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ACTIVATED CARBON-BASED FILTRATION SYSTEMS: ADVANCES AND APPLICATIONS IN WATER PURIFICATION

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ABSTRACT

Water contamination poses a critical global challenge, necessitating effective purification strategies to ensure safe drinking water and sustainable wastewater treatment. Activated carbon (AC), owing to its high surface area, tunable pore structure, and adsorption efficiency, has emerged as a widely adopted material for water purification. This paper reviews the role of AC in water purification, focusing on preparation methods, types of AC (powdered, granular, extruded, bead, carbon block, and impregnated forms), adsorption mechanisms, and diverse applications across medical, industrial, agricultural, and environmental sectors. The review also evaluates the comparative performance of AC-based filters, highlights limitations in removing inorganic pollutants such as heavy metals and nitrates, and emphasizes the integration of AC with hybrid technologies including membranes and nanocomposites. Finally, future directions are discussed, with particular attention to bio-based precursors, surface modification techniques, and cost reduction strategies for large-scale implementation.

INTRODUCTION

Access to clean and safe water remains one of the most pressing global challenges of the 21st century, as rapid industrialization, urbanization, and agricultural expansion continue to introduce a wide range of pollutants into both drinking water and wastewater streams. Conventional treatment technologies, though effective to a certain degree, often struggle with the removal of micro-contaminants, disinfection by-products, pharmaceuticals, and other persistent organic pollutants. Activated carbon (AC), a carbon-rich material characterized by an exceptionally high surface area and a highly developed microporous structure, has long been recognized as one of the most effective and versatile adsorbents for water purification. Unlike raw carbon, AC is produced through chemical or thermal activation processes that create millions of fine pores, significantly enhancing adsorption efficiency. This unique property enables AC to capture a broad spectrum of contaminants, while its relatively low cost, scalability, and adaptability make it indispensable for applications ranging from household filters to large-scale municipal and industrial treatment systems. Building on decades of development and innovation, this review provides a comprehensive analysis of AC-based water purification technologies, with a focus on preparation methods, types of AC filters, adsorption mechanisms, practical applications, and recent advances in hybrid and modified systems.

2.LITERATURE REVIEW

2.1. Preparation & Activation Methods

Thermal activation (TA) — TA creates micropores by treating carbonaceous precursors at high temperature in an inert atmosphere or steam; it produces AC with well-developed microporosity suited for organic adsorption (Marsh & Rodríguez-Reinoso, 2006).Chemical activation (CA) — CA (e.g., $ZnCl_2$, KOH) is applied before carbonization and often yields higher surface area at lower energy cost compared with TA; CA-derived carbons show different pore-size distributions that influence adsorption selectivity (Bandosz, 2006; Marsh & Rodríguez-Reinoso, 2006).
Biomass / waste precursors — Multiple studies highlight coconut shell, wood, coal, and agricultural residues as feedstocks; biomass-derived ACs offer sustainable, low-cost routes with tunable properties after activation (Dias et al. reviews summarized in Mezohegyi *et al.*, 2012; recent reviews detail bio-based AC trends). (Marsh & Rodríguez-Reinoso, 2006; Mezohegyi *et al.*, 2012; Azam *et al.*, 2022)

2.2. Types & Forms of Activated Carbon (PAC, GAC, CB, EAC, BAC, Impregnated)

Powdered Activated Carbon (PAC) — Widely used as a doseable adsorbent for taste/odor control and removal of dissolved organics in drinking-water plants; PAC contact time and dosing strategy strongly affect removal efficiency (Gai & Kim, 2008; Meinel *et al.*, 2016).Granular Activated Carbon (GAC) — Suited for continuous fixed-bed systems; thermal reactivation makes GAC economical for full-scale use, but channeling and biofouling remain operational concerns (Pelekani & Snoeyink, 1999; Lu *et al.*, 2020).Carbon Blocks (CB) — Densely packed carbon with reduced channeling and improved particle utilization; CBs often outperform loose-bed GAC for household filtration applications (user draft overview; Bandosz, 2006).Extruded / Bead / Impregnated carbons — EAC and BAC provide mechanical strength and low dust; impregnated carbons (e.g., Ag- or I-impregnated) add antimicrobial or catalytic functions for specific applications (user draft; Rey *et al.*, 2008). (Gai & Kim, 2008; Pelekani & Snoeyink, 1999; Rey *et al.*, 2008)

2.3. Pore Structure, Surface Chemistry & Adsorption Mechanisms

Pore-size importance — Pore size distribution controls competitive adsorption in complex waters: micropores favor small organics while meso/macropores accommodate larger molecules; matching pollutant size to pore distribution is critical (Pelekani & Snoeyink, 1999; Lu *et al.*, 2020).Physical vs. chemical adsorption — Van der Waals forces dominate physical adsorption, while surface functional groups (oxygenated, acidic/basic) enable chemisorption or catalytic reactions (Marsh & Rodríguez-Reinoso, 2006; Rey *et al.*, 2008).Influencing parameters — pH, ionic strength, temperature, contact time, and pre-treatment (e.g., coagulation) affect adsorption kinetics and capacity (Mezohegyi *et al.*, 2012; Bhatnagar *et al.*, 2013).

2.4. Removal of Organic Micropollutants, DBPs & VOCs

Endocrine disruptors & pharmaceuticals — AC (especially GAC/PAC) effectively adsorbs many neutral and hydrophobic micropollutants; membrane + AC combinations improve removal of polar compounds (Snyder *et al.*, 2007; Stoquart *et al.*, 2012).Disinfection by-products (DBPs) & THMs — AC reduces chlorine and chlorine-byproducts by adsorption and catalytic dechlorination, improving taste/odour and lowering DBP formation potential (Pelekani & Snoeyink, 1999; Mezohegyi *et al.*, 2012). (Snyder *et al.*, 2007)

2.5. Removal of Emerging Contaminants (PFAS, Pesticides, Polar Micropollutants)

PFAS — Recent pilot and full-scale studies show GAC can remove many long-chain PFAS, but performance depends on chain length, pore structure, and competitive NOM; periodic media replacement or more adsorptive carbons are often required (Kempisty *et al.*, 2022).

Pesticides & polar micropollutants — Tailored ACs with appropriate porosity achieve significant pesticide uptake; studies focusing on design of ACs for pesticide adsorption highlight surface chemistry tuning as key (Zieliński *et al.*, 2022; Minkus *et al.*, 2022).

2.6. Biological Activated Carbon (BAC) & Hybrid Systems

BAC (biologically active GAC) — BAC integrates adsorption with biodegradation on the carbon surface, reducing fouling and extending service life; pore distribution and biofilm dynamics control performance (Jin *et al.*, 2013; Lu *et al.*, 2020).AC-membrane hybrids — PAC/GAC combined with membranes (UF/MF/RO) improves micropollutant removal and can mitigate membrane fouling when properly implemented (Stoquart *et al.*, 2012; Qu *et al.*, 2018). Recent studies show AC functionalized membranes or TFN membranes with AC additives enhance separation and fouling resistance (Kim *et al.*, 2022; Kasula *et al.*, 2024).

3.METHODOLOGY

3.1 Preparation of Activated Carbon

- **Thermal Activation (TA):** involves high-temperature treatment in the presence of gases such as CO_2, N_2, or steam, leading to pore formation.
- **Chemical Activation (CA):** applies chemical agents (acids, bases, salts) to raw carbon precursors prior to carbonization, producing higher pore density at lower energy costs.
- **Raw Materials:** AC can be derived from coconut shells, peat, lignite, wood, olive pits, and agricultural waste, making it both versatile and sustainable.

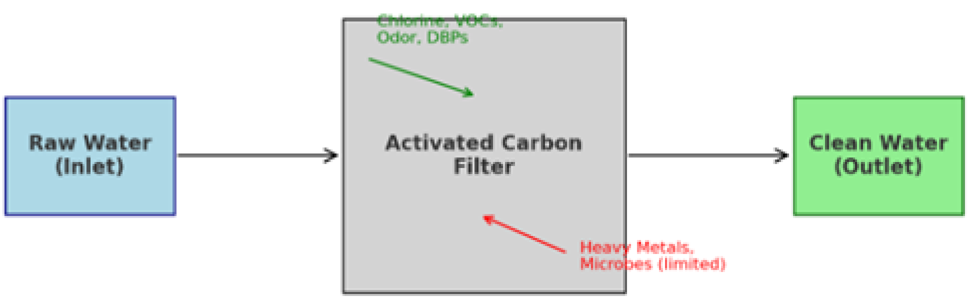

Fig no 1:Schematic Diagram of Activated Carbon Filtration in Water Purification.

3.2 Types of Activated Carbon for Water Treatment

- **Powdered Activated Carbon (PAC):** fast-acting, effective for taste/odor control and organic pollutant removal, typically dosed at 1–20 mg/L.

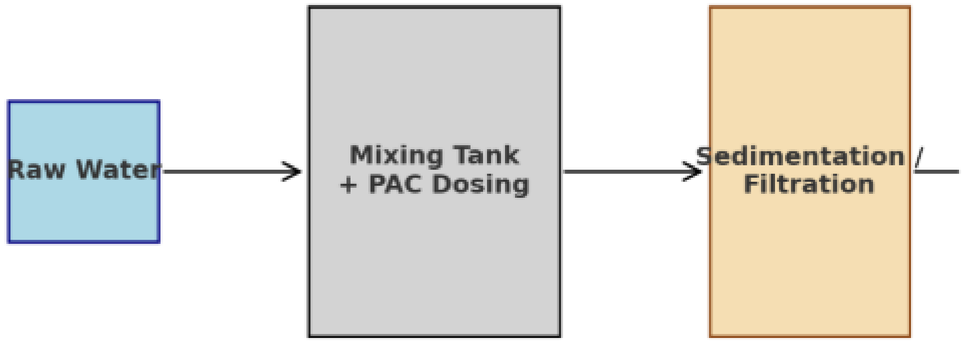

Fig no 2: Powdered Activated Carbon System

- **Granular Activated Carbon (GAC):** widely used in continuous systems, cost-effective due to thermal reactivation, suitable for fixed-bed filters.
- **Extruded Activated Carbon (EAC):** cylindrical pellets with high mechanical strength, often used in air/gas purification but adaptable for water treatment.
- **Bead Activated Carbon (BAC):** spherical particles with low dust content, applied in wastewater treatment.
- **Carbon Block (CB) Filters:** compressed AC providing high contaminant removal efficiency with minimized channeling.
- **Impregnated/Woven/Polymer AC:** modified forms incorporating agents like silver, iodine, or polymers to enhance antimicrobial or catalytic functions.

3.3. Adsorption Mechanisms

- **Physical adsorption:** Van der Waals forces trapping contaminants within micropores.
- **Chemical adsorption:** Reactions with functional groups, e.g., chlorine reduction to chloride ions.
- **Pore size selectivity:** Larger pores capture bulky organics, while micropores adsorb smaller contaminants.
- **Influencing factors:** pH, temperature, contact time, contaminant concentration, and AC surface chemistry.

4. RESULTS AND DISCUSSION

1. Adsorptive Efficiency and Mechanisms

Activated carbon (AC) demonstrates high efficiency in removing organic micropollutants, chlorine by-products, and volatile organic compounds (VOCs) due to its large surface area and microporous structure. For instance, Pelekani & Snoeyink (1999) reported that pore-size distribution plays a decisive role in competitive adsorption in natural waters, while Mezohegyi *et al.* (2012) highlighted the removal of dyes through both physical adsorption and chemical interactions. These findings confirm that adsorption is the dominant mechanism, influenced by operational parameters such as pH, temperature, and contact time.

2. Comparative Performance of PAC and GAC

In contrast, granular activated carbon (GAC) in fixed beds offers long-term operation with the added benefit of reactivation and reuse, although operational issues such as channeling and biofilm growth remain challenges (Lu *et al.*, 2020). PAC is therefore more suited for shock-load treatment, whereas GAC is favorable for continuous purification.

Parameter	Powdered Activated Carbon (PAC)	Granular Activated Carbon (GAC)
Particle Size	Very fine (<0.18 mm)	Granular (0.2–5 mm)
Typical Use	Added directly to water (batch/mixing)	Fixed-bed continuous filtration
Dosage/Operation	1–20 mg/L (shock dosing)	Flow-through operation (months before regeneration)
Advantages	Fast action, effective for taste/odor and micro-pollutants	Reusable (can be thermally reactivated), good for continuous use
Limitations	Requires removal via sedimentation/filtration; cannot be reused	Channeling, biofilm growth, higher initial cost
Common Applications	Taste & odor control, seasonal pollutant removal	Drinking water treatment, wastewater polishing, industrial filtration

Table 1: Comparison table PAC vs. GAC.

3. Hybrid AC-Membrane Systems

Hybrid configurations are emerging as promising alternatives to enhance water treatment performance. Snyder *et al.* (2007) showed that PAC combined with ultrafiltration significantly improves removal of pharmaceuticals and endocrine disruptors. Similarly, Qu *et al.* (2018) demonstrated that biologically active carbon (BAC) pre-treatment reduced ultrafiltration membrane fouling in rural water supplies. These results highlight the synergistic effect of AC adsorption and membrane separation, paving the way for next-generation treatment technologies.

4. Removal of Emerging Contaminants

Recent studies emphasize the importance of AC in removing per- and polyfluoroalkyl substances (PFAS), pesticides, and polar micropollutants. Kempisty *et al.* (2022) reported effective PFAS adsorption in pilot- and full-scale systems, though regeneration frequency is a limitation. Zieliński *et al.* (2022) developed modified ACs with enhanced pesticide adsorption, while Minkus *et al.* (2022) showed PAC's ability to adsorb polar contaminants with distinct molecular fingerprints. These findings suggest that tailoring pore structures and surface chemistry is crucial for tackling emerging pollutants.

CONSLUSION

ctivated carbon (AC) continues to stand out as one of the most effective, adaptable, and widely studied materials for water purification. Its unique combination of high surface area, tunable pore structure, and adsorption capacity enables the removal of a wide spectrum of contaminants, ranging from chlorine by-products and pesticides to pharmaceuticals and volatile organic compounds. Both powdered activated carbon (PAC) and granular activated carbon (GAC) systems have proven successful in practical applications, with PAC providing fast-response treatment during seasonal contamination events and GAC offering sustainable, long-term operation through reactivation and reuse. The ability of AC to integrate seamlessly into household, municipal, and industrial-scale treatment systems underscores its versatility.

Recent research points toward promising solutions. Advances in nanostructured composites (e.g., AC–TiO_2, AC–graphene hybrids), bio-based precursors from agricultural residues, and tailored surface functionalization for selective adsorption are expanding the applicability of AC to emerging contaminants such as PFAS, pesticides, and endocrine disruptors. Moreover, hybrid treatment systems that combine AC with membrane filtration, advanced oxidation processes, or biological treatment units are showing superior contaminant removal efficiencies while mitigating issues such as fouling and regeneration costs. These developments indicate that the role of AC is transitioning from a stand-alone adsorbent to a multifunctional component within integrated water treatment frameworks.

6.FUTURE WORK

Future studies should focus on functionalizing activated carbon to improve removal of inorganic pollutants like arsenic, nitrates, and heavy metals. Greater attention is needed on hybrid systems combining AC with membranes, oxidation, or biological treatments, supported by full-scale trials. Sustainable production from agricultural wastes and energy-efficient regeneration methods should be advanced to lower costs and environmental impact. Research must also target emerging contaminants such as PFAS, pharmaceuticals, and microplastics, while integrating smart monitoring and AI tools to optimize system performance. Finally, context-specific, low-cost solutions are essential to make AC-based technologies accessible for developing regions.

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