supercapacitors, energy storage, and solar energy-based interfacial evaporation systems.

5. CONCLUSION

This systematic review shows that biomass has a very high potential as a precursor for activated carbon due to its high lignocellulosic content, its renewable nature, and its abundant availability. The characteristics of the produced activated carbon are greatly influenced by the biomass composition and the activation strategy used during the synthesis process. The lignin content contributes to the increase in carbon yield and thermal stability, while cellulose and hemicellulose play a role in the development of pore structure during the carbonization and activation processes. The activation method has proven to be the main factor determining the surface area, pore distribution, and performance of activated carbon material. Physical activation using steam and CO_2 produces relatively stable microporous structures, but requires high temperatures and longer processing times. In contrast, chemical activation using KOH, H_3PO_4, $ZnCl_2$, and NaOH can more intensively enhance pore development and result in higher specific surface areas. Among the various activators, KOH demonstrates the most effective ability to produce highly developed microporous structures with superior adsorption performance and electrochemical properties.

In addition to surface area, pore size distribution also plays an important role in the material's performance. Hierarchical pore structures that combine micropores and mesopores have been proven to enhance adsorption capacity, mass transport, and ion diffusion, thereby supporting the application of activated carbon in the fields of environment and energy. Based on the study results, biomass-based activated carbon has a wide range of application potentials, including pollutant adsorption, water treatment, energy storage, supercapacitors, and even solar energy conversion systems. Overall, this study emphasizes that controlling activation parameters and selecting the right biomass are fundamental aspects in the engineering of biomass-based activated carbon. This approach enables the development of porous carbon materials with customizable characteristics for various environmental and sustainable energy applications.

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