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Activated Carbon For Cleaner Air, Water, And A Healthier Planet

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Abstract: Activated carbon (AC) is a highly porous and efficient adsorbent that offers significant potential in addressing the environmental pressures posed by desertification and climate change. Produced from renewable plant biomass and other natural sources through carbonization and activation, AC possesses a large surface area (500–3000 m^2/g) and high adsorption capacity, enabling the effective removal of contaminants such as heavy metals, dyes, pesticides, and volatile organic compounds. By improving water quality, purifying air, and supporting sustainable industrial processes, AC contributes to resource conservation in regions vulnerable to land degradation and water scarcity. Its availability in granular, powdered, and fibrous forms allows for tailored applications in environmental remediation, food and pharmaceutical industries, and energy storage technologies. As a sustainable, cost-effective, and regenerable material, activated carbon plays a vital role in developing adaptive solutions for mitigating the impacts of desertification and climate change.

Key words: Activated carbon, plant biomass, adsorption, sustainable, climate change.

1. **Introduction**: Activated carbon, also referred to as activated charcoal, is an amorphous carbonaceous material with a highly crystalline form and is characterized by a large internal surface area and high porosity. It is primarily derived from plant-based sources and other organic matter [1]. Common raw materials for its production include biomass such as bamboo, coconut husks, wood, coir, willow peat, and lignocellulosic materials, including agricultural residues and natural fibers.

Its high surface area allows it to adsorb impurities from water and gas, leading to its use in water filter candles and gas masks [2, 3]. The highly porous structure of activated carbon makes it effective for filtration and decontamination by removing contaminants from water, air, and industrial waste [4]. Its high adsorption capacity plays a crucial role in eliminating toxins and pollutants, making it valuable for wastewater treatment,

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air filters, and pharmaceutical applications [5]. The chemical reactivity of AC supports catalytic reactions in industries and assists in the removal of unwanted chemicals [6]. Its electrical conductivity makes it useful for energy storage applications, including supercapacitors and battery electrodes [7]. The high thermal stability of activated carbon allows its use in industrial applications that require heat resistance [8]. Its biocompatibility makes it suitable for medical applications such as drug delivery, poisoning treatment, and wound care [9]. The combination of high surface area and porous structure makes activated carbon valuable in water and air purification, metal recovery, solvent and sewage treatment, energy storage, food processing, cosmetology, automotive applications, teeth whitening, hydrogen chloride production, and medical treatments like hemoperfusion [10].

2. Preparation of activated carbon (AC):

Any material with a low inorganic content and high carbon content can be utilized for AC preparation. Activated carbon can be produced from both plant-based sources, such as coconut shells, wood, and agricultural waste, and animal-based sources, like bone char and blood carbon. While plant-derived activated carbon is widely preferred for its high porosity and renewability, animal-based carbon, particularly bone char, is effective in specific applications like decolorization and heavy metal removal.

Lignocellulosic biomass from agricultural by-products is a low-cost and abundant material for producing AC. It consists of cellulose, hemicellulose, and lignin, with lignin being the primary component responsible for adsorption [11]. As the second most abundant renewable carbon resource after cellulose, lignin accounts for a global production of 50–70 million tons annually [12]. Its high carbon content makes lignocellulosic biomass an ideal precursor for activated carbon. Various sources, such as durian shell, coconut shell, rubber seed shell, hazelnut shell, palm kernel shell, almond shell, plum stones, cotton stalks, rice husk, pistachio shell, walnut shell, and wood, have been widely utilized for this purpose [13].

The synthesis of activated carbon from lignocellulosic biomass or animal waste involves a two-step process: carbonization and activation [14, 15]. In the first phase, carbonization is carried out at 700–800 K (427–527°C) in an oxygen-free environment to eliminate volatile compounds, leaving behind a carbon-rich char. The second phase, activation, occurs at 1100–1300 K (827–1027°C) to enhance the material's porosity and surface area, significantly improving its adsorption capacity. Activation can be achieved through three main methods: chemical activation, where chemical agents such as KOH, H_3PO_4, or $ZnCl_2$ are used; physical (thermal) activation, which involves gases like CO_2, air, or steam; or a combination of both methods [16]. While physical activation is more cost-effective and environmentally friendly, chemical activation is often preferred due to its superior ability to enhance porosity [17,18].

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3. Properties and characteristics:

1. Physical Properties :

a) High Surface Area: Ranges from 500 to 3000 m^2/g, enhancing adsorption capacity.
b) Porous Structure: Contains micropores, mesopores, and macropores for efficient contaminant removal.
c) Low Density: Typically light-weight due to its porous nature.
d) Black, Odorless, and Tasteless: Appears as a fine black powder or granules.
e) Thermal Stability: Can withstand high temperatures without decomposition.

2. Chemical Properties:

a) Chemical Stability: Resistant to acids, bases, and oxidation under normal conditions.
b) pH-Dependent Behavior: Can be slightly acidic, neutral, or alkaline, affecting adsorption efficiency.
c) Ion Exchange Capacity: Capable of adsorbing both organic and inorganic pollutants.
d) Electrically Conductive: Has moderate conductivity due to its carbon structure.

3. Adsorption Properties:

a) High Adsorption Capacity: Effectively removes organic compounds, heavy metals, and gases.
b) Hydrophobic and Hydrophilic Adsorption: Can attract both polar and non-polar substances.
c) Fast Kinetics: Quickly adsorbs contaminants due to its extensive pore structure.

4. Regeneration and Reusability:

a) Can Be Regenerated: Restored using thermal, chemical, or steam activation.
b) Sustainable and Renewable: Plant-based sources make it eco-friendly and widely used in water and air purification.

3. Mechanism of sorption:

Sorption refers to the interaction of substances with solids and liquids. It includes adsorption, where molecules accumulate on a material's surface, and absorption, where substances penetrate into the bulk of the material. Activated carbon (AC) effectively removes heavy metals (Pb^{2+}, Cd^{2+}, Ni^{2+}, Cu^{2+}, Cr^{6+}), metalloids, organic pollutants, and dyes through mechanisms like electrostatic attraction, ion exchange, surface complexation, pore filling, hydrophobic interaction, π-π interactions, and partitioning [19]. Its high surface area, porous structure, and functional groups enhance contaminant binding, making AC a cost-effective and efficient adsorbent for water purification.

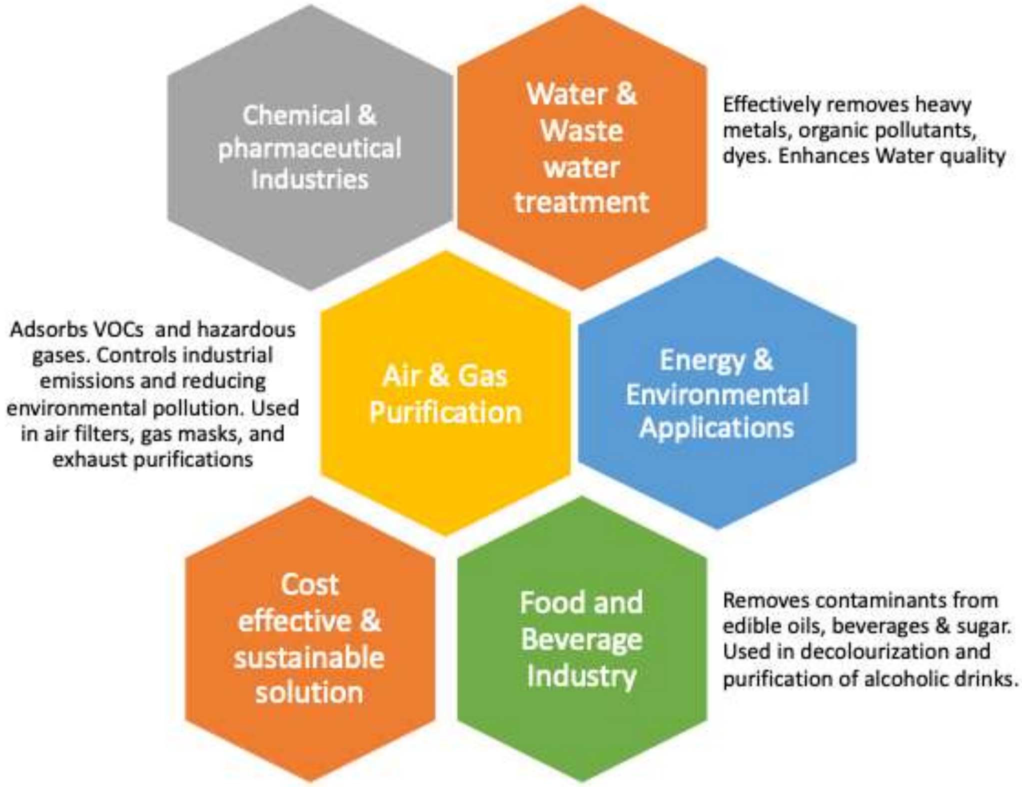
Electrostatic interaction plays a crucial role in pollutant removal by attracting charged organic pollutants and other species to oppositely charged functional groups on the adsorbent surface. This process is highly pH-dependent, as pH variations influence both the adsorbent's surface charge and the pollutant's ionization state, thereby affecting adsorption efficiency [20].

The removal of organic pollutants through π-π interactions occurs via non-covalent π-stacking between the π-electron systems of aromatic or conjugated pollutants and the surface of adsorbents like activated carbon, enabling efficient adsorption [21]. Pore filling is a key adsorption mechanism in activated carbon

(AC), where organic pollutants are physically adsorbed into its porous network through intermolecular forces like Van der Waals and capillary forces. The diverse pore structure of AC, including micropores (<2 nm) and mesopores (2–50 nm), along with surface functional groups, enhances pollutant retention, making it an efficient adsorbent for organic contaminant removal [22]. Hydrophobic interaction is a key mechanism for removing non-polar organic pollutants, where hydrophobic contaminants preferentially adsorb onto the non-polar sites of activated carbon. Higher pyrolysis temperatures enhance AC's hydrophobicity by reducing polar functional groups, allowing hydrophobic pollutants to aggregate on its surface due to thermodynamically driven hydrophobic effects in aqueous environments [23]. Pollutant removal by adsorption typically involves multiple mechanisms, influenced by activated carbon properties, functional groups, pyrolysis temperature, and pollutant nature.

4. Industrial applications of Activated Carbon:

Activated carbon (AC) is extensively used across industries for its high adsorption capacity, large surface area, and versatility. The key benefits are highlighted in this figure. It plays a crucial role in various industrial processes [24,25,26], promoting efficiency [27], renewable energy conversion & storage systems [28], sustainability, and environmental protection [29].



Water treatment: Activated carbon is widely used in water treatment across municipal, industrial, and residential sectors. In municipal treatment, it removes organic compounds, chlorine, disinfection byproducts, and micropollutants to improve water quality. Industrial applications include wastewater treatment, heavy metal adsorption, and removal of dyes, oils, and pharmaceuticals. In residential use, activated carbon is a key component in water filters, eliminating chlorine, odors, volatile organic compounds (VOCs), and contaminants like pesticides. It also enhances reverse osmosis systems by preventing membrane fouling. Due to its high adsorption capacity, activated carbon is essential for ensuring safe, clean water in various water

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treatment applications. Adsorption capacity of activated carbon derived form various animal and plant biomass are tabulated below:

AC Source (adsorbent)	Adsorbate	Adsorption capacity (mg/g)	Ref.
Pulp mill sludge and rice straw	Pb^{2+}	256.4	30
Citrus limetta peel	Cr^{3+}	174.98	31
Coconut shell charcoal	Methylene blue	166.7	32
Prickly pear seed cake	Methylene blue	260	33
Sunflower piths	Methylene blue	965	34
Olive stones	Cd^{2+}	148.8	35
Date pit carbon	Brilliant green dye	77.8	36
Sugarcane bagasse	Sodium diclofenac	315	37
Date press cake	Cr^{6+}	282.8	38
Rice husk	Hg^{2+}	768.9	39

Air purification: Activated carbon is widely used in air purification due to its high adsorption capacity for gases, odors, and volatile organic compounds (VOCs). It removes pollutants such as benzene, formaldehyde, and ammonia in industrial exhaust treatment [40]. In residential settings, it is used in air purifiers to eliminate smoke, pet odors, and chemical fumes [41]. Hospitals and laboratories use activated carbon to control airborne contaminants and toxic gases. It is also essential in gas masks and respirators for adsorbing harmful pollutants [42]. Due to its effectiveness, activated carbon plays a crucial role in improving indoor and outdoor air quality across various applications.

Food & Beverage Industry: Activated carbon is widely used in the food and beverage industry for purification and decolorization. It removes impurities, odors, and unwanted colors from products like sugar, syrups, and fruit juices [43]. In beverage production, it eliminates contaminants, off-flavors, and excess chlorine from water used in brewing and soft drinks [44]. It is essential in edible oil refining to remove toxins and improve clarity. Activated carbon also plays a role in wine and liquor filtration by eliminating undesirable compounds while preserving taste. Its ability to adsorb contaminants ensures product safety, consistency, and enhanced quality in modern food and beverage processing.

Medicals and Pharmaceuticals: Activated carbon is widely used in the medical and pharmaceutical fields for its adsorption properties. It is a key ingredient in activated charcoal tablets used to treat poisoning and drug overdoses by preventing toxin absorption in the digestive tract [45]. In pharmaceutical manufacturing, activated carbon helps purify drugs by removing impurities, residual solvents, and organic contaminants [46]. It is also used in hemoperfusion for blood detoxification in cases of severe poisoning. Additionally, activated carbon is utilized in wound dressings to absorb toxins and odors, aiding in infection control. Its effectiveness in toxin removal makes it essential for medical treatments and drug purification.

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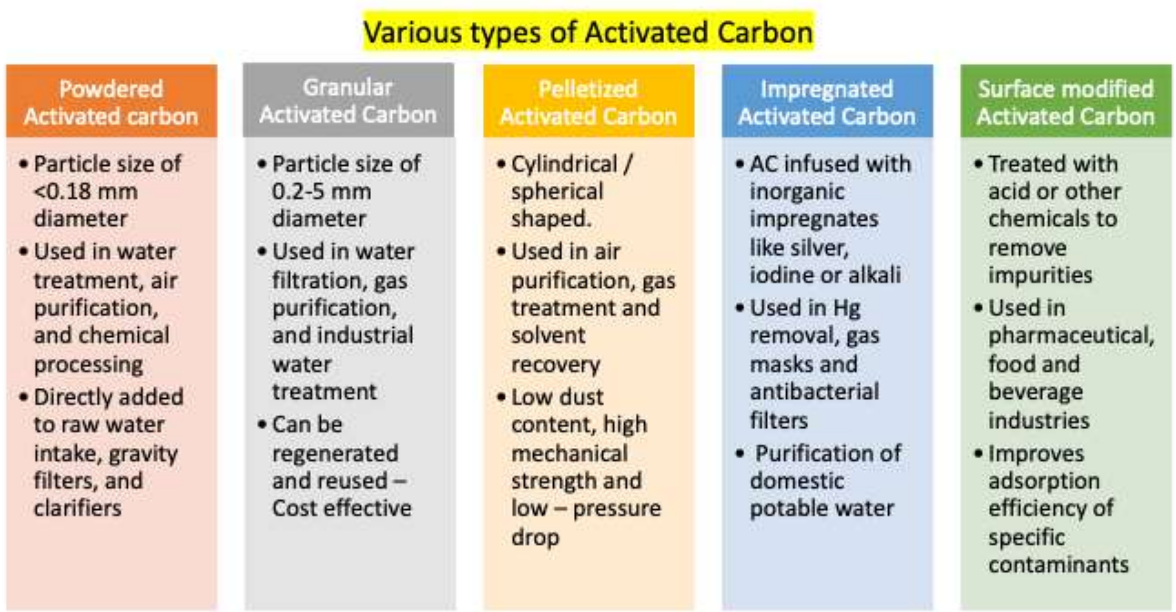
Energy storage devices: Activated carbon is widely used in energy storage systems, particularly in batteries and supercapacitors, due to its high surface area, porosity, and excellent electrical conductivity. In supercapacitors, it serves as an electrode material, enabling rapid charge and discharge cycles with high power density [47]. Its porous structure enhances ion adsorption, improving capacitance and energy efficiency. In lithium-ion and sodium-ion batteries, activated carbon is used as an anode material and in conductive coatings to enhance charge transfer and cycling stability [48]. Its low cost, environmental friendliness, and superior electrochemical performance make it crucial for modern energy storage applications.

5. Choosing the Right Activated Carbon :

Activated carbon is widely used across industries and is available in various forms based on its intended use. It is classified according to its physical form, production method, and application. Businesses must select the right grade and form of activated carbon based on their specific application and target contaminants. Granular Activated Carbon (GAC) is ideal for water and air filtration due to its durability and reusability, while Powdered Activated Carbon (PAC) is best for rapid adsorption in wastewater and food processing. Pelletized carbon suits gas purification, and Activated Carbon Fibers (ACF) excel in high-performance filtration and energy storage.



Factors like adsorption capacity, pH compatibility, lifespan, and regulatory compliance must be considered to ensure optimal efficiency and cost-effectiveness in industrial, medical, and environmental applications.

Conclusion:

Activated carbon plays a crucial role in water purification, air filtration, food processing, medical applications, and energy storage due to its exceptional adsorption properties. It effectively removes contaminants such as organic pollutants, heavy metals, VOCs, and toxins, ensuring cleaner environments and safer products. Available in various forms via granular, powdered, pelletized, and fibrous, activated carbon serves diverse industries with tailored solutions.

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Call to Action:

To maximize efficiency, one must select the right type based on application needs, adsorption capacity, and regulatory compliance. Whether for municipal water treatment, industrial filtration, or high-performance energy storage, choosing high-quality activated carbon ensures optimal results.

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