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A Review on Activated Carbon: Synthesis, Properties, and Applications

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ABSTRACT

Activated carbon (AC) is a versatile, highly porous material with a large surface area and significant adsorptive properties, making it indispensable across a wide range of industrial and environmental applications. This review paper provides a detailed exploration of activated carbon, focusing on its synthesis methods, chemical and physical properties, and extensive applications. The paper delves into the mechanisms of both physical and chemical activation, examines the properties that make activated carbon a unique material, and outlines its applications in areas like water treatment, air purification, energy storage, catalysis, and environmental remediation. The paper concludes with an analysis of the challenges facing activated carbon utilization and potential future advancements that could enhance its applications.

Keywords: Carbonization, precursor material, activation, porosity, surface area, adsorption, water treatment, and air filtration.

INTRODUCTION

Activated carbon is a form of carbon processed to create small, low-volume pores that significantly increase its surface area. This high surface area makes activated carbon an exceptionally powerful adsorbent, ideal for capturing and holding molecules from liquid and gas phases. The material is produced from a variety of carbon-rich sources, such as coal, wood, coconut shells, and agricultural residues (H Guan et al., 2013). By subjecting these materials to carbonization and activation processes, manufacturers can tailor the pore structure and surface chemistry of activated carbon to suit different industrial applications (Ogungbenro et al., 2018). The role of activated carbon in industrial and environmental sectors is well-established. It has been widely used in water purification, air filtration, and solvent recovery (Marsh & Reinoso, 2006). In recent years, the interest in activated carbon has expanded to include applications in energy storage, such as in supercapacitors and batteries, as well as in emerging environmental remediation technologies. Given the increasing importance of environmental sustainability, the demand for effective and economical materials like activated carbon has surged (Li et al., 2013; Lua & Guo, 2000). The purpose of this review is to comprehensively cover the synthesis, properties, and applications of activated carbon, providing an in-depth look at its future potential (Marsh & Reinoso, 2006).

SYNTHESIS OF ACTIVATED CARBON

Carbonaceous Precursors for Activated Carbon Production

The production of activated carbon begins with the selection of an appropriate precursor material. These carbon-rich precursors can range from conventional sources like coal and wood to more sustainable materials such as agricultural waste and biomass. For instance, oil palm stones are major solid wastes generated from palm-oil processing mills is used as raw material source for activated carbon (Lua & Guo, 2000). The choice of precursor significantly influences the properties of the final product, including its surface area, porosity, and adsorption capacity. For instance, coconut shells are known to produce activated carbon with a high surface area and microporous structure, ideal for gas-phase adsorption, while lignocellulosic materials like wood produce more mesoporous activated carbon, which is better suited for liquid-phase adsorption.

Agricultural residues such as rice husks, sugarcane bagasse, and corn stover have gained attention as sustainable and low-cost sources of activated carbon (Chen et al., 2011; Wang et al., 2014). These materials not only reduce waste but also minimize the environmental impact associated with carbon production. Despite their differences, all carbonaceous materials undergo similar thermal treatments to produce activated carbon, but the specific characteristics of the precursor material determine the ultimate properties of the activated carbon.

Carbonization Process

The carbonization process is the first step in the production of activated carbon and involves the thermal decomposition of the precursor material in an inert atmosphere, typically under nitrogen or argon. This process occurs at temperatures ranging from 400°C to 900°C, during which the volatile components of the precursor are driven off, leaving behind a carbon-rich chair. The carbonization process is crucial as it creates the initial framework for the porous structure that will later be enhanced through activation. Carbonization typically results in the formation of a material with a low surface area and limited porosity. However, by carefully controlling the temperature and time of carbonization, it is possible to influence the distribution and size of pores in the final product. For instance, higher carbonization temperatures often lead to the development of more extensive pore networks. This stage lays the groundwork for the subsequent activation process, which further refines the material's porosity and surface characteristics.

Physical Activation

Physical activation is one of the two primary methods used to transform carbonized material into activated carbon. This method involves treating the char with oxidizing gases, such as steam or carbon dioxide, at high temperatures between 800°C and 1100°C (Gale et al., 2021). The oxidizing gases react with the carbon in the chart, selectively removing atoms from the material's surface and creating a network of pores. This process not only increases the surface area of the carbon but also develops micropores that are critical for adsorption applications. The primary advantage of physical activation is that it produces a highly microporous material with a large surface area, typically ranging from 500 to 1500 m^2/g. This makes it particularly well-suited for applications where the adsorption of small molecules is required, such as in gas purification. However, the high temperatures and long processing times required for physical activation can make this method energy-intensive and expensive. Despite this, physical activation remains one of the most widely used techniques for producing activated carbon.

Chemical Activation

Chemical activation is an alternative method that involves treating the precursor material with chemical agents, such as potassium hydroxide (KOH), phosphoric acid (H_3PO_4), or zinc chloride ($ZnCl_2$), before subjecting it to carbonization (Gale et al., 2021). The chemical agent penetrates the carbonaceous material and assists in breaking down its structure during carbonization, which typically takes place at lower temperatures (400°C to 600°C) compared to physical activation. Chemical activation can produce activated carbon with both micropores and mesopores, depending on the choice of chemical agent and processing conditions. The primary advantage of chemical activation is that it can achieve higher porosity and surface area with less energy input compared to physical activation. Furthermore, it offers more control over the pore size distribution, allowing to produce mesoporous activated carbon, which is highly desirable for liquid-phase adsorption applications. However, the use of chemical agents introduces environmental concerns, particularly with the disposal of chemical waste. Recent advancements in green chemistry have focused on developing more sustainable chemical activation processes that minimize environmental impact.

Alternative Synthesis Methods

In addition to the traditional physical and chemical activation methods, alternative synthesis approaches have emerged in recent years. One such method is microwave-assisted activation, which uses microwave radiation to rapidly heat the precursor material. This method is energy-efficient and allows for greater control over the activation process, resulting in more uniform pore distribution. Another emerging technique is hydrothermal carbonization, which involves treating biomass in water at elevated temperatures and pressures to produce hydrochar. The hydrochar can then be activated to produce a highly porous carbon material. Template synthesis is another innovative approach that involves using a templating agent, such as silica, to create a highly ordered porous structure in the carbon material. After carbonization, the template is removed, leaving behind a mesoporous or microporous carbon structure. This method offers precise control over the pore size and distribution, making it ideal for applications that require highly specific adsorption properties. As sustainability becomes increasingly important, there has also been a push to use waste materials, such as food waste and industrial by-products, as precursors for activated carbon production, reducing environmental impact and providing a low-cost source of carbon.

PROPERTIES OF ACTIVATED CARBON

Pore Structure and Porosity

The effectiveness of activated carbon as an adsorbent is largely determined by its pore structure and porosity. Activated carbon is characterized by a hierarchical pore structure, which is typically classified into three categories: micropores (pore diameters less than 2 nm), mesopores (2–50 nm), and macropores (greater than 50 nm) (Gale et al., 2021). Micropores are essential for the adsorption of small molecules and gases, while mesopores provide access for larger molecules and facilitate diffusion through the carbon matrix. Macropores act as transport channels, allowing adsorbates to reach microporous regions. The pore structure of activated carbon is developed during the carbonization and activation processes and can be tailored to suit specific applications (H Guan et al., 2013). For example, activated carbon with a predominantly microporous structure is ideal for gas-phase adsorption, such as in air purification systems. In contrast, mesoporous activated carbon is better suited for liquid-phase adsorption, where larger molecules need to be adsorbed. The characterization of pore structure is typically performed using techniques such as nitrogen adsorption isotherms, which provide information on the surface area and pore size distribution of the material.

Surface Area and Adsorption Capacity

One of the defining features of activated carbon is its exceptionally high surface area, which can range from 500 to 3000 m^2/g, depending on the precursor material and activation method used. This large surface area is critical for its adsorptive capacity, as it provides more sites for molecules to adhere to. The relationship between surface area and adsorption capacity is well-established, with higher surface areas generally corresponding to greater adsorption capacities (Gale et al., 2021). However, the effectiveness of adsorption also depends on the size and distribution of the pores, as well as the chemical properties of the surface (Cao et al., 2006). In practical applications, the adsorption capacity of activated carbon is typically measured using adsorption isotherms, which describe how a particular adsorbate interacts with the surface of the carbon at constant temperature. The most common isotherm models used are the Langmuir and Freundlich isotherms, which provide insights into the maximum adsorption capacity and the nature of the adsorption process (whether it is a monolayer or multilayer adsorption). Understanding the adsorption behavior of activated carbon is essential for optimizing its performance in different applications, such as water treatment and air purification.

Surface Chemistry

In addition to its physical structure, the surface chemistry of activated carbon plays a crucial role in determining its adsorption properties. The surface of activated carbon is typically covered with various functional groups, such as hydroxyl (-OH), carboxyl (-COOH), carbonyl (C=O), and phenolic groups, which influence its interactions with different adsorbates. These functional groups can be introduced during the activation process or modified post-synthesis to enhance the material's selectivity for specific adsorbates.

For instance, activated carbon with a high concentration of acidic functional groups (such as carboxyl and hydroxyl groups) is more effective at adsorbing basic molecules, while carbon with basic surface functionalities (such as amine groups) is better suited for adsorbing acidic compounds. The surface chemistry of activated carbon can be characterized using techniques such as Boehm titration, X-ray photoelectron spectroscopy (XPS), and Fourier-transform infrared spectroscopy (FTIR). These techniques provide insights into the types and quantities of functional groups present on the surface, enabling researchers to tailor the material's properties for specific applications.

Electrical and Thermal Conductivity

In addition to its adsorptive properties, activated carbon also exhibits notable electrical and thermal conductivity, making it a valuable material for applications in energy storage and thermal management. The electrical conductivity of activated carbon is influenced by its degree of graphitization, pore structure, and surface chemistry.

Although activated carbon is not as conductive as materials like graphene or carbon nanotubes, its conductivity can be enhanced by controlling the carbonization temperature or by incorporating conductive additives.

The thermal conductivity of activated carbon is also a critical property in applications where heat dissipation is important, such as in catalysis or thermal insulation. Similar to its electrical conductivity, the thermal conductivity of activated carbon can be tailored by adjusting the carbonization process or by impregnating the material with metals or other conductive agents. The balance between adsorptive capacity and conductivity is particularly important in applications like supercapacitors, where both properties are required for optimal performance.

APPLICATIONS OF ACTIVATED CARBON

Water Treatment

One of the most well-established applications of activated carbon is in water treatment, where it is used to remove contaminants from drinking water, industrial effluents, and wastewater (Li et al., 2013). Activated carbon is highly effective at adsorbing a wide range of organic and inorganic pollutants, including heavy metals, pesticides, pharmaceuticals, and volatile organic compounds (VOCs) (Ibrahim, 2021). Its large surface area and porous structure allow for the efficient capture of contaminants, while its surface chemistry can be tailored to target specific pollutants. Granular activated carbon (GAC) and powdered activated carbon (PAC) are the two most common forms used in water treatment. GAC is typically used in fixed-bed filters, where water flows through a column of activated carbon, allowing contaminants to adsorb onto the surface. PAC, on the other hand, is added directly to the water and later removed by filtration or sedimentation. Both forms of activated carbon are widely used in municipal water treatment plants, industrial wastewater treatment facilities, and household water filters. In addition to its use in conventional water treatment systems, activated carbon is also employed in advanced treatment processes, such as adsorption-catalysis hybrid systems and membrane filtration. These advanced systems combine the adsorptive properties of activated carbon with other treatment technologies to enhance the removal of contaminants. Despite its widespread use, activated carbon-based water treatment systems face challenges related to the regeneration and disposal of spent carbon, as well as the fouling of the carbon surface by organic matter.

Air Filtration and Pollution Control

Activated carbon also plays a significant role in air filtration and pollution control. Its ability to adsorb gaseous pollutants makes it indispensable in various industries for removing volatile organic compounds (VOCs), sulfur oxides (SO_2), nitrogen oxides (NO_x), and other harmful airborne contaminants. The primary mechanism by which activated carbon functions in air filtration is adsorption, where pollutant molecules are trapped within the porous structure of the carbon. In industrial settings, activated carbon is often used to remove VOCs, which are common byproducts of manufacturing processes (Das et al., 2004). VOCs can contribute to smog formation and are hazardous to human health, so their removal is critical. Activated carbon-based air filters are typically used in both industrial and commercial environments, such as in factories, hospitals, and office buildings, where air quality is a priority. Impregnated activated carbon, which is treated with chemicals such as potassium permanganate or phosphoric acid, can further enhance the selectivity of the carbon for certain pollutants. For example, impregnated carbon is particularly effective at removing sulfur and nitrogen oxides from flue gases in power plants and other industrial facilities. The adsorption of odors and toxic gases in confined spaces is another key application, with activated carbon being a common component in gas masks, HVAC systems, and odor control systems. In addition to its conventional applications, activated carbon is also used in advanced air filtration technologies, such as catalytic air filters. These systems combine the adsorptive properties of activated carbon with catalytic materials to facilitate the oxidation or reduction of pollutants. For instance, catalytic activated carbon can be used to convert harmful gases like carbon monoxide (CO) into less harmful products, such as carbon dioxide (CO_2). The potential to integrate activated carbon into emerging air purification technologies continues to grow as the demand for clean air rises in urban and industrial areas.

Energy Storage

The use of activated carbon in energy storage devices, particularly in supercapacitors and batteries, has garnered significant attention in recent years. Supercapacitors, also known as electrochemical capacitors, are energy storage devices that store energy via the electrostatic accumulation of charge at the interface between an electrode material (such as activated carbon) and an electrolyte. The large surface area and conductivity of activated carbon make it an ideal material for supercapacitor electrodes, allowing for high energy storage capacity and fast charge-discharge cycles (Chmiola et al., 2006). Activated carbon supercapacitors are known for their high-power density and long cycle life, although they generally exhibit lower energy density compared to conventional batteries. The key to improving the performance of supercapacitors lies in optimizing the porosity and surface chemistry of the activated carbon (Li et al., 2020). By tailoring the pore size distribution, researchers can enhance the capacitance and charge storage capacity of activated carbon-based supercapacitors. Beyond supercapacitors, activated carbon is also used as an anode material in various types of batteries, including lithium-ion, sodium-ion, and zinc-air batteries. In these applications, the porosity and electrical conductivity of activated carbon enable the rapid movement of ions within the battery, contributing to improved performance. In lithium-ion batteries, for example, activated carbon can be used to create high-performance anode materials with enhanced cycling stability and capacity retention. Additionally, its ability to host various dopants and functional groups allows for the development of modified carbon materials that enhance battery efficiency. Recent advancements have explored the use of hybrid carbon materials, where activated carbon is combined with other carbon-based nanomaterials, such as graphene or carbon nanotubes, to create electrodes with superior electrochemical properties. These hybrid materials offer improved conductivity, higher surface areas, and enhanced ion transport pathways, making them promising candidates for next-generation energy storage devices.

Catalysis

Activated carbon is also widely used in catalysis, either as a catalyst or as a support material for various catalytic reactions. Its high surface area, tunable pore structure, and ability to adsorb reactants make it an effective catalyst in many chemical processes, including hydrogenation, oxidation, and dehydrogenation reactions. The versatility of activated carbon in catalysis stems from its ability to interact with a wide range of reactants and to be modified with metal or metal oxide nanoparticles, which further enhance its catalytic properties. In catalytic hydrogenation reactions, for example, activated carbon is often used as a support material for metal catalysts, such as palladium (Pd), platinum (Pt), or nickel (Ni). The porous structure of the carbon provides a high surface area for the dispersion of metal nanoparticles, improving the accessibility of active sites and enhancing reaction rates. Similarly, in oxidation reactions, activated carbon can serve as both a catalyst and an adsorbent, facilitating the removal of unwanted byproducts while promoting the desired reaction. One notable application of activated carbon in catalysis is in environmental remediation, where it is used in catalytic converters to reduce the emissions of harmful gases, such as carbon monoxide (CO), hydrocarbons, and nitrogen oxides (NO_x), from vehicle exhaust systems. By supporting catalytic metals like platinum or rhodium, activated carbon helps to convert these pollutants into less harmful substances, such as carbon dioxide (CO_2) and nitrogen (N_2). In addition to its role as a support material, activated carbon can also act as a catalyst for pollutant degradation in advanced oxidation processes (AOPs). In these processes, activated carbon is used to generate reactive species, such as hydroxyl radicals (OH•), which are highly effective at breaking down organic contaminants in water and air. The ability to modify the surface chemistry of activated carbon through oxidation or doping further enhances its catalytic performance in these applications.

Environmental Remediation

Environmental remediation is another critical area where activated carbon finds extensive application. Due to its excellent adsorptive properties, activated carbon is used to remove pollutants from soil, groundwater, and industrial effluents (Zhang et al., 2016). It is particularly effective at adsorbing organic pollutants, such as pesticides, petroleum hydrocarbons, and polycyclic aromatic hydrocarbons (PAHs), as well as inorganic contaminants like heavy metals and radioactive compounds. One of the key advantages of activated carbon in environmental remediation is its versatility. It can be used in situ (directly at the contaminated site) or ex situ (in a treatment facility) to capture pollutants from water or soil. In groundwater remediation, for example, activated carbon is often employed in permeable reactive barriers (PRBs), where it acts as a passive filter that removes contaminants as groundwater flows through the barrier. The high surface area of activated carbon allows for the efficient capture of dissolved pollutants, preventing their migration and reducing the risk of groundwater contamination. Activated carbon is also used in soil remediation to adsorb contaminants that have accumulated in the subsurface. It is highly effective at immobilizing hydrophobic organic compounds, which can persist in soil for long periods and pose significant environmental risks. By adsorbing these pollutants, activated carbon prevents their leaching into groundwater and facilitates their eventual degradation by natural processes. In addition to its use in traditional remediation techniques, activated carbon is also being integrated into emerging remediation technologies, such as bioremediation and phytoremediation. In these systems, activated carbon serves as an adsorbent and a catalyst for microbial or plant-mediated degradation of pollutants. For example, in bioremediation, activated carbon can enhance the microbial degradation of organic pollutants by providing a surface for microbial colonization and facilitating the adsorption of substrates.

CHALLENGES AND FUTURE PERSPECTIVES

Challenges in Activated Carbon Use

Despite its widespread use, the application of activated carbon is not without challenges. One of the primary concerns is the regeneration and reuse of activated carbon after it has been saturated with adsorbates. Thermal regeneration, which involves heating the spent carbon to remove adsorbed contaminants, is the most used method, but it can lead to a loss of carbon material and a reduction in adsorption capacity over time. Chemical regeneration, which uses solvents or chemical agents to desorb contaminants, is another option, but it is often associated with the generation of hazardous waste. Another challenge is the cost of producing high-quality activated carbon, particularly for applications that require materials with specific pore structures or surface chemistries. The activation process, whether physical or chemical, can be energy-intensive and expensive, and the choice of precursor materials can also impact the overall cost. While biomass-derived activated carbon offers a more sustainable and cost-effective alternative to conventional sources like coal, the variability in biomass composition can lead to inconsistencies in the properties of the final product. Environmental concerns related to the disposal of spent activated carbon are also a growing issue, particularly in applications such as water treatment and air purification, where large volumes of carbon are used. Spent activated carbon that contains hazardous contaminants must be properly disposed of or regenerated to prevent environmental harm. Additionally, the use of chemical agents in the activation process can generate toxic byproducts, which pose a risk to both human health and the environment.

Future Trends in Activated Carbon Research

Looking ahead, there are several emerging trends in activated carbon research aimed at addressing these challenges and expanding the material's applications. One of the most promising areas of research is the development of more sustainable and energy-efficient methods for producing activated carbon. Researchers are exploring alternative activation techniques, such as microwave-assisted activation and hydrothermal carbonization, which offer lower energy requirements and shorter processing times compared to traditional methods. These techniques also allow for greater control over the pore structure and surface chemistry of the final product, enabling the development of highly tailored materials for specific applications. Another area of interest is the use of novel precursor materials for activated carbon production, particularly those derived from agricultural waste and other renewable sources. By utilizing waste materials that would otherwise be discarded, researchers can reduce the environmental impact of carbon production while also lowering costs. Additionally, advances in surface functionalization techniques are enabling the development of activated carbon materials with enhanced adsorption selectivity, catalytic activity, and conductivity.

Advanced Applications

The ongoing development of activated carbon materials with improved properties is opening new possibilities in fields such as energy storage, environmental remediation, and catalysis. In energy storage, for example, the integration of activated carbon with other carbon-based materials, such as graphene and carbon nanotubes, is leading to the creation of hybrid materials with exceptional electrochemical performance. These materials are expected to play a key role in the development of next-generation supercapacitors and batteries with higher energy densities and longer cycle lives. In environmental applications, the combination of activated carbon with advanced oxidation processes (AOPs) and bioremediation techniques is likely to result in more efficient and cost-effective solutions for pollution control. For example, the use of activated carbon as a catalyst in photocatalytic or electrochemical degradation processes could enhance the removal of emerging contaminants, such as pharmaceuticals and personal care products, from water sources.

Environmental Impacts of Activated Carbon Use

The environmental footprint of activated carbon is a subject of growing concern, particularly as its use expands across various industries. While activated carbon offers significant benefits in pollution control, water treatment, and energy storage, its production and disposal raise important environmental considerations. The carbonization and activation processes used to produce activated carbon often require high energy inputs, particularly when physical activation methods are employed. The use of chemical activators, such as potassium hydroxide (KOH) and zinc chloride ($ZnCl_2$), also introduces the risk of generating hazardous byproducts that must be carefully managed. Moreover, the regeneration and disposal of spent activated carbon present additional environmental challenges. Thermal regeneration, which involves heating the spent carbon to remove adsorbed contaminants, consumes significant energy and may lead to the release of pollutants, such as volatile organic compounds (VOCs), into the atmosphere. Chemical regeneration methods, while effective in recovering the adsorptive capacity of activated carbon, can produce hazardous chemical waste that requires treatment before disposal. These environmental costs highlight the need for more sustainable approaches to both the production and regeneration of activated carbon. Efforts are being made to reduce the environmental impact of activated carbon through the development of more eco-friendly production techniques and the use of renewable precursor materials. For example, researchers are exploring the potential of agricultural byproducts, such as coconut shells, rice husks, and corn stalks, as sustainable sources of carbon for activated carbon production. These biomass-based materials not only reduce the reliance on fossil fuel-derived precursors but also provide a means of recycling waste products that would otherwise contribute to environmental pollution.

Additionally, the exploration of less energy-intensive activation methods, such as microwave-assisted activation and hydrothermal carbonization, offers promising pathways for reducing the environmental impact of activated carbon production. These methods require lower energy inputs and generate fewer harmful byproducts, making them more environmentally sustainable alternatives to traditional activation techniques.

Advanced Applications in Emerging Technologies

As research on activated carbon continues to advance, its potential applications in cutting-edge technologies are becoming more apparent. Beyond traditional uses in water and air purification, activated carbon is playing an increasingly important role in fields such as carbon capture and storage (CCS), gas separation, and medical applications.

- **Carbon Capture and Storage (CCS)**

With the growing emphasis on mitigating climate change, activated carbon is being explored for its potential in carbon capture and storage (CCS) technologies (Ogungbenro et al., 2018). CCS is a process that involves capturing carbon dioxide (CO_2) emissions from industrial sources and power plants and storing them underground to prevent their release into the atmosphere. Activated carbon's high surface area and tunable pore structure make it an attractive material for capturing CO_2 from flue gases. By tailoring the pore size distribution and surface chemistry of activated carbon, researchers have been able to enhance its selectivity for CO_2 over other gases, such as nitrogen (N_2) and oxygen (O_2). In addition to its use in post-combustion CO_2 capture, activated carbon is being investigated for its potential in direct air capture (DAC) technologies, which involve removing CO_2 directly from the atmosphere. DAC systems face significant challenges related to the low concentration of CO_2 in ambient air but activated carbon materials with high adsorption capacities and fast kinetics offer promising solutions for improving the efficiency of these systems.

- **Gas Separation**

Another emerging application of activated carbon is in gas separation technologies, where it is used to selectively adsorb certain gases from gas mixtures. This application is particularly important in industries such as natural gas processing, hydrogen production, and air separation. Activated carbon's tunable pore structure and surface functionalization allow for the selective adsorption of gases based on their size, shape, and polarity.

For example, in natural gas processing, activated carbon is used to remove impurities such as sulfur compounds and carbon dioxide from raw natural gas, improving its quality and reducing the risk of corrosion in pipelines. Similarly, in hydrogen production, activated carbon can be used to separate hydrogen from other gases, such as methane or carbon monoxide, through pressure swing adsorption (PSA) or temperature swing adsorption (TSA) processes. The development of advanced carbon materials, such as metal-organic framework (MOF)-modified activated carbon, has further enhanced the performance of activated carbon in gas separation applications. These hybrid materials combine the high surface area and stability of activated carbon with the tunable pore structures of MOFs, resulting in materials with improved selectivity and adsorption capacity for target gases.

- **Medical and Biomedical Applications**

Activated carbon's biocompatibility, high surface area, and adsorption capacity make it an ideal material for a range of medical and biomedical applications. One of the most well-known medical uses of activated carbon is in the treatment of poisoning and drug overdoses, where it is administered orally to adsorb toxic substances from the gastrointestinal tract, preventing their absorption into the bloodstream. The large surface area of activated carbon allows it to effectively bind a wide variety of toxins, making it a valuable tool in emergency medicine. In addition to its use in toxin adsorption, activated carbon is also being explored for applications in drug delivery, wound care, and medical device coatings. In drug delivery, activated carbon can be used as a carrier for drugs, allowing for controlled release and targeted delivery to specific tissues or organs. Its porous structure can be loaded with drug molecules, which are then released in response to environmental triggers, such as pH changes or the presence of specific enzymes. Activated carbon is also being incorporated into wound dressings due to its ability to adsorb harmful bacteria, toxins, and odor-causing compounds. These activated carbon-based dressings not only promote healing by keeping the wound environment clean but also reduce the risk of infection by adsorbing bacterial toxins.

In medical devices, activated carbon is used as a coating material to improve the biocompatibility and functionality of implants, catheters, and other devices. Its ability to adsorb proteins and other biomolecules can reduce the risk of biofouling, while its high surface area provides a platform for the attachment of bioactive molecules, such as growth factors or antimicrobial agents.

Future Research Directions

The future of activated carbon research is characterized by ongoing efforts to develop materials with enhanced properties and broaden their applications in new and emerging technologies. Several key research directions are expected to drive the development of next-generation activated carbon materials:

- **Nanostructured and Hierarchically Porous Carbon Materials**

One promising area of research involves the development of nanostructured and hierarchically porous carbon materials. By controlling the arrangement of pores at multiple length scales, researchers can design activated carbon materials with optimized adsorption kinetics, improved mass transport, and enhanced selectivity for specific adsorbates. These materials are particularly valuable in applications such as gas separation, energy storage, and catalysis, where the ability to rapidly adsorb and desorb molecules is critical. Nanostructured activated carbons are also being explored for their potential in electrochemical applications, such as supercapacitors and batteries (Hu et al., 2021). By incorporating nanostructured carbon materials, such as carbon nanofibers or graphene, into activated carbon, researchers can enhance the conductivity and mechanical strength of the material, leading to improved performance in energy storage devices.

- **Functionalization and Doping**

Surface functionalization and doping represent another important research direction in the development of advanced activated carbon materials. By introducing heteroatoms, such as nitrogen, sulfur, or phosphorus, into the carbon framework, researchers can modify the surface chemistry of activated carbon, enhancing its adsorption capacity and selectivity for specific molecules. Nitrogen-doped activated carbon, for example, has been shown to exhibit improved adsorption of CO_2 and enhanced catalytic activity in oxygen reduction reactions (ORR), making it a promising material for carbon capture and fuel cell applications. In addition to heteroatom doping, the incorporation of metal or metal oxide nanoparticles into activated carbon can create composite materials with enhanced catalytic properties. These materials are being investigated for use in environmental catalysis, such as the degradation of organic pollutants in water or the reduction of nitrogen oxides in flue gases.

- **Sustainable and Green Synthesis Methods**

As environmental concerns continue to shape research priorities, the development of sustainable and green synthesis methods for activated carbon is gaining momentum. Researchers are exploring the use of alternative activation techniques, such as microwave-assisted activation and hydrothermal carbonization, which offer energy-efficient alternatives to traditional thermal and chemical activation methods. These techniques not only reduce the environmental impact of carbon production but also provide greater control over the pore structure and surface chemistry of the final product. Furthermore, the use of renewable and waste-derived precursor materials, such as agricultural residues, food waste, and algae, is being investigated as a means of reducing the reliance on fossil fuel-based carbon sources. These biomass-derived activated carbons offer a more sustainable and cost-effective alternative to traditional activated carbon materials while also contributing to the circular economy by recycling waste products (H Guan et al., 2013).

- **Integration with Advanced Technologies**

The integration of activated carbon with advanced technologies, such as nanotechnology, biotechnology, and artificial intelligence (AI), is expected to drive the development of next-generation materials with unprecedented performance characteristics. For example, the combination of activated carbon with nanoscale materials, such as carbon nanotubes or metal-organic frameworks (MOFs), is leading to the creation of hybrid materials with enhanced adsorption capacity, selectivity, and catalytic activity. In addition, advances in biotechnology are enabling the development of bio-inspired activated carbon materials, such as those derived from natural polymers or produced using microbial processes. These bio-based carbons offer the potential for enhanced biocompatibility, biodegradability, and functionality in medical and environmental applications.

CONCLUSIONS

Activated carbon remains a versatile and essential material with a wide range of applications, from water and air purification to energy storage and catalysis. Its unique properties, including high surface area, tunable porosity, and chemical stability, make it a critical component in many industrial processes and emerging technologies. However, the environmental challenges associated with its production and regeneration, as well as the need for more sustainable synthesis methods, highlight the importance of continued research in this field. Looking to the future, the development of nanostructured and functionalized carbon materials, along with the exploration of renewable precursor sources and green activation techniques, will play a key role in advancing the capabilities of activated carbon. As new applications emerge, particularly in fields such as carbon capture, gas separation, and medical technologies, activated carbon is poised to remain a cornerstone of material science and environmental engineering for years to come.

REFERENCES

[1]. Cao, Q., Xie, K. C., Lv, Y. K., & Bao, W. R. (2006). Process effects on activated carbon with large specific surface area from corn cob. Bioresource Technology, 97(1), 110–115. https://doi.org/10.1016/j.biortech.2005.02.026

[2]. Chen, X., Chen, G., Chen, L., Chen, Y., Lehmann, J., McBride, M. B., & Hay, A. G. (2011). Adsorption of copper and zinc by biochars produced from pyrolysis of hardwood and corn straw in aqueous solution. Bioresource Technology, 102(19), 8877–8884. https://doi.org/10.1016/j.biortech.2011.06.078

[3]. Chmiola, J., Yushin, G., Gogotsi, Y., Portet, C., Simon, P., & Taberna, P.-L. (2006). Anomalous increase in carbon capacitance at pore sizes less than 1 nanometer. Science, 313(5794), 1760–1763.

[4]. Das, D., Gaur, V., & Verma, N. (2004). Removal of volatile organic compound by activated carbon fiber. Carbon, 42(14), 2949–2962. https://doi.org/10.1016/J.CARBON.2004.07.008

[5]. Gale, M., Nguyen, T., Moreno, M., & Gilliard-Abdulaziz, K. L. (2021). Physiochemical Properties of Biochar and Activated Carbon from Biomass Residue: Influence of Process Conditions to Adsorbent Properties. ACS Omega, 6(15), 10224–10233. https://doi.org/10.1021/acsomega.1c00530

[6]. H Guan, B. T., Abdul Latif, P., H Yap, T. Y., & Author, C. (2013). PHYSICAL PREPARATION OF ACTIVATED CARBON FROM SUGARCANE BAGASSE AND CORN HUSK AND ITS PHYSICAL AND CHEMICAL CHARACTERISTICS. In Int. J. Engg. Res. & Sci. & Tech. http://www.ijerst.com/currentissue.php

[7]. Hu, W., Xiang, R., Lin, J., Cheng, Y., & Lu, C. (2021). Lignocellulosic biomass-derived carbon electrodes for flexible supercapacitors: An overview. In Materials (Vol. 14, Issue 16). MDPI AG. https://doi.org/10.3390/ma14164571

[8]. Ibrahim, B. M. (n.d.). Heavy metal ions removal from wastewater using various low-cost agricultural wastes as adsorbents: a survey. https://doi.org/10.21271/zjpas

[9]. Li, Y., Du, Q., Liu, T., Peng, X., Wang, J., Sun, J., Wang, Y., Wu, S., Wang, Z., & Xia, Y. (2013). Comparative study of methylene blue dye adsorption onto activated carbon, graphene oxide, and carbon nanotubes. Chemical Engineering Research and Design, 91(2), 361–368.

[10]. Li, Y., Zhang, D., Zhang, Y., He, J., Wang, Y., Wang, K., Xu, Y., Li, H., & Wang, Y. (2020). Biomass-derived microporous carbon with large micropore size for high-performance supercapacitors. Journal of Power Sources, 448. https://doi.org/10.1016/j.jpowsour.2019.227396

[11]. Lua, A. C., & Guo, J. (2000). Activated carbon prepared from oil palm stone by one-step CO2 activation for gaseous pollutant removal. Carbon, 38(7), 1089–1097.

[12]. Marsh, H., & Reinoso, F. R. (2006). Activated carbon. Elsevier.

[13]. Ogungbenro, A. E., Quang, D. V., Al-Ali, K. A., Vega, L. F., & Abu-Zahra, M. R. M. (2018). Physical synthesis and characterization of activated carbon from date seeds for CO2 capture. Journal of Environmental Chemical Engineering, 6(4), 4245–4252. https://doi.org/10.1016/J.JECE.2018.06.030

[14]. Wang, Z., Wu, J., He, T., & Wu, J. (2014). Corn stalks char from fast pyrolysis as precursor material for preparation of activated carbon in fluidized bed reactor. Bioresource Technology, 167, 551–554. https://doi.org/10.1016/j.biortech.2014.05.123

[15]. Zhang, X., Guo, W., Ngo, H. H., Wen, H., Li, N., & Wu, W. (2016). Performance evaluation of powdered activated carbon for removing 28 types of antibiotics from water. Journal of Environmental Management, 172, 193–200. https://doi.org/10.1016/J.JENVMAN.2016.02.038