Activated Carbon: A Comprehensive Research Review

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Abstract

Activated carbon (AC) is a carbon-rich material characterized by a high surface area, porosity, and outstanding adsorption capabilities. Its versatile structure and surface chemistry make it a preferred material in environmental, industrial, and medical applications. This review explores the origin, synthesis methods, structural properties, characterization techniques, and diverse applications of activated carbon. Emerging trends and future prospects, especially in energy storage and nanotechnology, are also discussed.

1. Introduction

Activated carbon (AC) is a highly porous form of carbon with an extensive surface area and variable surface chemistry, making it one of the most widely used adsorbent materials in industrial and environmental processes. The exceptional adsorption properties of activated carbon arise from its micro- and mesoporous structure, high surface area (typically ranging from 500 to 3000 m^2/g), and the presence of a variety of surface functional groups (Bansal & Goyal, 2005). These characteristics allow activated carbon to effectively trap gases, vapors, and dissolved substances, making it indispensable in applications such as water purification, air filtration, chemical recovery, food processing, and energy storage.

Historically, the use of carbon-based materials for purification purposes can be traced back to ancient civilizations. However, scientific interest in activated carbon intensified during the 20th century, driven by industrial demands for efficient adsorbents (Marsh & Rodríguez-Reinoso, 2006). Today, the growing emphasis on environmental sustainability, circular economy models, and waste-to-resource technologies has expanded the interest in producing activated carbon from low-cost, renewable, and waste-derived biomass sources such as coconut shells, agricultural residues, fruit peels, and sewage sludge (Ioannidou & Zabaniotou, 2007).

The production process of activated carbon involves two major steps: carbonization and activation. Carbonization removes volatile matter from the precursor, resulting in a char, while the activation step (either physical or chemical) develops porosity and enhances surface area. Chemical activation, typically using agents such as KOH, $ZnCl_2$, or H_3PO_4, occurs at lower temperatures and often produces higher surface area materials compared to physical activation, which relies on steam or CO_2 at elevated temperatures (Ahmadpour & Do, 1996; Lua & Yang, 2004).

With recent technological advances, activated carbon is now being engineered at the nanoscale and integrated into composite materials for high-performance applications in catalysis, energy storage (e.g., supercapacitors, batteries), and biomedical devices. Its role as a functional material continues to evolve alongside developments in materials science, nanotechnology, and environmental engineering (Chen et al., 2017; Thines et al., 2017).

This review presents a comprehensive overview of the sources, synthesis strategies, structural characteristics, and diverse applications of activated carbon. It also highlights recent innovations and future prospects in the field, offering insights for researchers, industries, and environmental policymakers.

2. Sources and Precursors

The selection of a precursor material plays a crucial role in determining the surface area, pore structure, surface functionality, and overall adsorption performance of activated carbon. Almost any carbon-rich organic material can be used as a precursor for activated carbon, with the choice depending on factors such as availability, cost, carbon content, and environmental impact.

2.1 Conventional Precursors

Traditionally, activated carbon has been derived from **non-renewable sources** such as coal (bituminous, anthracite, and lignite), petroleum pitch, and peat. These materials are known for producing activated carbon with well-developed microporosity and mechanical strength (Bansal & Goyal, 2005). However, concerns about environmental sustainability and resource depletion have led to a gradual shift towards alternative sources.

2.2 Biomass-Derived Precursors

In recent decades, **biomass-based materials** have become prominent precursors due to their low cost, renewability, biodegradability, and widespread availability. These include:

- **Agricultural wastes**: Coconut shells, walnut shells, corn cobs, rice husks, sugarcane bagasse, sawdust, and palm kernel shells are frequently used to prepare activated carbon due to their high carbon and low ash content (Ioannidou & Zabaniotou, 2007).
- **Fruit peels and food wastes**: Orange peels, banana peels, mango seeds, and spent coffee grounds have been investigated as emerging low-cost carbon sources (Sudaryanto et al., 2006).
- **Industrial wastes and sludges**: Waste tires, sewage sludge, paper mill sludge, and brewery waste are also being explored for carbon activation, often in the context of circular economy and waste valorization strategies (Jain et al., 2016).

These biomass precursors typically contain lignin, cellulose, and hemicellulose—organic polymers that decompose upon heating to form a stable carbon matrix ideal for activation (Guo & Lua, 2000).

2.3 Criteria for Precursor Selection

The choice of precursor significantly affects the yield, pore size distribution, adsorption performance, and chemical reactivity of the final activated carbon product. The ideal precursor should have:

- High fixed carbon content,
- Low inorganic (ash) content,
- Adequate volatile matter,
- Good mechanical strength,

- Low cost and widespread availability.

Biomass materials, particularly those classified as **waste**, meet these criteria well, making them highly attractive for sustainable activated carbon production (Ioannidou & Zabaniotou, 2007).

2.4 Environmental and Economic Considerations

From an environmental perspective, using waste biomass helps in waste management and reduces the reliance on fossil-based feedstocks. Economically, biomass-derived ACs offer cost advantages due to minimal or zero raw material cost, especially when the feedstock is a by-product or waste material. Moreover, the carbon footprint of biomass-derived activated carbon is typically lower, aligning with global goals of carbon neutrality and green chemistry (Thines et al., 2017).

3. Synthesis Methods

There are two main activation processes: **physical** and **chemical**.

3.1 Physical Activation

Involves carbonization at temperatures around 600–900°C followed by activation using steam or CO_2. This method is environmentally safer but may yield a lower surface area (Lua & Yang, 2004).

3.2 Chemical Activation

Involves impregnation of precursors with chemicals like phosphoric acid (H_3PO_4), potassium hydroxide (KOH), or zinc chloride ($ZnCl_2$) followed by heat treatment. It generally produces activated carbon with higher porosity and better adsorption capacity (Ahmadpour & Do, 1996).

4. Characterization of Activated Carbon

To evaluate the performance and application potential, AC is characterized using various techniques:

- **BET Surface Area Analysis** – to determine the surface area (Sing et al., 1985).
- **Scanning Electron Microscopy (SEM)** – for surface morphology.
- **Fourier Transform Infrared Spectroscopy (FTIR)** – to identify surface functional groups (Marsh & Rodríguez-Reinoso, 2006).
- **X-ray Diffraction (XRD)** – to examine crystallinity.
- **Thermogravimetric Analysis (TGA)** – to assess thermal stability.

5. Properties

Activated carbon exhibits:

- High surface area (500–3000 m^2/g),
- Micro to mesoporous structure,
- Surface chemistry rich in oxygen-containing functional groups,
- Chemical stability and thermal resistance.

These properties make AC highly suitable for adsorption, catalysis, and energy storage (Guo & Lua, 2000).

6. Applications

6.1 Environmental Applications

AC is widely used in air and water purification due to its high adsorption capacity. It effectively removes pollutants like heavy metals, dyes, and pesticides (Ali et al., 2012). In wastewater treatment, AC is used for removing organic contaminants like phenol and COD.

6.2 Energy Storage

AC-based electrodes are integral in supercapacitors due to their high electrical conductivity, porosity, and stability (Zhao et al., 2010). Activated carbon is also used in lithium-ion batteries and fuel cells.

6.3 Medical Applications

In pharmaceuticals, AC is used for drug delivery, toxin removal (as in activated charcoal), and as a component in wound dressings (Jain et al., 2016).

6.4 Industrial Uses

Industries use AC in deodorization, gas storage, catalysis, and solvent recovery (Babel & Kurniawan, 2003).

7. Recent Advances

- **Nanostructured Activated Carbon**: Improved with higher surface areas and tailored pore distribution.
- **Functionalized AC**: Surface modification with chemical or biological agents to enhance selectivity (Thines et al., 2017).
- **Hybrid Composites**: AC combined with graphene, metal oxides, or polymers for energy and environmental applications (Chen et al., 2017).

8. Challenges and Future Prospects

Despite its versatility, activated carbon faces challenges such as regeneration difficulty, cost of activation, and environmental concerns during chemical activation. Future research is directed towards green synthesis, regeneration techniques, and integration with emerging nanomaterials.

9. Conclusion

Activated carbon remains a cornerstone material due to its remarkable adsorption properties and wide-ranging applications. Innovations in synthesis, functionalization, and hybridization continue to expand its potential in high-value applications such as energy storage and environmental remediation. Sustainable, cost-effective production from waste biomass will further enhance its relevance in the coming decades.

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