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Review article

Insights into Adsorbents: Activated Carbon for Effective Adsorption

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ABSTRACT

This review highlights the exploration of activated carbon with transformative capabilities of activated carbon but also outlines potential avenues for further research, contributing to the ongoing quest for sustainable and effective adsorption technologies. From traditional precursors like coal and wood to emerging materials such as agricultural residues and waste biomass, we explore the diverse origins of activated carbon. Synthesis methods, structural characteristics, and adsorption mechanisms associated with these sources are systematically examined, providing a comprehensive understanding of the pivotal role played by activated carbon in addressing contemporary environmental challenges.

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1. Introduction

Adsorption has emerged as a crucial process in the quest for sustainable and efficient solutions in environmental remediation, gas separation and water purification. Among the diverse array of adsorbents, activated carbon, proves to be a versatile and widely utilized material, showcasing exceptional adsorptive capabilities across various applications. This review explores the complex realm of adsorption, specifically concentrating on the broad domain of activated carbon. Activated carbon, derived from various precursor materials, has become the preferred material in numerous industries due to its high surface area, porous structure, and adjustable surface chemistry. Its capacity to selectively capture and retain a wide range of, contaminants, gases, and pollutants establishes it as a fundamental component in addressing contemporary environmental challenges (Yang and Lua, 2006; Yusuf et al., 2023a & 2023b). As the demand for sustainable and effective adsorption technologies continues to grow, a comprehensive understanding of the intricacies of activated carbon sources becomes essential for researchers, engineers, and practitioners alike.

Carbonaceous materials, including carbon nanofibers, carbon nanotubes, and activated carbon, have become subjects of intensive research due to their exceptional properties and diverse applications. Carbon nanofibers, with their nanometer-scale diameters, exhibit remarkable mechanical strength and thermal conductivity, making them ideal for reinforcing composite materials in industries like aerospace and automotive (Srinivasan and Viraraghavan 2010; Azevedo et al., 2007). Carbon nanotubes, cylindrical structures composed of graphene sheets, possess extraordinary mechanical, thermal, and electrical properties, leading to potential applications in advanced materials and nanoelectronics. Activated carbon, known for its high surface area and porosity, serves as a versatile adsorbent in water purification, air filtration, and gas separation, contributing to environmental and industrial solutions. The exploration of carbonaceous materials extends to cutting-edge fields, including nanotechnology, energy storage, and biomedical research. In nanotechnology, carbon nanotubes show promise in nanomedicine for drug delivery and diagnostic imaging, while the biocompatibility of certain carbonaceous materials opens avenues for medical applications. In energy storage, activated carbon's high surface area and conductivity make it valuable for batteries and supercapacitors, advancing electric vehicles and renewable energy (Abbas et al., 2014; Guo and Rockstraw, 2007). Moreover, carbonaceous materials play a crucial role in environmental remediation, with carbon nanotubes being investigated for water treatment and activated carbon addressing air pollution and industrial waste (Abechi et al. 2011; Acharya et al., 2009). Despite their vast potential, challenges such as scalability, cost-effectiveness, biocompatibility, toxicity, and environmental impact need careful consideration. Ethical and regulatory frameworks must evolve alongside technological advancements. In conclusion, the ongoing exploration of carbonaceous materials signifies a dynamic research landscape with profound implications for industries ranging from advanced materials to environmental protection. As innovation continues, carbonaceous materials are poised to shape the future,

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contributing to scientific progress and addressing global challenges responsibly and sustainably.

A burgeoning area of research focuses on the development of low-cost activated carbons derived from renewable biomass wastes, such as apricot stones, almond shells, coconut shells, cotton stalk, date pits, nut shells, olive seeds, rice husk, sugar cane bagasse, wood, and more (Fierro et al., 2010; Zuo et al., 2009; Ju et al., 2023; Azevedo et al., 2007). This sustainable approach aims to repurpose agricultural and agro-industrial byproducts, diverting them from waste streams and addressing the demand for activated carbons. By utilizing a diverse range of biomass precursors, researchers aim to tailor the properties of these activated carbons for specific applications, fostering a sustainable alternative to traditional carbon sources and contributing to the principles of the circular economy (Huang et al. 2010). The production process typically involves carbonization, where biomass undergoes controlled heating in an inert atmosphere, followed by activation steps that enhance the material's porous structure. This approach aligns with the goals of cost-effectiveness and environmental sustainability, ensuring a renewable supply of raw materials and reducing the environmental impact associated with biomass waste disposal. These low-cost activated carbons find applications in water purification, gas separation, and energy storage, showcasing their potential to address global challenges while promoting responsible resource utilization in a variety of industries.

2. Classification of Activated Carbon

Activated carbon, a versatile adsorbent with a wide range of applications, can be classified into various types based on physical form, production methods, and surface characteristics. This classification aids in understanding the specific properties and applications of each type. Among the prominent classifications are Powdered Activated Carbon, Granular Activated Carbon, Extruded Activated Carbon, Impregnated Carbons, and Polymers Coated Carbon.

2.1 Powdered Activated Carbon (PAC)

Powdered Activated Carbon, commonly known as PAC, is characterized by its finely ground particles, typically with an average diameter of less than 0.075 mm. The small particle size results in a high surface area, facilitating rapid adsorption. PAC is commonly used in liquid-phase, for example, wastewater treatment, due to its enhanced reactivity and the ability to form a suspension in aqueous solutions. The fine particles ensure a large exposed surface area for adsorption of contaminants, making PAC effective in removing organic pollutants, colorants, and various impurities from liquids. Its versatility extends to applications in the food and beverage industry, where it aids in decolorization and purification processes.

2.2 Granular Activated Carbon (GAC)

Granular Activated Carbon, or GAC, comprises larger particles compared to PAC, typically ranging from 0.2 to 5 mm in size. The granular form allows for easy handling and regeneration, making GAC suitable for both liquid and gas-phase adsorption applications. Commonly used in water treatment, GAC effectively removes organic compounds, taste and odor-causing substances, and certain dissolved chemicals. Municipal water treatment plants often employ GAC beds in filtration systems for the removal of contaminants like chlorine, pesticides, and volatile organic compounds (VOCs). In air purification, GAC is utilized to capture and adsorb airborne pollutants, providing a solution for improving indoor air quality.

2.3 Extruded Activated Carbon (EAC)

Extruded Activated Carbon, denoted as EAC, represents a specialized form where activated carbon is shaped into cylindrical pellets or rods. This form enhances the mechanical strength and density of the material, making it suitable for applications requiring robust adsorbents. EAC is commonly employed in gas-phase adsorption processes, such as air purification and gas masks, where mechanical strength and durability are crucial. The extrusion process allows for the creation of uniform and dense structures, providing enhanced resistance to abrasion and dust generation. This makes EAC an ideal choice for environments where strict particle control is essential.

2.4 Impregnated Carbons

Impregnated Carbons are activated carbon materials that undergo a treatment process involving the addition of specific chemicals, typically in a liquid phase, to enhance their adsorption capabilities. The impregnation process introduces chemical functionalities that target particular contaminants with high affinity. Common impregnants include metal oxides, acids, and bases. Metal impregnated carbons, such as silver or copper, exhibit enhanced antimicrobial properties, making them valuable in water disinfection applications. Impregnated carbons are employed when specific adsorption requirements are needed, expanding the versatility of activated carbon in addressing targeted pollutants.

2.5 Polymers Coated Carbon

Polymers Coated Carbon involves the encapsulation of activated carbon particles with a polymer layer. This coating enhances the adsorbent's selectivity, stability, and resistance to abrasion. The polymer layer serves as a protective barrier, preventing the release of carbon fines and improving the overall mechanical strength of the material. This type of activated carbon is particularly suitable for applications where the potential for abrasion or disintegration needs to be minimized. Additionally, the polymer coating can be tailored to enhance adsorption selectivity for specific contaminants, making it valuable in niche applications where targeted removal is critical. The continuous exploration of innovative production methods and tailored functionalities ensures that activated carbon remains a key player in addressing environmental challenges and advancing various industries.

3. Preparation of activated carbon

The preparation of activated carbon involves a series of controlled processes designed to create a highly porous structure with an extensive surface area, maximizing its adsorption capabilities. The specific methods employed can vary based on the raw material used, whether it be coconut shells, wood, peat, or other carbonaceous sources (Marouane et al., 2012). Below is a generalized overview of the preparation process:

3.1 Selection of Raw Material

The choice of raw material plays a crucial role in determining the properties and applications of the activated carbon. Common sources include coconut shells, wood, peat, coal, lignite, and agricultural by-products.

3.1.1 Carbonization

The first step is carbonization, during which the raw material undergoes controlled heating in an oxygen-deficient environment (usually nitrogen or argon) at temperatures ranging from 600 to 900 degrees Celsius. This process drives off volatile components, leaving behind a carbon-rich residue. Carbonization is essential for creating the basic carbon structure.

3.1.2 Activation

The carbonized material undergoes activation, a process that introduces porosity by creating pores and increasing the surface area. There are two main methods of activation: physical activation and chemical activation.

- *Physical Activation*
  In physical activation, the carbonized material is exposed to an activating agent, often steam or carbon dioxide, at high temperatures (800-1000 ºC). This method involves the removal of the carbon atoms between the existing layers, creating pores. The resulting activated carbon has a well-developed pore structure, providing a high surface area for adsorption. The physical activation of various raw materials is detailed in Table 1. Chemicals like zinc chloride and potassium hydroxide act as catalysts, while high-temperature steam serves as a thermal activating agent. Carbonaceous precursors, such as coconut shells and wood, undergo transformations to influence the final AC's porosity and adsorption properties. The careful selection and combination of these materials are crucial for tailoring activated carbon for specific applications.
- *Chemical Activation*
  Chemical activation involves impregnating the carbonized material with a chemical activating agent, such as potassium hydroxide (KOH) or phosphoric acid (H_3PO_4). This is followed by heating the impregnated material at moderate temperatures (450-900 ºC) (Ju et al., 2023; Azevedo et al., 2007). The activating agent reacts with the carbon, creating pores in the structure. Chemical activation is known for producing activated carbons with specific pore size distributions and tailored properties. An overview of the different chemical agents used in the activation of activated carbon made from various raw materials is given in Table 2.

3.1.3 Washing and Purification

The activated carbon undergoes a meticulous washing process, wherein it is thoroughly cleansed to eliminate any lingering impurities or remnants of activating agents. This meticulous cleansing ensures that the activated carbon attains a high level of purity, free from any unwanted substances that may affect its performance or properties. This step is crucial to ensure that the final product meets quality standards and is suitable for its intended applications.

3.1.4 Drying and packaging

The washed activated carbon is then dried to remove excess water. The drying process is typically carried out at relatively low temperatures to avoid structural changes in the activated carbon. The final step involves sizing the activated carbon to meet specific particle size requirements. This can involve crushing or grinding the material. The activated carbon is then packaged for distribution and use in various applications.

Table 1: Various physical activating agents and precursors are essential in the production of activated carbon (AC).

Activating agent	Raw Materials	Ref.
Steam	Rice husk, cotton residues, coal, rubber wood sawdust	(Zhang et al., 2011)
Air	Almond tree pruning, almond shells, Peanut hulls etc.	(Liu et al., 2008)
CO_2	sugarcane bagasse, rice straw, nutshells, rice hulls, coffee endocarp	(Zhao et al., 2009)

Table 2: Various precursors used for AC production and chemical activating agents.

Activating agent	Material	Ref.
$ZnCl_2$	Macadamia nutshells, Hazelnut shells, Tamarind wood, Almond shells, apricot stones, Bagasse, cattle manure, Coconut shells, Corn cob, Peanut hulls etc.	(Lua and Yang, 2005).
KOH	Cassava peel, Corn cob, coal, cotton stalk, macadamia nutshells, Olive seed, Petroleum coke, Peanut hulls, Pineapple peel, Rice straw, Rice straw.	(Zhang et al., 2011)
K_2CO_3	Almond shell, bamboo, corn cob, cotton stalk, coconut shell, pineapple peel, pistachio shell, walnut shell,	(Rahmat et al., 2023).
H_3PO_4	Almond shells, bagasse, chestnut wood, eucalyptus bark, grain sorghum, hemp, lignin, peanut hulls, pecan shells, oak, sewage sludge, sunflower seed hulls, rice hull, rice straw, jackfruit peel.	(Fierro et al., 2010).

It's important to note that the choice of activation method, temperature, and duration can significantly influence the characteristics of the activated carbon, such as pore size distribution, surface area, and adsorption capacity. The tailored properties make activated carbon a versatile material with applications ranging from water and air purification to gas separation, industrial processes, and beyond. Continuous research and development in the field of activated carbon production aim to optimize these processes for specific applications and improve the sustainability of the overall production method.

Carbon gasification, with varying rates within the structure, is responsible for pore development in activated carbon. Preferential porosity is produced by less organised carbon being more prone to gasification in comparison to organized graphitic-like regions. Pore development depends on the activating agent or gas, temperature, and duration. Coal-based carbons have a more diverse impurity mix than biomass-derived products, impacting adsorptive properties. Efforts to optimize adsorptive properties have focused on structural characteristics, with limited attention to surface chemistry. Some research explores carbon surface chemistry manipulation, but its utility for vapour adsorption applications and stability in humid air remains less explored.

4. Factors Affecting Activated Carbon Characteristics

Activated carbon is a highly versatile adsorbent and suitable for a wide range of applications. The characteristics of activated carbon are influenced by various factors, ranging from the raw material used to the specific processes employed during its production. Understanding these factors is crucial for tailoring activated carbon to meet the requirements of specific applications. Here, we delve into the key factors that affect activated carbon characteristics, including raw material selection, activation methods, temperature, and particle size.

4.1 Raw Material Selection

The choice of raw material is fundamental in determining the properties and performance of the activated carbon. Various carbonaceous sources can be utilized, such as coconut shells, wood, peat, coal, lignite, and agricultural by-products. Each raw material imparts unique characteristics to the resulting activated carbon. For instance, coconut shell-derived activated carbon is renowned for its high hardness, low ash content, and excellent adsorption capacity, making it suitable for water treatment and air purification applications. Wood-based activated carbon is valued for its large surface area and pore volume, often finding application in gas-phase adsorption processes. The inherent properties of the raw material, including carbon content, mineral content, and ash content, significantly influence the characteristics of the activated carbon. Additionally, the activation process itself plays a crucial role in shaping the final product.

4.2 Activation Methods

The activation process is a key determinant of activated carbon characteristics. There are two primary methods of activation: physical activation and chemical activation.

Activated carbon is prepared through physical activation, involving exposure to agents like steam or carbon dioxide at temperatures of 800 to 1000 ^{o}C, resulting in a well-defined pore structure. Alternatively, chemical activation entails impregnating the carbonized material with activating agents such as KOH or phosphoric acid, followed by heating between 450 to 900 ^{o}C. This method allows for the precise control of pore size distributions and specific properties, catering to varied application needs. The choice between physical and chemical activation depends on the desired characteristics of the activated carbon and the targeted applications. Physical activation often results in activated carbons with well-defined pore structures, while chemical activation allows for greater control over pore size distributions and surface chemistry.

4.3 Temperature

The temperature during the activation process is a critical parameter influencing the final characteristics of activated carbon. The temperature range varies depending on the activation method employed. Higher temperatures generally result in activated carbons with larger surface areas and enhanced porosity. The relationship between temperature and activated carbon characteristics is complex, and optimization depends on the specific requirements of the intended application. Higher temperatures generally contribute to increased pore development and surface area, factors crucial for efficient adsorption.

4.4 Particle Size

Activated carbon’s particle size influences its effectiveness in various applications. Different applications may require activated carbon with specific particle size distributions to ensure optimal performance.

4.5 Surface Area and Pore Structure

The surface area and pore structure of activated carbon are perhaps the most crucial characteristics influencing its adsorption performance. These properties directly impact the adsorption capacity and efficiency of the material. Activated carbon is renowned for its extensive surface area, often measured in square meters per gram (m^2/g). The activation process, whether physical or chemical, plays a significant role in creating the pore structure. Micropores, mesopores, and macropores contribute to the overall pore distribution. Micropores, with diameters less than 2 nm, are essential for adsorbing small molecules, while mesopores (2-50 nm) and macropores (greater than 50 nm) contribute to adsorption of larger molecules. Achieving an optimal balance of micropores and mesopores is crucial for maximizing adsorption capacity. The surface area and pore structure are often characterized using techniques like nitrogen adsorption isotherms, providing insights into the specific characteristics of the activated carbon.

4.6 Surface Chemistry

The surface chemistry of activated carbon plays a crucial role in adsorption selectivity. Chemical functionalities introduced during the activation process contribute to the material's affinity for specific contaminants. The surface chemistry is often modified to target particular contaminants, making activated carbon a highly versatile material with tailored functionalities for diverse applications. In addition, the characteristics of activated carbon are intricately linked to various factors, from the selection of raw material to the activation methods employed. The careful consideration of these factors allows for the customization of activated carbon properties to meet the specific requirements of applications ranging from water and air purification to industrial processes.

5. Theoretical aspects

Adsorption is a surface phenomenon that occurs when atoms, molecules, or ions bind to the surface of an adsorbent. This binding process creates a molecular or atomic film known as the adsorbate. Adsorption is a widely used unit operation for treating contaminated water, such as raw water and wastewater.

Typically, adsorption studies are conducted through batch and column studies. Batch studies determine the kinetics and isotherm constants, while column studies determine the breakthrough curve. Adsorption can be categorized into two main types: physical adsorption and chemical adsorption, also known as chemisorption. Physical adsorption is primarily driven by van der Waals forces, and its reversibility stems from a delicate equilibrium between the molecular forces of attraction. In this process, the solute adheres to the adsorbent surface due to these intermolecular forces. This reversible nature is indicative of the dynamic interaction between the adsorbate (solute) and the adsorbent, where the balance of attractive forces ensures the adsorption is not permanent. Although the bonds involved are individually weak, they can represent a dominant force when combined. Chemisorption, on the other hand, occurs due to stronger specific forces such as the formation of chemical links, including covalent or ionic bonds. Sorption refers to the general phenomenon of gas uptake by solids when adsorption and absorption cannot be differentiated.

5.1 *Adsorption Mechanism*

Adsorption can be elucidated as a captivating surface phenomenon wherein molecules or ions exhibit an affinity for adhering to the surface of either a solid or liquid substance. This interaction leads to the establishment of a distinct layer, referred to as the adsorbate, which encapsulates the material. This captivating process plays a pivotal role in numerous scientific and industrial applications, showcasing the intriguing ability of substances to selectively bind and accumulate on surfaces. Whether occurring on the microscopic scale of particles or on the macroscopic level of materials, adsorption contributes significantly to our understanding of material behaviors and holds paramount importance in fields ranging from catalysis to environmental remediation. The mechanism of adsorption involves attractive forces between the adsorbate molecules and the surface of the adsorbent. There are two primary types of adsorption mechanisms: physical adsorption (physisorption) and chemical adsorption (chemisorption). Fig. 1 illustrates the general overview of the mechanism.

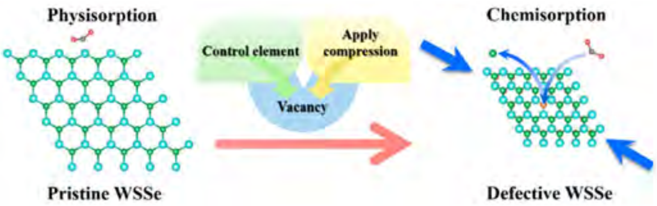

Fig. 1: Schematic diagram for physical-to-chemical adsorption transition (Adapted from Ju et al., 2023 under CCBY MDPI).

5.1.1 *Physical Adsorption (Physisorption)*

Physical adsorption, also known as physisorption, is a fascinating phenomenon that plays a significant role in various fields such as chemistry, materials science, and environmental science. It is characterized by its relatively weak and reversible nature, primarily driven by van der Waals forces or London dispersion forces between the adsorbate molecules and the surface of the adsorbent material. It is crucial to note that physical adsorption is a weak interaction compared to chemical adsorption, making it reversible under appropriate conditions. Physisorption commonly occurs at relatively low temperatures, making it distinguishable from chemisorption, which generally requires higher temperatures and involves stronger chemical bonds. The adsorption process is influenced by several key factors, with surface area, temperature, and pressure being paramount.

The surface area of the adsorbent material is a critical determinant of the extent of physical adsorption. Greater surface area provides more sites for adsorption, facilitating a higher quantity of adsorbate molecules to attach to the surface. Therefore, materials with high surface areas, such as activated carbon or zeolites, are often preferred for applications where physical adsorption is a crucial mechanism. Temperature plays a significant role in physical adsorption kinetics. Generally, physisorption occurs at lower temperatures, and as the temperature decreases, the adsorption capacity tends to increase. This is due to the lower kinetic energy of molecules at lower temperatures, making them more prone to being adsorbed onto the surface. However, extreme temperatures can also impact physical adsorption, leading to desorption or reduced adsorption efficiency. Pressure is another influential factor in physical adsorption. An increase in pressure typically enhances adsorption, as more gas molecules are driven to the adsorbent surface. This relationship is governed by the adsorption isotherm, which describes the amount of adsorbate at a given temperature and pressure. Physical adsorption is particularly common in gases or vapors and is often characterized by multilayer adsorption. As the first layer of molecules adheres to the surface, additional layers form, each experiencing weaker interactions with the underlying layers. This multilayer formation contributes to the observation of increased adsorption at higher pressures. The loosely bound nature of physisorption is reflected in the ease with which adsorbate molecules can be desorbed from the surface. Typically, the process is exothermic, meaning that heat is released during adsorption. This characteristic makes physical adsorption reversible, allowing the adsorbate molecules to be released from the surface when conditions change, such as variations in temperature or pressure.

In addition, physical adsorption is a captivating and intricate process governed by weak intermolecular forces. Understanding the factors influencing physisorption, such as surface area, temperature, and pressure, is essential for tailoring adsorption processes in applications ranging from gas separation to environmental remediation. The reversible nature of physical adsorption and its dependence on external conditions make it a versatile tool in various scientific and industrial contexts.

5.1.2 *Chemical Adsorption (Chemisorption)*

Chemical adsorption involves a stronger and more specific interaction between the adsorbate and the adsorbent, often resulting in the formation of chemical bonds. Unlike physisorption, chemisorption is an irreversible process and requires a higher activation energy. This mechanism is prevalent at higher temperatures and involves the sharing or transfer of electrons between the adsorbate and the adsorbent, forming stable chemical bonds. Chemisorption is selective and typically specific to certain types of adsorbate molecules. It is commonly observed in reactions where the adsorbate is chemically transformed on the surface of the adsorbent.

Both physisorption and chemisorption play crucial roles in various applications, such as adsorption in porous materials like activated carbon or in catalytic processes. The choice between these mechanisms depends on the nature of the adsorbent, the specific properties of the adsorbate, and the environmental conditions.

5.2 *Adsorption Isotherms*

The adsorption isotherm assists as a key representation of the equilibrium relationship governing adsorption phenomena, playing a pivotal role in adsorber design and process evaluation (Zuo et al., 2009; Yusuf 2023; Yusuf et al. 2017). This equilibrium data is indispensable for understanding the interaction between adsorbate and adsorbent, expressed by the relationship between the amount of adsorbate adsorbed per gram of adsorbent, qe (mg/g), and the equilibrium solution concentration, Ce (mg/l), at a constant temperature. Optimization of adsorbent utilization relies heavily on insights derived from adsorption isotherms (Baek et al., 2010; Yusuf et al., 2017). Among the widely favoured isotherms for characterizing non-linear equilibrium are the Langmuir, Freundlich, and Redlich–Peterson models.

5.2.1 *Langmuir Isotherm*

The Langmuir isotherm postulates that an adsorbent material's surface harbours active sites for the attachment of adsorbate, either through physical (physio-sorption) or chemical (chemi-sorption) means, such as van der Waals interactions or covalent bonding, respectively. Once saturation is achieved, no further adsorption occurs due to limited interaction between adsorbate molecules (Shawabkeh et al., 2007; Yusuf et al., 2017). This model assumes uniform energies of adsorption on the surface without adsorbate transmigration within the surface plane. The non-linear equation representing the Langmuir isotherm is commonly expressed as

$$q_e = \frac{Q_m K_2 C_e}{1 + K_2 C_e}$$

The linear form of Langmuir model is as follows:

$$\frac{C_e}{q_e} = \frac{1}{Q_m b} + \frac{C_e}{Q_m}$$

where C_e refers concentration of dye (mg/l) at equilibrium and q_e denotes the amount of the dye adsorbed (mg/g). Q_m and b are the Langmuir constants related to the adsorption capacity (mg/g) and the equilibrium constant (l/mg), respectively.

5.2.2 *Freundlich Isotherm*

Freundlich isotherm can be expressed as-

$$q_e = K_F C_e^{\frac{1}{n}}$$

where; the equation is used in determining the adsorption capacity of a substance. In this equation, KF is the constant related to the overall adsorption capacity in milligrams per gram, and 1/n is the constant related to the surface heterogeneity of the adsorbent in dimensionless units. By plotting qe versus Ce, we can obtain a non-regression line that allows us to determine KF and 1/n. The value of 1/n ranges from 0 to 1, and the closer it is to zero, the more heterogeneous the adsorbent surface (Yusuf et al., 2017; Halyal et al., 2023). This equation can be linearized as:

$$\log \mathrm{q_e} = \frac{1}{n} \log C_e + \log K_F$$

5.2.3 *Temkin Isotherm*

The Temkin isotherm postulates that the heat of adsorption for all molecules exhibits a linear increase with coverage (Halyal et al., 2023). The Temkin isotherm has commonly been applied in the following form:

$$q_e = \frac{RT}{b} \ln(AC_e)$$

The linear form of this isotherm can be given by

$$q_e = \frac{RT}{b_T} \ln A + \frac{RT}{b_T} \ln C_e$$

q_e refers at equilibrium, the amount adsorbed (mg/g). The slopes and intercept obtained from the graphical plot qe against *ln Ce* were used to calculate the Temkin constants. Where $B = \frac{RT}{b_T}$

5.2.4 *Dubinin-Rudushkevich Isotherm*

Dubinin-Radushkevich isotherm (Yusuf et al., 2017; Halyal et al., 2023) can be given as:

$\ln q_e = \ln qD - B\varepsilon^2$

Where theoretical saturation capacity denoted by qD (mg/g), B is a mean free energy of adsorption per mole of the adsorbate constant (mol^2/J^2) and Polanyi potential is denoted by ε.

From Table 3 it is clear that agricultural wastes have great potential to be used as raw materials economically attractive for producing activated carbon which can further be used in the water purification process, pollution removal, medical purposes, hydrogen storage and catalyst support.

Table 3: Summary of the available information on activated carbon prepared from agro-biomass.

S. No.	Raw Material	Activation agent, Reactor type and parameters	Parameters studied and characterization technique	Description	Ref.
1.	Mango nuts	HCl (25%, 50%, 75% and 100%); Temperature-200, 400, 600 ^{o}C; 30 min residence time and 1 ml/g mix ratio; Tubular furnace	RSM, ash content, surface area, carbon yield	AC obtained were suitable for dye remediation.	Kwaghger et al. (2013)
2.	Rice bran	Carbon dioxide at 850^{0}C for different period of times (40-120 min) tubular furnace	Surface area, pore volume	Prepared Activated Carbon has BET surface area of 652 m^2/gm and pore volume of 0.137 cm^3/gm.	Suzuki et al. (2007)
3.	Bagasse and rice husk	H_3PO_4 300-600^{0}C Tubular furnace	Surface area, iodine number, dye uptake	The bagasse-activated carbon exhibited a peak surface area of 1100 m^2/g, surpassing the alternative variant which registered a value of 780 m^2/g. Analytical evaluations revealed iodine numbers ranging from 608 to 746 and methylene blue uptake levels between 213 and 261 mg/g for the examined sample.	Kalderis et.al. (2008)
4.	Mango seed	Phosphoric acid 45% v/v and 4% w/v NH_4Cl for 12 h followed by pyrolysis in a tubular furnace	Organic compound removal	The results obtained suggest that the endocarp of mango seeds has the likely to be used for wastewater remediation.	Umudi and Ukpebor (2012)
5.	Rice and saw dust	EDTA and activated carbon followed by thermal decomposition in CO_2 atm. Activation Time: 30 minutes	Removal of Cu, Mn, Fe, Cd, Pb, Zn, Ni, Cr	Chemically activated sawdust attains removal rates in the range of 75% - 100%.	Tang et al. (2009)
6.	Carbon nanofibers, activated carbon fibres, carbon nanotubes	-	Surface area, hydrogen storage capacity	At 298 K, H_2 adsorption capacity is contingent upon both the micropore volume and the distribution of micropore sizes.	Chen et.al. (2011)
7.	Mango seed shell	$MgCl_2$ with impregnation ratio 0.25, 0.50, 0.75	Colour removal from silk filature composite wastewater with time, different dosages and pH	The corresponding removal efficiencies are 81.11%, 96.66%, and 96.66%.	Umudi and Ukpebor (2012)
8.	Mango seed	KOH, NaOH impregnation ratio-3:1, activation- argon flow by heating to 823 K in tubular furnace with 1 h soaking time	Pore structure, porosity, pore distribution by physical adsorptions of N_2 at 77 K and CO2 at 273 K	The porosity in precursors characterized by low structural order (exhibiting high reactivity) is more effectively achieved through the utilization of NaOH compared to KOH. On the other hand, for precursors demonstrating high structural order, the reverse holds. KOH-activated carbons feature narrower micropore distributions in contrast to those activated through NaOH.	Kumar and Kumaran (2005)
9.	Coal, coconut shell	KOH (activation agent) impregnation ratio 4:1, 3:1 at 900°C	Surface area, pore volume, methane and hydrogen storage 25^{o}C and pressures	The highest adsorption was achieved by activated carbon derived from coal, with a KOH with an impregnation ratio of 4:1. Methane and hydrogen adsorption reached 7 mmol/g, and 1.4	Sudibandriyo (2011)

			up to 6 MPa using volumetric techniques.	mmol/g respectively. The experimental data were effectively correlated using the Ono-Kondo lattice model, demonstrating a good fit within the experimental uncertainties for pure-component adsorption. The adsorption capacity exhibited a direct proportionality to the activated carbon's surface area. It was concluded that a smaller pore size is essential for enhancing the H_2 adsorption efficiency.	
10.	Nanoporous carbon materials		review	Hydrogen adsorption in porous solids presents a viable avenue for low-stringency hydrogen storage. Hydrogen molecules adsorbed physically exhibit weak binding to the surface, facilitating easy release. Porous carbons stand out as promising candidates for efficient hydrogen storage due to their cost-effectiveness and ease of preparation among various surface options.	Yang et.al. (2012)
11.	Porous carbon material	-	Hydrogen storage	Porous carbon can accommodate H_2 storage up to 5 wt%, while metal-organic framework materials can achieve storage capacities of up to 7.5 wt% at a temperature of 77 K. However, the hydrogen adsorption levels on porous materials significantly decrease to 90.5 wt% under ambient temperatures and elevated pressures.	Thomas (2007)
12.	Sugar Cane Bagasse	Chemical $ZnCl_2$,500 C,1 hour of activation	-	Pore volume observed was from 27.5 to 14.3 on increasing the impregnation ratio from 25 to 100. Effective for Cr(VI) removal.	Cronje et al. (2011)
13.	Corn cob	Chemical KOH/K_2CO_3, Activation Temp- 550°C, followed by CO_2	BET surface area	Surface Areas from 1000 to 1800 m^2/gm have been observed.	Wang et al. (2009)
14.	Coconut shell	KOH	Hydrogen adsorption upto 100 bars at 298K	A maximum hydrogen adsorption capacity of 0.85 wt.% at 100 bars and 298 K was achieved.	Zhang et al. (2004)
15.	Carbon prepared by mechanical milling in an H_2 atmosphere	-	Hydrogen storage, milling conditions	The H_2 storage capacity showed an increase with the initial H_2 pressure in the milling pot, signifying a potential contribution of physisorption to the hydrogen storage mechanism.	Shindo et al. (2005)
16.	Mahogany saw dust and rice husk		Dyes and phenol removal	Adsorption capacity 183.8 mg and 86.9 mg per gram of adsorbent. The best result is at pH 3.0	Shindo et al. (2005)
17.	Lignin	KOH	Hydrogen storage and micro-pore structure at 298 and 77K	The activated carbon's surface area and micro-pore volume decreased from 2290 to 1140 m^2/g and 1.49 to 0.48 cm^3/g respectively with an increase in carbonization temperature from 400 to 800°C.	Akasaka et al. (2011)
18.	Peels of Jackfruit	H_3PO_4, activation temperature 450, 550°C	Temperature, surface chemistry	Temperatures are in the range of 907–1260m^2/g and 0.525–0.733 cm^3/g, respectively.	Prahas et al. (2008)

19.	Banana empty fruit bunch (BEFP), Delonix regia fruit pod(DRFP)	H_3PO_4 and KOH, Activation temperature 450°C and 400°C	Bulk density, yield, surface area, FTIR	BEFP and DRFP exhibited significant removal of methylene blue via reduction.	Sugumaran et al. (2012)
20.	Neem husk	$ZnCl_2$, H_3PO_4 KOH, carbonized at 400ºC	particle size, adsorbent dosage, shaking duration, and adsorbent regeneration on dye removal	Adsorption experiments were conducted using carbonized neem carbon, activated neem carbon, and a commercial adsorbent from coconut shell relative to methylene blue.	Alau et al. (2010)
21.	Commercial Activated Carbon	KOH, CO_2	Hydrogen storage, study of pore structure, texture	KOH activation significantly contributes microporosity to the activated carbon frameworks resulting in porous carbon with an exceptional surface area of 3190 m^2 g-1 and a substantial gravimetric hydrogen uptake capacity of 7.08 wt % at 77 K and 20 bar.	Wang et.al. (2009)
22.	Indigenous waste	-	Methylene blue removal as a function of agitation time, initial dye concentration, carbon dose, pH and temperature	Equilibrium data (first-order reaction equation, with intra-particle diffusion) were analyzed using Freundlich and Langmuir isotherm models.	Arivoli et al. (2010)
23.	Teak tree bark	-	agitation time, agitation speed, temperature and particle size, initial dye concentration, dose of adsorbent, pH,	Langmuir and Freundlich among isotherm models (Freundlich, Langmuir, and Temkin) emerged as the most appropriate models, indicated by their high linear regression coefficients (R2 ≈ 0.99).	Molina-Sabio et.al. (1996)
24.	Bamboo scaffolds	Nitric acid, $Ca(OH)_2$, H_3PO_4, Activation time- 6 h, Activation temperature 600°C and 900°C	characterized by elemental analysis, adsorption isotherm, Boehm titration, He pyncometry.	This phenomenon is likely a result of the dissolution of permeated inorganic matter and the oxidation of deposited carbon.	Cheung (2012)
25.	Palm shells	H_3PO_4 impregnation ratio of 0.5 to 3 with 425ºC, 30 min	Surface area, iodine number, pore size	The pore size demonstrated a wide distribution, with micro-pores comprising 50% of the total. The activated carbon, achieved through a 3:1 impregnation ratio with an iodine number of 1035 mg/g, exhibited a BET surface area of 1109 m^2/g.	Olowoyo and Orere et al. (2012)

6. Future Dimensions

This review on activated carbon as an adsorbent anticipates exploring innovative applications and advancements in the field with a focus on sustainability and environmental stewardship. Researchers are expected to investigate methods for improving adsorption efficiency, such as surface modification or the incorporation of nanomaterials. The scope of the review may also encompass emerging areas like the utilization of activated carbon in energy storage, particularly in supercapacitors and energy conversion devices, leveraging its unique porous structure. Advanced computational models have the potential to offer insights into the complex dynamics of adsorption, facilitating the design of customized activated carbon materials for specific applications. The future trajectory of this review is dynamic, reflecting ongoing developments in the synthesis and characterization of activated carbon, as well as its expanding practical applications across various sectors.

7. Conclusion

This review aims to explore the various aspects of adsorption, with a focus on activated carbon as an exceptional adsorbent. Our exploration into the porous structure, extensive surface area, and versatile applications of activated carbon provide valuable insights into its effectiveness for adsorption purposes. The unique properties of activated carbon make it a powerful tool for capturing and removing a diverse range of substances from different mediums, with applications ranging from environmental remediation to industrial processes. The adaptability and sustainability of activated carbon, derived from diverse sources, including coconut shells, wood, peat, and coal, further underscores its importance in meeting the demands of different applications. This review emphasizes the crucial role of activated carbon in addressing contemporary challenges related to pollution control and resource management, highlighting it as a high-performing adsorbent.

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