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Review

Activated carbon: An effective and affordable solution for water purification

Reza Joia[1], Mohammad Ali Nasiri[2], Meiram Atamanov[3], Sayed Reza Sarwari[1], Mohammad Sanayi Haqmal[1]

[1] Department of Chemistry, Faculty of Education, Nimruz University, Zaranj 430101, Afghanistan;
[2] Department of Chemistry, Faculty of Natural science, Bamyan University, Bamyan 160101, Afghanistan;
[3] Department of Chemical Physics and Material Science, Faculty of Chemistry and Chemical Technology, Al-farabi Kazakh National University, Almaty 050040, Kazakhstan
[*] **Corresponding author:** Reza Joia; rezajoia56@gmail.com

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Abstract: Access to safe drinking water is universally recognized as a fundamental human right; however, millions of people worldwide continue to face limited access to clean and safe water resources. The presence of contaminants such as heavy metals, organic compounds, dyes, pesticides, pharmaceuticals, and pathogenic microorganisms poses significant threats to human health and aquatic ecosystems. Conventional water treatment technologies, although effective in certain applications, are often associated with high operational costs, energy requirements, and limited efficiency toward emerging pollutants. Consequently, the development of sustainable, low-cost, and efficient water purification materials has gained increasing scientific attention. This review investigates the effectiveness of activated carbon as a promising adsorbent for drinking water purification and examines the principal mechanisms involved in pollutant removal. Various forms of activated carbon produced from agricultural waste-derived precursors were comparatively evaluated. Reported studies indicate that activated carbon exhibits a high specific surface area ranging from 300 to 2500 $m^2.g^{-1}$ and achieves removal efficiencies exceeding 90% for volatile organic compounds (VOCs), chlorine, dyes, and toxic heavy metals including Pb^{2+}, Cd^{2+}, and Cr^{6+}. The adsorption capacities of activated carbon for different contaminants were reported to range from 50 to more than 500 $mg.g^{-1}$, depending on precursor type, activation process, and operational conditions. Furthermore, regeneration efficiencies commonly remained within 70–85% after multiple adsorption–desorption cycles, highlighting the economic feasibility and environmental sustainability of activated carbon.

Keywords: water purification; contaminants; pollutants; adsorption mechanisms; activation methods.

1. Introduction

Ensuring access to clean and safe drinking water is a major challenge faced globally [1], and on the other hand, various industrial, agricultural [2], pollution of surface and ground waters such as springs, seas, streams, lakes, and water storage dams, thereby directly and indirectly endangering human and animal lives. These pollutants include municipal wastes, storms, improper waste, chemical accidents, oil spills and other pollutants see (**Figure 1**). Pollutants such as organic compounds, chlorine, sediments, and undesirable tastes and odors often compromise water quality and pose significant health risks. Scientists have used various methods for water purification such as adsorption, magnetic separation, flocculation, aerobic and anaerobic processes, reverse osmosis, filtration, and oxidation [3], as shown in (**Table 1**). Among the water purification methods mentioned, the use of activated carbon is significant because of its efficiency, versatility, and cost-effectiveness. Activated carbon is a porous form of carbon that has been processed to have a high surface area, and it is widely used for water purification due to its significant adsorption properties [4]. Activated carbon is created by carbonizing organic materials such as wood [5], peat [6], coal [7], and coconut shells [8]. The activation process includes chemicall [5], physical [4], physicochemical [9], and microwave activation [10], as well as other techniques such as plasma-assisted activation [11], electrochemical activation [12], template-assisted synthesis [13], and ultrasound-assisted activation [14]. Some of the most commonly used methods for the production of activated carbon will be discussed in this review.

These methods allowed scientists to obtain activated carbons with a large network of small pores on the carbon surface. These pores enhance the surface area of the material that enables it to adsorb a broad spectrum of impurities from water. This adsorption capability is critical in the removal of contaminants that impact the taste, odor, and safety of drinking water. Activated carbon has the important advantage of being able to treat a broad spectrum of contaminants. A common disinfectant in water treatment, chlorine can cause unpleasant tastes and odors, and this is very effective for its removal. Activated carbon is also very good for the adsorption of organic compounds such as pesticides and industrial chemicals, which are toxic even at very low concentrations. The versatility of activated carbon makes it essential in both household water filters and large municipal water treatment plants [15].

Table 1. Methods utilized for water purification.

No	Methods	References
1	Adsorption	[16]
2	Magnetic Separation	[17]
3	Flocculation	[18]
4	Aerobic and anaerobic	[19,20]
5	Reverse Osmose	[21,22]
6	Filtration	[1,23]
7	Oxidation	[24]

In addition to its adsorption properties, activated carbon has several practical advantages. It is relatively easy to work with and can be regenerated or replaced if it becomes saturated with contaminants [2]. This regeneration process, which often involves thermal or chemical methods, restores the carbon's adsorption capacity, making it a cost-effective solution for long-term use [25]. Activated carbon can also be used in combination with other purification techniques such as membrane filtration and UV disinfection, thus enhancing the overall efficiency of water treatment systems [22]. Activated carbon is used for drinking water treatment not only in developed areas but also in areas where access to clean water is a constant challenge. Activated carbon is important in many developing countries for community-based water treatment systems and provides a safe, reliable, and affordable way to provide safe drinking water. It is especially useful in emergency situations such as natural disasters or humanitarian crises where quick deployment of effective water treatment solutions is required [26].

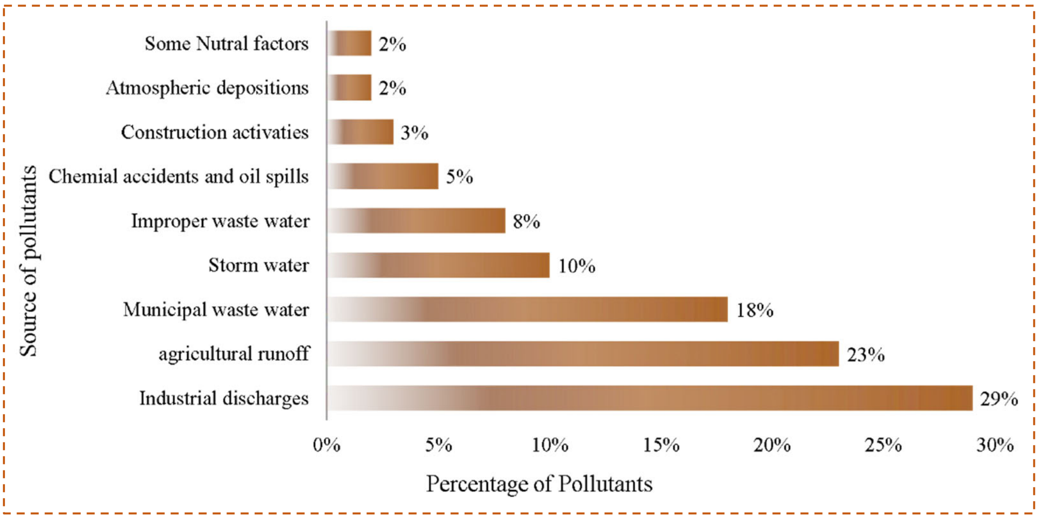

Figure 1. Show the water pollutant sources in percentage [27].

As mentioned, numerous research and review studies have investigated the application of activated carbon in water purification; however, most previous works primarily focused on adsorption performance, synthesis methods, or specific categories of contaminants. In addition, limited attention has been given to the comparative evaluation of agricultural waste-derived activated carbons, regeneration efficiency, large-scale applicability, and the relationship between pore structure, surface chemistry, and adsorption mechanisms for both organic and inorganic pollutants. The novelty of the present review lies in its comprehensive and integrated assessment of activated carbon derived from agricultural waste materials for drinking water purification. This review not only summarizes the preparation and regeneration methods of activated carbon but also critically discusses the adsorption mechanisms involved in the removal of heavy metals, dyes, volatile organic compounds, and emerging contaminants. Furthermore, the study comparatively analyzes the influence of precursor materials, activation techniques, pore characteristics, and surface chemistry on adsorption efficiency and regeneration performance.

2. Preparation methods of activated carbon

The production of activated carbon begins with selecting, cleaning, washing, and drying a suitable raw material. Following these preparatory steps, the process involves two main stages: carbonization and activation [28], which are detailed below.

2.1. Carbonization process

During the carbonization process, the chosen and dried material is exposed to heat in a non-reactive medium, such as nitrogen. The temperatures used for carbonization normally range between 400 and 700 °C. During the carbonization process, the material loses its volatiles and decomposes to form a carbon-rich solid. As a consequence, the porosity of the material starts to develop [29].

This particular process is essential since it forms the basis on which activation is done by developing a substance with sufficient surface area in order for the process of adsorption to occur in the context of water purification. Through proper regulation of the carbonization process and the conditions under which it occurs, such as temperature and the atmosphere in which the reaction takes place, the structure of the activated carbon is created. Carbonization is an important stage in the production of activated carbon whereby the carbon source is transformed into the required char form through which activation is done [30].

2.2. Activation process

The char undergoes activation to develop a porous structure and adsorption properties. Researchers utilize various activation methods (**Figure 2**) based on the type of precursor and available equipment. Each method is chosen to optimize the production of activated carbon, ensuring effective adsorption capabilities for different applications [31].

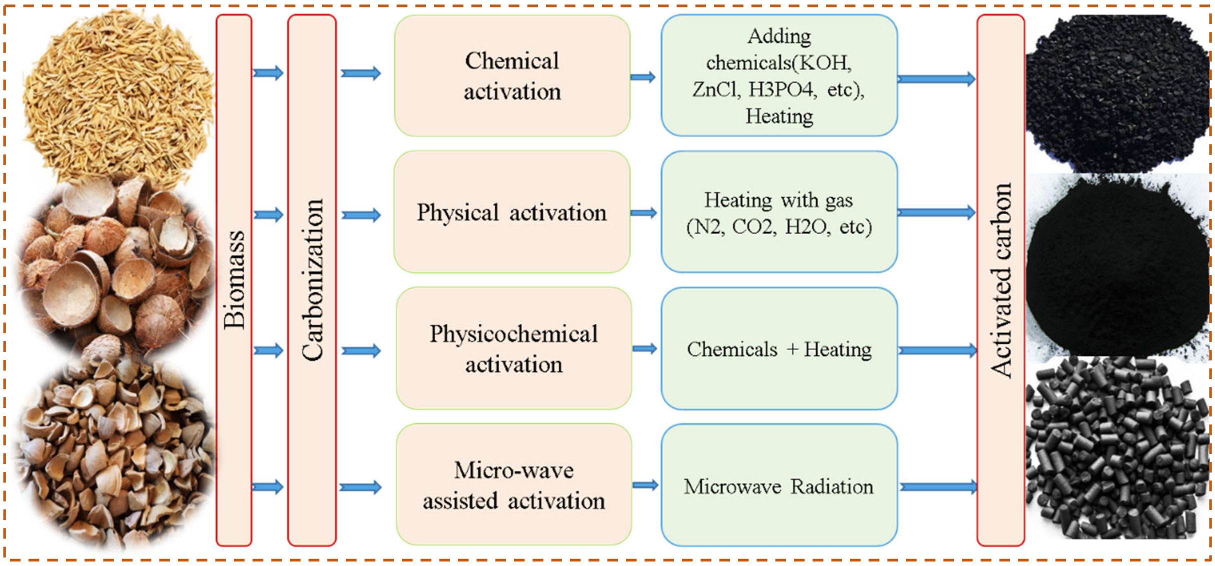

Figure 2. Illustrate the production methods of activated carbon.

2.3. Physical activation

Physical activation is one technique that involves the production of activated carbon through increased porosity and adsorption capability. There are two major steps that make up this technique: carbonization, which is followed by the second step, that is, activation. Let us examine this technique in detail. First, there is the selection of a raw material for the activation process, such as wood, coconut shell, and coal. Raw materials are usually heated in an inert environment, for instance, nitrogen gas, between the temperatures of 400 to 700 °C [32]. The char is then subjected to physical activation, where it is exposed to an oxidizing gas, such as steam or carbon dioxide, at high temperatures (800 to 1100 °C). This step further develops the porous structure by reacting with the carbon material [33]. These gases act on the carbon and form a structure of micropores and mesopores, thereby greatly increasing the surface area and the adsorption capacity of the activated carbon. Lastly, the activated carbon is cooled down, and in some cases, it is even cleaned of any leftover ash or impurities. This results in the creation of an activated carbon that is highly porous and has great adsorption characteristics [29]. The researchers obtained very efficient and applicable activated carbon for the purification of water from different pollutants such as shown in (**Table 2**).

Table 2 Present research highlights the use of physical production methods to obtain activated carbon (AC) for water purification.

Table 2. Activated carbons obtained by the physical activation method for water purification.

No	Precursor	Activator	T_{AC}	Surface area	Adsorbed	Adsorption capacity	Ref
1	(Acacia mangium) wood	N_2	500 °C	377.18 m^2/g	Cr(VI)	37.16 mg/g	[34]
2	Tropical almond shells	80% CO_2 + 20% steam	850 °C	1074 m^2/g	Lead	114.8 mg/g	[32]
3	Guava seeds	80% CO_2 + 20% steam	850 °C	1201 m^2/g	Lead	92.9 mg/g	[32]
4	Dindé stones	80% CO_2 + 20% steam	850 °C	1029 m^2/g	Lead	53.1 mg/g	[32]
5	Distiller’s grain (DG)	N_2/CO_2	800 °C	1430 m^2/g	Methylene blue	934.6 mg/g	[35]
6	Avocado seed	CO_2	1173°K	206 m^2/g	Phenol	90 mg/g	[36]
7	Vine shoot	CO_2	800 °C	956 m^2/g	Phenol	249 mg/g	[36]
8	Oil palm wood	CO_2/steam	806 °C	1084 m^2/g	Methylene blue	90.9 mg/g	[37]
9	Date stones	steam	-	263 m^2/g	Aldrin, dieldrin, endrin	373.2, 259.3, 228.04 mg/g respectively	[38]
10	Powder of cork	steam	750 °C	-	Ibuprofen	378.1 mg/g	[39]
11	date seeds	CO_2	800 °C	502.70 m^2/g	CO_2	141.14 mg/g	[28]

2.4. Chemical activation

Chemical activation is a crucial process in the production of activated carbon, and scientists produce a wide range of activated carbon by this with high adsorption capacity, as shown in (**Table 3**). It involves the impregnation of raw materials such as wood, coconut shells, or coal with chemical activating agents like phosphoric acid (H_3PO_4) [40], potassium hydroxide (KOH) [41], or zinc chloride ($ZnCl_2$) [37,42]. This process significantly enhances the material's porosity and adsorption capacity. The first step is impregnation, where the raw material is mixed with a chemical activating agent. The choice of chemical depends on the desired properties of the activated carbon and the type of precursor material [43]. The mixture is typically heated to ensure thorough impregnation. Next, the impregnated material is subjected to high temperatures, generally between 400 and 700 °C. This heating process, conducted in an inert atmosphere such as nitrogen, facilitates the chemical reactions necessary for activation [15]. During heating, the activating agent reacts with the raw material, leading to the decomposition of organic substances and the creation of a porous structure. The chemical agents help in breaking down the material and forming a network of micro- and mesopores [44]. After activation, the product is washed with water or acid to remove any residual chemicals and by-products formed during the activation process. This washing step is essential to neutralize the activated carbon and ensure it is safe for use. At the end, the activated carbon is dried to remove any remaining moisture. The resulting product is a highly porous and adsorptive material ready for various applications, such as water purification, air filtration, and industrial processes [45].

Table 3 Exhibits research highlights the use of chemical production methods to obtain activated carbon (AC) for water purification.

Table 3. Activated carbons obtained by chemical activation method for water purification.

No	Precursor	Chemical agent of activation	Applied temperature of activation	Surface area	Adsorbed	Adsorption capacity	Ref
1	Sugarcane bagasse	H_3PO_4	500 °C	320 m^2/g	Pb^{2+}	170.90 mg/g	[46]
2	Stump wood	KOH, NaOH	750 °C	1937 m^2/g	Bis-phenol A	2.195mmol/g	[5]
3	Olive stone	H3PO4	600 °C	1565 m^2/g	Cd^{2+}	24.83 mg/g	[47]
4	Hazelnut shell	$ZnCl_2$	700 °C	1067 m^2/g	Pb^{2+}	13.05 mg/g	[48]
5	Coconut shell	KOH	800 °C	1135 m^2/g	Pb^{2+}	151.52 mg/g	[49]
6	Prickly pear seeds	H_3PO_4	800 °C	1161.3 m^2/g	Deltamethrin	1.13 mg/g	[50]
7	Olive stone	$ZnCl_2$	650 °C	790 m^2/g	Cd^{2+}	1.85 mg/g	[42]
8	Banana peel	KOH	800 °C	2086 m^2/g	Methylene blue	385.12 mg/g	[51]
9	Pineapple waste	$ZnCl_2$	500 °C	915 m^2/g	Methylene blue	288.34 mg/g	[2]
10	Cotton stalk	H_3PO_4	500 °C	1570 m^2/g	Pb^{2+}	119 mg/g	[40]
11	Tea seed shell	$ZnCl_2$	500 °C	1531 m^2/g	Methylene blue	342.70 mg/g	[52]
12	Coconut husk	KOH	700 °C	1356 m^2/g	Methylene blue	418.15 mg/g	[53]

2.5. Physicochemical activation method

Physicochemical activation is an activation process that utilizes both the physical and chemical aspects for making activated carbon. The advantage of both carbonization and chemical activation is harnessed through the process. It makes for an excellent adsorbent with superior performance [16], see (**Table 4**). The process begins with the selection and drying of a suitable raw material, such as wood, coconut shells, or coal. The raw material is first impregnated with a chemical activating agent, such as phosphoric acid (H_3PO_4), potassium hydroxide (KOH) [43], or zinc chloride ($ZnCl_2$) [37]. The chemical treatment increases the reactivity of the material and helps form the porous structure. The blend is then carbonized by heating it under an inert atmosphere, normally nitrogen gas, at a temperature between 400 °C and 700 °C. In this process, the volatile materials are removed, and the formation of the carbon structure begins. After carbonization, the impregnated material is physically activated by treating it with oxidizing gases like steam and carbon dioxide at high temperatures of 800 to 1100 °C [29,43]. This additional step further develops the material's pore structure and significantly increases its surface area and adsorption capacity. The oxidizing gases react with the carbon, creating a network of micro- and mesopores that enhance the material's ability to adsorb contaminants. After activation, the activated carbon is washed to remove any residual chemicals and by-products formed during the process [54]. The final product is then dried, resulting in a highly porous and adsorptive material ready for use in various applications, including water purification, air filtration, and industrial processes. Physicochemical activation is favored for its ability to produce activated carbon with superior adsorption properties, combining the advantages of both chemical and physical activation methods [9,55].

Table 4 Exhibit the literature of physicochemical methods for the production of ACs utilized in water purification.

Table 4. Activated carbons obtained by physicochemical activation methods for water purification.

No	Precursor	activator	Activation temperature (°C)	SBET (m^2/g)	Adsorbed	Adsorption capacity	Ref
1	Acacia nilotica	N_2/H_3PO_4	250		Reactive Black 5 dye	41.01mg/g	[56]
2	Date stone	Steam/H_3PO_4	800	1100	Methylene blue	240 mg/g	[57]
3	Rice husk	CO_2/KOH	800	1836	Phenol	-	[58]
4	Date seed	CO_2/KOH	850	1322.2	Bentazon, Carbofuran	86.3 mg/g	[59]
5	Date seed	CO_2/KOH	850	-	Carbofuran, 2,4-D	78.13, 135.14 and 175.4 mg/g respectively	[60]
6	Acacia wood	CO_2/KOH	110	1045.56	Methylene blue	81.20 mg/g	[9]

2.6. Microwave-assisted activation

Microwave-assisted activation is a technique that enhances the porosity and adsorption properties of activated carbon. Raw materials like coconut shells are impregnated with chemical activating agents such as phosphoric acid or potassium hydroxide [61]. These materials are then exposed to microwave energy, which heats them rapidly, facilitating the chemical reactions needed for activation [25]; the procedure of production is illustrated in (**Figure 3**). This process creates a highly porous structure with a large surface area. The material is then cooled, washed to remove residual chemicals, and dried, resulting in activated carbon with excellent adsorption properties. This method is efficient, consumes less energy, and produces superior activated carbon [62].

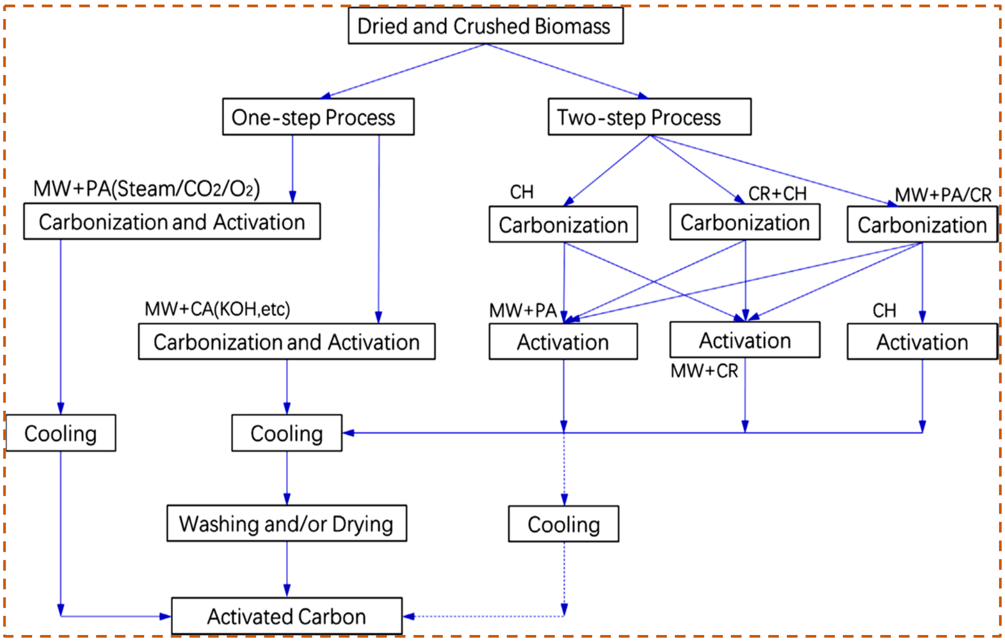

Figure 3. Schematic representation of activated carbon (AC) preparation from biomass using microwave (MW) irradiation. The process includes conventional heating (CH), chemical reagents (CR), and physical activation agents (PA) [25,2,33].

3. Application of activated carbon

Activated carbon is a versatile material used in various applications due to its exceptional adsorption properties [63]. It plays a critical role in water purification, removing contaminants such as chlorine [64], pesticides [65], herbicides [25], and volatile organic compounds (VOCs) [66] from drinking water, which improves taste and odor while ensuring safety. In air purification, activated carbon is utilized in air filters to remove pollutants, odors, and harmful gases, enhancing indoor air quality and industrial settings [67]. In the medical field, activated carbon is used to treat poisoning and overdose cases by adsorbing toxins and chemicals from the gastrointestinal tract, preventing their absorption into the bloodstream [33]. The food and beverage industry employs activated carbon to remove impurities, decolorize products, and improve taste and quality [68]. Environmental remediation relies on activated carbon to treat contaminated soil and water, helping to remove pollutants such as heavy metals and organic contaminants [69]. Various industrial processes benefit from activated carbon in solvent recovery, gold purification, and as a catalyst support in chemical reactions. In cosmetics and personal care, activated carbon is increasingly used in skincare products and cosmetics for its ability to absorb impurities and toxins from the skin [70]. Its broad range of applications makes activated carbon invaluable in multiple industries, contributing to cleaner water, air, and improved health and safety [33].

3.1. Water purification mechanisms

The quality of water is evaluated and measured based on a long variety of chemical and physical parameters [27] as shown in (**Figure 4a,b**). Scientists have used different methods and materials to purify it, but activated carbon is one of the most effective materials in water purification and is widely used in various water purification systems. Due to its special properties, this material can remove various contaminants from water [71], as schematically shown in (**Figure 4c**). It is widely used in drinking water purification, helping to remove chlorine, unpleasant odors and tastes and thus improving water quality [72]. In the wastewater treatment process, activated carbon can reduce organic pollutants and toxic substances, which is especially important in industries producing wastewater containing harmful chemicals [73]. Many home water filters use activated carbon to remove contaminants and are usually installed in taps, water bottles, and water purification systems. In aquariums, activated carbon helps maintain water quality by removing toxins and pollutants that are harmful to fish [74]. Various industries use activated carbon for industrial water purification and chemical pollution reduction, helping to remove heavy metals and other hazardous contaminants [48]. Activated carbon is used effectively for water purification in some groundwater treatment projects that are challenged by chemical contamination [75]. It purifies water through several key mechanisms, mainly based on adsorption, chemical, and physical reactions as shown in (**Figure 5a–d**).

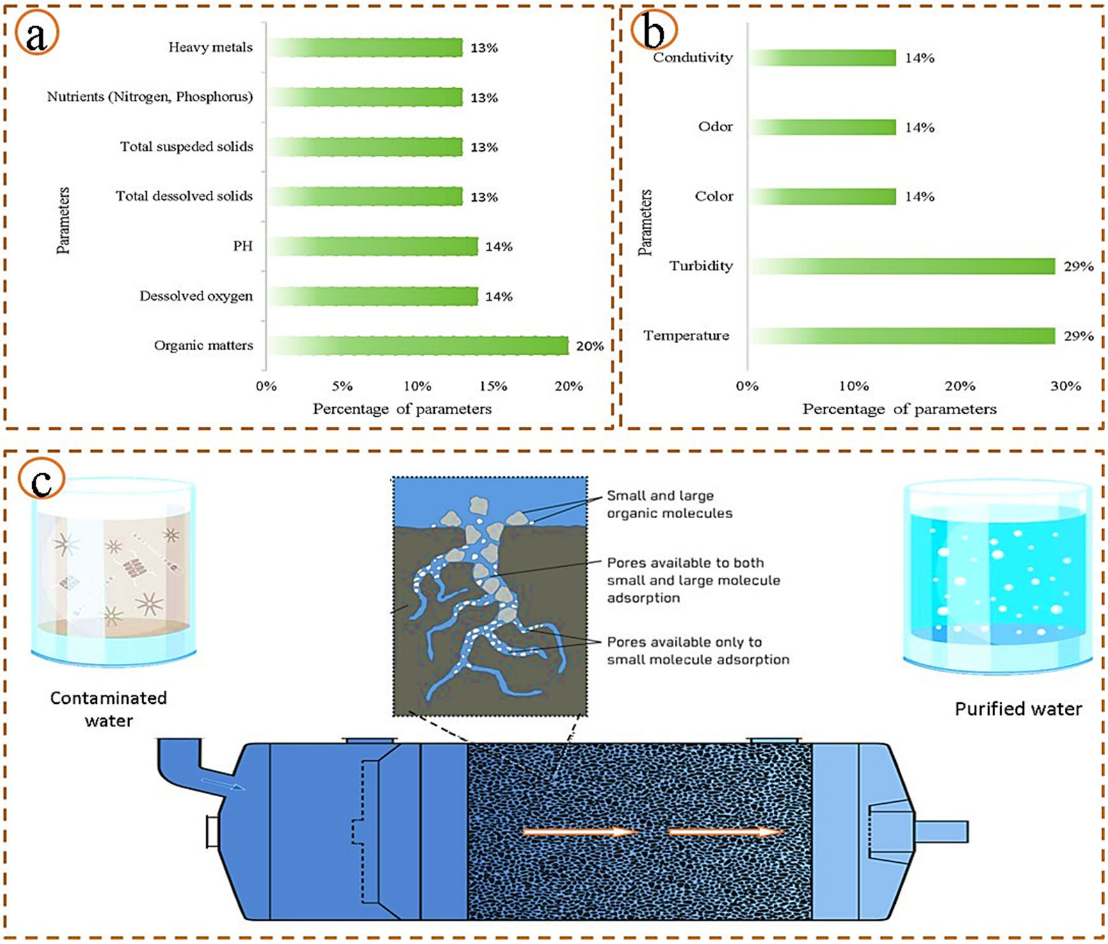

Figure 4. (**a**) Illustrate the chemical parameters. (**b**) physical parameters for water quality control [27]. (**c**) Show the effect of activated carbon for purification of water.

Adsorption: This is the primary mechanism through which activated carbon removes impurities (**Figure 5a**). The large surface area and porous structure of activated carbon allow it to trap and hold a wide range of contaminants [76]. Pollutants adhere to the surface of the carbon particles through physical adsorption. This process effectively removes organic compounds, chlorine, and undesirable tastes and odors from water [77].

Chemical Reactions: Activated carbon also facilitates chemical reactions that break down specific contaminants [78], (**Figure 5b**). For instance, it can catalyze the reduction of chlorine into chloride ions, effectively neutralizing the taste and odor of chlorinated water. Additionally, it decomposes various organic compounds through oxidation or reduction reactions. These chemical mechanisms, including the formation of chemical bonds and irreversible adsorption, enable activated carbon to trap pollutants and purify water efficiently [79].

Pore Size Distribution: The effectiveness of activated carbon is influenced by the distribution of pore sizes within the material [80]. Micro-pores are ideal for adsorbing small molecules, while meso- and macro-pores can capture larger contaminants (**Figure 5c**). This multi-pore structure ensures a broad spectrum of pollutants can be removed [81].

Physical filtration: Although it’s not its primary role, activated carbon’s porous structure enables it to function as a physical filter. It traps particulate matter and sediments in the water through Van der Waals forces and reversible adsorption mechanisms [82], (**Figure 5d**). This additional filtration capability helps to further improve water clarity and quality. These combined mechanisms make activated carbon a highly effective and versatile material for water purification, capable of significantly improving water quality by removing a wide range of contaminants [83].

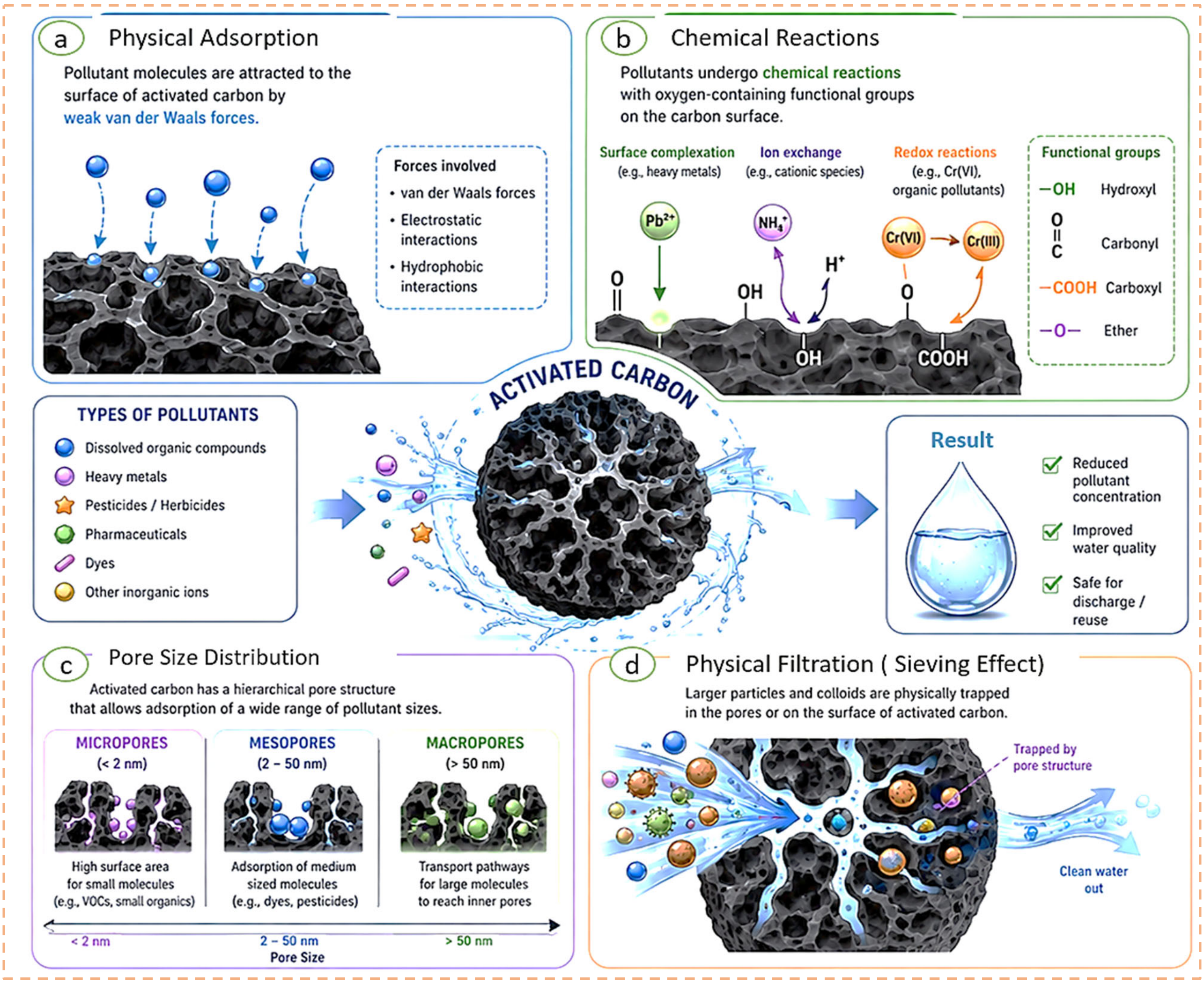

Figure 5. The schematic illustrates the mechanisms involved in the adsorption of pollutants from water by activated carbon: (**a**) physical adsorption, (**b**) chemical adsorption, (**c**) pore size distribution, and (**d**) physical filtration.

3.2. Removing of pollutants

3.2.1. Role of activated carbon for organic pollutants removal

Activated carbon is widely recognized as one of the most effective materials for removing a wide range of organic pollutants from water [84], (**Figure 6a**). The unique adsorption capacity is attributed to the high surface area and porous nature of the material, allowing for effective pollutant capture and retention. This review examines the process of organic contaminant adsorption by activated carbon, focusing on VOCs, pesticides, herbicides, industrial solvents, natural organic materials, dye molecules [85].

3.2.1.1. Volatile organic compounds (VOCs)

Volatile Organic Compounds (VOCs) are a significant group of organic pollutants commonly found in water due to industrial discharge and urban runoff [2]. VOCs such as benzene, toluene, ethylbenzene, xylene, chloroform, trichloroethylene (TCE), methyl tert-butyl ether (MTBE), and perchloroethylene (PCE) are known for their volatility and potential health risks [86]. Activated carbon effectively adsorbs these compounds, preventing them from causing adverse health effects. The high surface area and porous structure of activated carbon provide ample sites for these molecules to adhere, significantly reducing their concentration in water and improving overall water quality [66]. Adsorption process starts once the water contaminated with the VOCs comes into contact with activated carbon. As soon as the VOC molecules come into contact with the carbon granules, they get attached to the surfaces. This process is physically based and occurs due to the existence of van der Waals forces and interactions between the molecules of the contaminants and carbon surface. Large amount of the adsorption sites provided by the activated carbon allows effective adsorption of the contaminants from water [87].

3.2.1.2. Pesticides

Pesticides, used extensively in agriculture to control pests and diseases, often find their way into water bodies through runoff and leaching [50]. Common pesticides that can contaminate water include imidacloprid (Confidor), permethrin, malathion, carbaryl (Sevin), mancozeb, chlorothalonil, copper sulphate, and propiconazole. These chemicals pose serious risks to aquatic ecosystems and human health [88]. Activated carbon is highly effective at removing these pesticides from water. The adsorption process captures pesticide molecules on the carbon's surface, reducing their presence in water supplies and mitigating their harmful effects [89].

Pesticides typically have a complex chemical structure, which can vary widely in terms of polarity, molecular size, and functional groups [90]. These characteristics influence the adsorption process on activated carbon. Hydrophobic pesticides, which do not dissolve well in water, are particularly well-adsorbed by activated carbon due to their affinity for the non-polar carbon surface. Additionally, the porous structure of activated carbon allows it to trap large pesticide molecules, ensuring comprehensive removal from water [38].

3.2.1.3. Herbicides

Herbicides such as glyphosate (Roundup), atrazine, 2,4-dichlorophenoxyacetic acid (2,4-D), and dicamba are commonly used to control unwanted vegetation [90]. These substances can also contaminate water sources, posing a threat to both the environment and public health. Activated carbon adsorbs herbicide molecules, effectively reducing their concentration in water. This removal process not only improves water quality but also protects aquatic life and reduces the potential for human exposure to these harmful chemicals [91]. The effectiveness of activated carbon in removing herbicides depends on the specific chemical properties of the herbicides. Some herbicides are more readily adsorbed due to their non-polar nature, while others may require modifications to the carbon surface to enhance adsorption [76]. The high surface area and pore structure of activated carbon provide ample adsorption sites, ensuring that a wide range of herbicides can be effectively removed from water [92].

3.2.1.4. Dyes and colors

Industrial processes, especially in textiles and dyeing, often release numerous dyes into water, impacting water quality [37]. With around 3,600 different dyes in use, activated carbon proves effective in removing these contaminants due to its large surface area and adsorption capacity [2]. By trapping dye molecules, activated carbon enhances both the visual and chemical quality of water, making it safer for the environment and human use [10,37]. The varying chemical structures and sizes of dye molecules influence their adsorption, but the porous nature of activated carbon ensures effective removal. This process also reduces color and turbidity, improving the water's appearance and safety [93].

3.2.2. Inorganic pollutants

Inorganic pollutants in water are diverse substances that pose significant risks to both human health and the environment. While activated carbon is primarily renowned for its efficiency in adsorbing organic pollutants, it also plays a crucial role in removing certain inorganic contaminants [94]. These pollutants include heavy metals, salts, radioactive substances, and other inorganic compounds (**Figure 6b**), all of which can have detrimental effects on water quality and safety [95]. Heavy metals such as lead (Pb), mercury (Hg), arsenic (As), cadmium (Cd), and copper (Cu) are common inorganic pollutants in water [96]. These metals often originate from industrial discharges, mining activities, and improper waste disposal. Lead, for example, can enter water supplies through the corrosion of old plumbing systems or industrial waste. Exposure to lead-contaminated water is particularly harmful to children, leading to developmental delays and neurological damage [40,49]. Mercury, another toxic heavy metal, can leach into water bodies from industrial processes, mining, and even improper disposal of household items like batteries. Chronic exposure to mercury can cause severe neurological and renal damage [97]. Arsenic, cadmium, and copper are similarly hazardous, with arsenic being notorious for its carcinogenic properties, cadmium for kidney damage, and copper for gastrointestinal distress at high levels [48,98]. Salts, another group of inorganic pollutants, include nitrates (NO_3^-), phosphates (PO_4^{3-}), sulphates (SO_4^{2-}), and chlorides (Cl^-). These salts frequently come from agricultural run-off, where fertilizers and pesticides are used extensively [76]. Nitrates, for instance, can cause methemoglobinemia or "blue baby syndrome" in infants, impairing the blood's ability to carry oxygen. Phosphates and sulphates contribute to eutrophication, a process where nutrient-rich waters promote excessive growth of algae, leading to oxygen depletion and harming aquatic life [99]. Chlorides, while less immediately toxic, can affect the taste of drinking water and corrode infrastructure, leading to increased maintenance costs and potential contamination from corroded pipes [27].

Radioactive substances such as cesium (Cs), iodine (I), uranium (U), and radon (Rn) can contaminate water from natural deposits, nuclear power plants, and medical waste [94]. Cesium and iodine are by-products of nuclear reactions and can be introduced into the environment through accidents or improper disposal of nuclear waste [100]. Uranium, naturally occurring in some geologic formations, can leach into groundwater and is hazardous due to its chemical toxicity and radioactivity [101]. Radon, a radioactive gas resulting from the decay of uranium, can dissolve in water and pose significant health risks, including lung cancer when released into the air during household activities like showering [102].

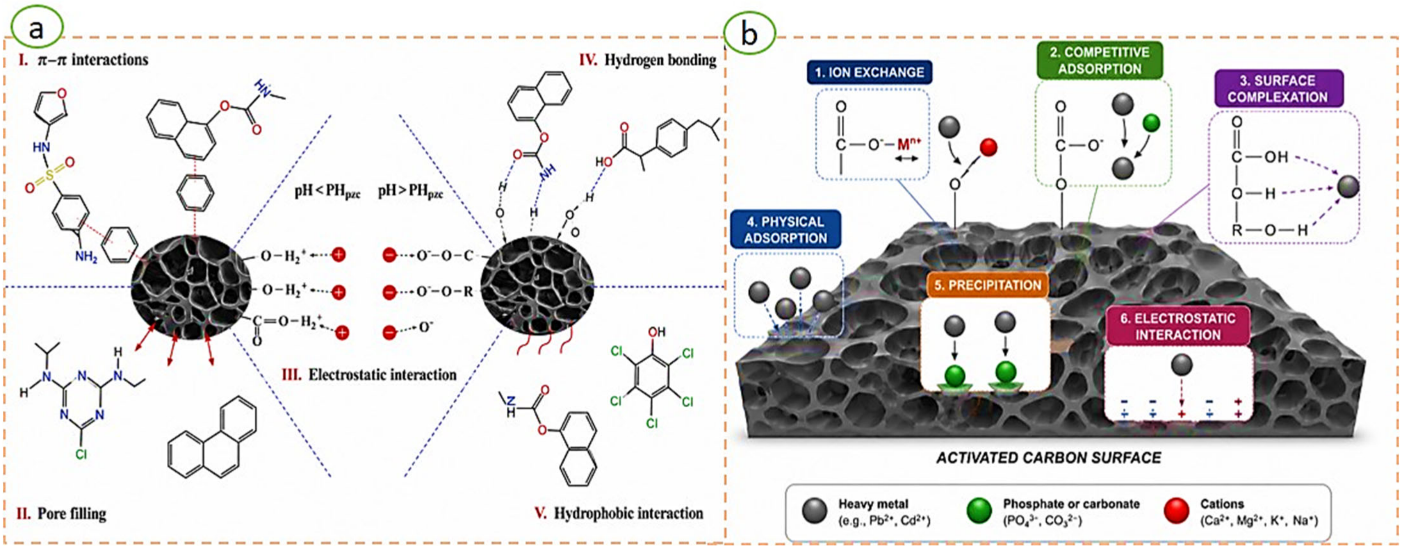

Figure 6. Illustration of pollutant adsorption by activated carbon: (**a**) adsorption mechanisms of organic compounds and (**b**) adsorption mechanisms of heavy metals and inorganic pollutants reproduced with permission from [103].

4. Regeneration and recycling methods for AC

Recycling and regeneration of activated carbon are important for the maintenance of its efficiency in water purification applications [82]. When water is passed through activated carbon, various impurities are adsorbed by the activated carbon. After a certain time, the activated carbon gets saturated and does not adsorb impurities anymore. The spent activated carbon can be regenerated by physical [104], chemical [105] or thermal methods [106] to recover the effectiveness, and each method owns its own advantages and mechanisms as shown in (**Table 5**).

Physical regeneration is the washing of spent activated carbon with solvents to remove the adsorbed contaminants. The solvent selected depends upon the nature of the pollutants. Typical solvents are water, acids, bases, and organic solvents. For example, organic compounds can be effectively desorbed by organic solvents such as methanol or acetone, whereas inorganic contaminants can be removed by acidic or alkaline solutions [107].

The advantage of the physical regeneration is that it is relatively simple and can be performed at low temperatures. The removal efficiency after each recycling cycle is generally in the range of 65–85% depending on the type of contaminant and regeneration conditions. However, it may not be able to restore the adsorption capacity of carbon completely if the contaminants are strongly bonded or if there are complex mixtures of pollutants [108]. Chemical regeneration involves treating activated carbon with chemicals that re-activate the adsorption sites. This method often involves the use of strong acids or bases such as hydrochloric acid (HCl) or sodium hydroxide (NaOH), which can break down and remove the adsorbed contaminants. Chemical regeneration is very effective, particularly for certain pollutants, and the selective removal of certain contaminants is possible [109]. For example, NaOH is good to regenerate carbon loaded with acidic contaminants, while HCl can reactivate carbon loaded with basic pollutants. The removal efficiency after each recycling cycle is usually reported in the range of 75% to 95% depending on the chemical reagent and the type of pollutant. This method is associated with the disadvantages of the possibility of chemical waste and the need to handle hazardous materials [77]. Finally, thermal regeneration consists of heating the spent activated carbon at high temperatures, normally between 600 °C and 900 °C in an inert or reducing atmosphere. This process burns off the adsorbed contaminants, essentially cleaning the pores of the carbon and restoring its adsorption capacity. Thermal regeneration is very effective and can achieve almost complete regeneration of the activated carbon [110]. The process is usually carried out in rotary kilns or fluidized bed reactors where the carbon is evenly heated. The removal efficiency after each recycling cycle is typically within the range of 85–98%, which is one of the most efficient regeneration techniques. Thermal regeneration can recover a large portion of the carbon's original capacity but requires a high energy input and can cause a decrease in the physical properties of the carbon due to thermal degradation [106].

Table 5. Removal efficiencies of regenerated activated carbon using various methods.

Regeneration method	Regenerant condition	Contaminants	Cycle 1 (%)	Cycle 2 (%)	Cycle 3 (%)	Ref
Physical (steam/hot water desorption)	RO water at 80 °C	Phenol	Up to 23.6%	*	*	[111]
Physical (microwave-assisted regeneration)	2.45 GHz, 600 W	Methylene blue	88.1	77	71	[112]
	2.45 GHz, 600 W	Methylene blue	91.2	82.2	74.9	
	2.45 GHz, 600 W	Methylene blue	80.8	71.9	70.1	
Chemical (acid/base/solvent washing)	0.1 M NaOH in 99% ethanol	Phenol	40–90%	*	*	[111]
	Ethanol (99%)	Phenol	62.1–62.6%	*	*	
	60% Acetone in water	Dye (Peach Red)	70%	58%	52%	
	40% Isopropanol in water	Dye (Mustard Yellow)	80%	64%	54%	
Chemical (oxidative regeneration: H_2O_2/NaOH)	NaOH	Organic compounds	42.5–54.5% for phenol; <5% for others	*	*	[111]
	250 °C, wet air oxidation	Dye (Chemicative Brilliant Blue R)	98.8%	*	*	[113]
	250 °C, wet air oxidation	Dye (Cibacron Turquoise Blue G)	97.5%	*	*	
026160003Thermal (600–900 °C steam/inert gas)	800 °C/N2	Iodine	95% (3 years AC)	89% (5 years AC)	*	[114]
	800 °C/N2	Methylene blue recovery	98% (3 years AC)	*	*	
	300–800 °C, reducing flue gas atmosphere	Iodine	91.6%	*	*	[108]
	300–800 °C	Methylene blue	100%	*	*	
Thermal (steam activation)	300–815 °C, reducing atmosphere + steam	Iodine	89.0%	*	*	[108]
	300–815 °C	Methylene blue	100%	*	*	

Ultrasonic regeneration	24.5 W/cm²	Isopropyl Alcohol	83%	64% (after 4 cycles)	*	[115]
	20 kHz ultrasound	trichloroethylene	64%	*	*	[116]

(*) Indicates that the corresponding study did not examine or report the adsorption/removal efficiency for the mentioned regeneration cycles.

5. Conclusion

Activated carbon is a versatile and effective material for water purification, significantly influenced by its preparation methods. Through adsorption and chemical reactions, it traps various pollutants, ensuring cleaner and safer water. Continuous advancements in preparation and regeneration further enhance its practical applications, contributing to public health and environmental sustainability.

Effect of Preparation Methods: Activated carbon's efficiency in water purification depends significantly on its preparation methods. Physical activation with steam and chemical activation using agents such as phosphoric acid or zinc chloride enhances its surface area and pore structure, making it highly effective at adsorbing contaminants.

Purification Mechanisms: Activated carbon purifies water primarily through adsorption and chemical reactions. It traps pollutants on its surface via Van der Waals forces, dipole-dipole interactions, and covalent bonds. Additionally, it catalyzes chemical reactions to decompose specific contaminants, further improving water quality.

Efficiency Across Pollutants: Activated carbon excels in trapping a wide range of pollutants:

Organic Pollutants: Highly effective at adsorbing volatile organic compounds, pesticides, and industrial solvents.

Inorganic Pollutants: Effective in removing certain heavy metals and salts, though efficiency varies with different substances.

Gases and Odors: Successfully adsorbs gases like chlorine and hydrogen sulfide, and removes unpleasant odors.

Dyes: Efficiently removes dyes from industrial processes, maintaining water's visual and chemical quality.

Despite significant advancements in activated carbon-based water purification technologies, several scientific, technical, and practical challenges remain unsolved. Future studies should include large scale applications, and optimization of regeneration methods. Moreover, the combination of activated carbon with advanced treatment techniques, such as membrane filtration, photocatalysis, and nanomaterial-assisted systems, may improve the efficiency of the pollutant removal and the selectivity of the adsorption.

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Nomenclature

AC	Activated Carbon
VOC	Volatile Organic Compounds
GAC	Granular Activated Carbon
PAC	Powdered Activated Carbon
CBF	Carbon Black Filters
UV	Ultra Violate light
TCE	Tri Chloro Ethylene
MTBE	MehtylTertButyl Ether
PCE	Per Chloro Ethylene

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