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Review

Electrochemical adsorption of water pollutants based on carbon materials: Materials, mechanisms, and applications

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Abstract: Carbon-based electrochemical adsorption technology has become an increasingly important method in the field of advanced water pollution treatment, and it is expected to provide critical technical support for water environmental restoration and drinking water safety. Traditional water treatment technologies have obvious limitations, such as poor selectivity, high energy consumption, difficulty in material regeneration, and the risk of secondary pollution. In this context, it is crucial to develop new water treatment technologies that are efficient, stable, low-consumption, and environmentally friendly. Carbon-based electrochemical adsorption technology makes full use of the superior electrical conductivity, high specific surface area, tunable surface chemistry, and relatively low cost of carbon materials, showing great potential in water pollution control. This paper systematically reviews carbon-based electrochemical adsorption technology, summarizes key adsorption materials, removal mechanisms for various pollutants, optimization strategies related to system configuration and operating parameters, and the latest application developments in different water treatment fields. The article clearly distinguishes the roles of non-Faradaic (capacitive) processes based on double-layer charging and Faradaic processes involving electron transfer in pollutant enrichment and transformation, constructing a clear mechanistic framework. Furthermore, the paper critically analyzes the main challenges faced by this technology, including the synergistic optimization of material performance, in-depth analysis of interfacial mechanisms, the complexity of actual water bodies, system-scale application, and long-term operational stability, and proposes future research directions to promote its engineering and large-scale application.

Keywords: carbon materials; electrochemical adsorption; water pollution control; pollutant removal; interfacial mechanisms; functionalization modification

1. Introduction

1.1. The grave challenge of water pollution

During the rapid development of industry, agriculture and other fields, water pollution has become more and more serious. The removal of emerging pollutants (EPs) is the most crucial remediation challenge [1]. These pollutants consist of heavy metal ions, pharmaceutical active compounds, dyes, perfluorinated compounds, and other types. They have the characteristics of low concentration, high toxicity, and poor biodegradation. These characteristics create challenges for existing water treatment technologies.

The low-concentration characteristic of EPs makes it difficult for traditional detection methods to capture their presence. However, high toxicity means that even trace residues may pose threats to ecosystems and human health. Heavy metal ions, primarily discharged in industrial wastewater, are strongly non-biodegradable and prone to bioaccumulation through the food chain [2]. Even at trace concentrations, they can cause irreversible damage. For instance, Pb^{2+} can damage the nervous system, and Cd^{2+} can impair the kidneys [3]. Some pharmaceutical active compounds, such as antibiotics, even if the content is very low in water. But long-term accumulation may lead to drug resistance in microorganisms. Moreover, synthetic dyes such as Rhodamine B are highly toxic. Traditional biological treatment is difficult to remove them. Perfluorinated compounds are difficult to degrade naturally in the environment due to their stable chemical structure. They will continuously bioaccumulate through the food chain [1]. These characteristics make water treatment technologies such as filtration and adsorption ineffective to deal with them.

Most pollutants in the water are at low concentrations. But their toxicity is extremely high. In addition, they are difficult to decompose by microorganisms. Traditional treatment methods can hardly completely remove these pollutants [1]. Advanced treatment technologies such as advanced oxidation and membrane separation are used in the process. But there are still problems of high cost and high energy consumption [2]. Thus, we need to develop new wastewater treatment technologies that are low-cost and highly selective. This is an important direction for solving water pollution.

1.2. Limitations of conventional treatment technologies

Established water treatment technologies, including adsorption, coagulation, advanced oxidation, and membrane separation, have long supported water purification demands. However, their shortcomings in efficiency, selectivity, energy consumption, potential for secondary pollution, and challenges in material regeneration have become increasingly apparent, making them less adaptable to complex water matrices and the requirements of sustainable development.

Adsorption technology commonly relies on activated carbon or novel adsorbents (e.g., biochar [4], MgO/C nanocomposites [5], or MXenes [6]) to capture pollutants. Their effect is obvious. But traditional powdered adsorbents have limitations such as agglomeration, low utilization of specific surface area, and limited adsorption capacity [7]. More importantly, in multi-component systems, their selectivity for target pollutants is generally poor [4, 5]. Their regeneration processes are complex, usually requiring high temperatures, chemical elution [7], or sophisticated treatments [8]. These steps may damage the structure of the material. It will also cause the adsorption capacity of the material to obviously decrease after multiple cycles. In addition, the separation and recovery of certain adsorbents are quite challenging. There is also a risk of causing secondary pollution during the treatment process [7].

Coagulation/flocculation technology has very low removal efficiency for dissolved small-molecule pollutants and emerging contaminants due to its non-specific mechanism. Its efficiency is easily affected by water quality factors like pH and temperature. Excess flocculant may remain in the water, and the resulting chemical sludge, if not properly managed, can cause soil and groundwater pollution [9].

Biological and Advanced Oxidation Processes face specific limitations. Microbial degradation, while a cornerstone of wastewater treatment, shows limited efficiency against recalcitrant and toxic EPs [10]. Advanced oxidation techniques (AOPs), such as TiO_2 photocatalysis, often require UV light activation, limiting their efficiency under visible light in practical applications. Traditional powdered catalysts are also prone to loss, reducing treatment efficiency and potentially causing secondary pollution [7].

Membrane separation technologies (e.g., reverse osmosis (RO)) face sustainability challenges. Their efficiency decreases significantly when treating high-salinity feed water. Membrane fouling is a severe issue, with irreversible fouling shortening membrane life. Furthermore, the management of the produced high-salinity brine concentrate poses a significant challenge for secondary pollution [11].

1.3. The emergence of electrochemical technologies

Given the limitations of conventional methods, electrochemical technologies have emerged as a highly promising alternative. This class of technologies encompasses processes such as electro-oxidation, electro-reduction, electrocoagulation, and the focal point of this review—electrochemical adsorption. Their core advantages include rapid reaction kinetics, minimal chemical consumption, mild operating conditions, and exceptional operational flexibility through the precise adjustment of electrical parameters (e.g., voltage, current density). These characteristics make electrochemical processes inherently more efficient and environmentally friendly than many conventional methods that rely on chemical additives [8] or generate secondary waste [9]. Research has demonstrated their significant potential for treating a wide range of challenging water pollutants, including nutrients (e.g., nitrates) and anions (e.g., fluorides), and recalcitrant organic compounds [1,12,13].

Electrochemical adsorption represents a unique and powerful technical route within this domain. It utilizes an applied electric field to drive the accumulation and immobilization of pollutants onto the surface of an electrode. When activated, carbon-based electrodes can enhance the adsorption of target pollutants through mechanisms like electrostatic attraction and potential-modulated ion exchange, offering a pathway to high efficiency and selectivity that surpasses conventional adsorption [4–6].

1.4. The core role of carbon materials

Carbon materials such as activated carbon, graphene, carbon nanotubes, and biochar, owing to their unique and ideal properties, have become the preferred choice for electrochemical adsorption electrodes. Their core advantages have been thoroughly validated in technologies such as capacitive deionization (CDI) and three-dimensional electrodes [14].

Its basic characteristics lie in having a high specific surface area and a rich porous structure. The specific surface area of activated carbon is as high as 1,943.2 m^2/g, providing ample adsorption sites for ions. The chestnut shell-based activated carbon electrode has an adsorption capacity for calcium ions (Ca^{2+}) of up to 21.0 mg/g [14]. After being compounded with reduced graphene oxide (rGO), its porous structure can accelerate the ion transfer process. Biochar composites can be prepared using grape pruning waste and chestnut shell waste as raw materials. The adsorption capacity of this composite material for Cu^{2+} can reach 2.19 mmol/g [15].

Excellent electrical conductivity enables carbon materials to use obviously less energy in electrochemical adsorption. Graphene-based composite materials can accelerate electron transfer. For example, rGO nanosheets can adsorb 34.20 mg of salt per liter. Its charging efficiency is 97%. Carbon nanotube composite electrodes exhibit excellent electrical conductivity. For example, TiO_2/CNT electrode exhibits a high adsorption capacity for desulfurization wastewater. It can reach 6.5 mg/g [14].

Carbon materials can also selectively adsorb certain specific ions. The functional groups on the surface of biochar can combine with Ca^{2+} and Mg^{2+}. The selectivity coefficient of chestnut shell biochar for Ca^{2+} is 8.02. Sulphhydryl-functionalised GO/activated carbon electrodes achieve over 80% Pb^{2+} removal, maintaining >70% efficiency after 300 cycles [14].

From the cost and environmental protection point of view, carbon materials also have advantages. Materials such as biochar and waste biomass carbon are abundant. The process of preparing carbon materials from them is more environmentally friendly. It meets the requirements of carbon neutrality [15].

1.5. Overview objectives and structural arrangement

This study focuses on the applications of carbon materials in the field of electrochemical adsorption for water treatment. It delivers solid theoretical support for the optimization and scale-up of relevant technologies in this sector. This study defines a clear research scope, including the types of carbon materials, functionalization strategies, and pollutant removal mechanisms. What's more, this review summarizes the optimization of system configuration.

This article is divided into seven sections. Section 1 analyzes the current state of global water pollution. At the same time, it explains the key role of carbon materials in the field of water treatment. Section 2 deeply analyzes the basic principles of electrochemical adsorption technology and its unique advantages. Section 3 provides a detailed introduction to the common types of carbon materials and typical synthesis methods. At the same time, it introduces strategies for the directional functionalization of carbon materials. Section 4 focuses on the removal efficiency of this technology for various water pollutants. At the same time, it provides an in-depth analysis of its corresponding mechanisms of action. Section 5 provides a comprehensive overview of system configuration optimization and the selection of operational parameters. At the same time, a corresponding comprehensive evaluation index system is established. Section 6 summarizes the various challenges currently faced by this technology. It also proposes directions for future research. Section 7 summarizes the core value of carbon-based electrochemical adsorption technology. It also points out its broad application prospects in the field of water pollution control.

2. The principle and advantages of electrochemical adsorption

2.1. Basic concepts

Electrochemical adsorption is an interfacial adsorption phenomenon. It occurs at the electrode-electrolyte boundary, which is governed by the electrode potential and the interfacial electric field. It can lead ions, molecules, or atoms in the solution to move toward the surface of the electrode. Its core characteristics are determined by the interplay between the interfacial electric field and the electrode surface. The process is different from traditional physical adsorption and electrochemical reduction.

Traditional physical adsorption only relies on van der Waals forces and weak electrostatic attraction. It is not regulated by external electric fields in the whole process. This process is mostly a multi-layered structure with strong reversibility and no interfacial charge directional rearrangement. It is a non-selective physical enrichment process. However, the core of electrochemical adsorption is the precise control of the electric field. Its adsorption strength, adsorption coverage, and the orientation of the adsorbate change regularly with the electrode potential. Its main form is the monolayer process. The adsorption process is highly reliant on the strength and direction of the interfacial electric field. Their most important difference is whether there is an electric field.

As for the difference between electrochemical adsorption and electrochemical oxidation/reduction, the former is an interfacial enrichment process primarily controlled by the electric field, where ions are concentrated in the double layer (near the outer Helmholtz plane) solely through electrostatic attraction; while for the latter, the core is the complete transfer of electrons across the electrode/electrolyte interface, which leads to the breaking and recombination of chemical bonds in the reactants, thereby converting them into new chemical substances. Based on the above information, changing the potential can achieve desorption of the adsorbate. However, chemical modification of the material will not occur. This is their key boundary. That is to say, electrochemical oxidation/reduction changes the chemical properties of pollutants by the transfer of electrons. It is very difficult to achieve precise control to reach the target. However, electrochemical adsorption can achieve it. We can adjust parameters such as potential and current to achieve the switching between adsorption and desorption. Moreover, electrochemical adsorption has high selectivity, low energy consumption, and simple regeneration, making it very advantageous for pollutant treatment. For example, traditional protein separation methods rely on high salt concentration or extreme pH values for desorption. This process generates a large amount of waste liquid. However, electrochemical adsorption can achieve the selective desorption of β-lactoglobulin by adjusting the potential of the gold electrode. This does not require any additional chemical reagents. It can control the double-layer potential and hydration by an electric field [16].

Granular activated carbon (GAC) has limited physical adsorption capacity in the field of water treatment. But its regeneration process meets certain challenges. Electrochemical adsorption technology can obviously improve the adsorption capacity of GAC for bromide by the application of an external electric field. This technology can increase the removal efficiency of bromides from 29% to 46% [17].

2.2. Core mechanism

Prior to the introduction of each mechanism, we need to understand the double-layer structure and the differences between the two distinct processes. When we apply a potential at the interface between the electrode and the solution, charges are rearranged on the electrode surface (electrons or holes) and on the solution side (ions), forming a double-layer structure composed of the inner Helmholtz plane (IHP) and the outer Helmholtz plane (OHP). It is clearly stated that the essence of potential-driven ion adsorption is to regulate the double layer structure by changing the electrode potential, so that ions with opposite charges accumulate in the double layer under electrostatic action.

On the one hand, non-Faradaic processes are typical of ideal double-layer charging and discharging. Charge storage is achieved solely through electrostatic attraction, located in the double layer, with no electron transfer or breaking of chemical bonds. The adsorption and desorption are highly reversible, and the adsorption capacity changes linearly with potential. This is the main mechanism for potential-driven ion adsorption (such as CDI desalination).

On the other hand, Faradaic processes involve the transfer of electrons across the electrode/solution interface, leading to redox reactions of adsorbates or species on the electrode surface. It essentially refers to potential-regulated chemisorption along with coupled electrochemical transformation. This process is usually accompanied by stronger specific bonding, but reversibility may be poor.

2.2.1. Electric field-enhanced physical adsorption

The electric field-enhanced physical adsorption is to take physical adsorption as the core. By applying an external electric field, we can induce dipole-dipole interaction or polarization between the adsorbent and the electrode surface. And the whole process does not involve the change of chemical bonds. Finally, we can improve the adsorption strength of the adsorbent for pollutants.

It can be shown in studies on pollutant removal. For example, in the hydrogen adsorption system, the adsorption energy of 8-Li-doped carbon nanotubes (Li_8/SWCN) decreased to -0.58 eV/H_2 under the action of an electric field, and the adsorption performance was increased by 93.33% [18]. The positive electric field ($F = +0.010$ AU) promotes the transfer of charge from Li atoms to carbon nanotubes, which increases the net charge and the negative charge of the surrounding C atoms, thus enhancing the polar bonding between them. The semicircular C atom on the carbon nanotube gets electrons, the charge tends towards negative, and forms a heteropolar bond with Li^+, which will produce extra dipole moments to further enhance the polarization of H_2. In the whole process, the electric field can regulate physical adsorption, and the adsorption intensity will change in a gradient with the field strength. Moreover, when the electric field is reversed, the pollutant desorption can be realized, which is more suitable for the application of actual water.

2.2.2. Potential-driven ion adsorption

Potential-driven ion adsorption is an ion separation technology that adjusts the electric double layer structure at the electrode-solution interface by applying an external electric potential. It makes use of an electric field force to enable the directional migration and enrichment of ions in the solution, with subsequent adsorption onto the electrode surface. As the core principle behind water treatment technologies such as capacitive deionization (CDI) and electro-adsorptive desalination, this process follows a straightforward mechanism: an external electric potential is applied to the system, driving target ions to move spontaneously towards charged electrodes and attach themselves to them. This thus achieves the effective separation and removal of ions from the solution.

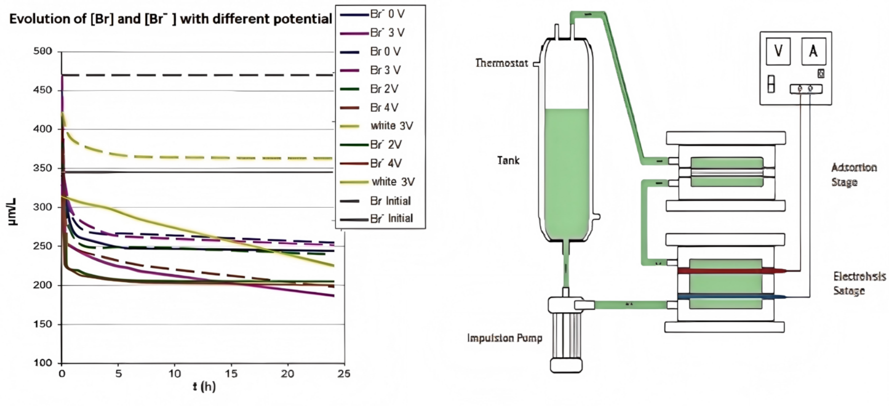
The regulating effect of the electric double layer directly determines the efficiency and selectivity of potential-driven ion adsorption. This process not only follows the Gouy-Chapman-Stern theory, but is also closely associated with the inherent material properties of the electrode itself. Granular activated carbon (GAC) has become a widely used carbon-based electrode material for potential-driven ion adsorption, due to its well-developed porous structure, good electrical conductivity, and excellent adsorptive performance. It can effectively form a stable electric double layer structure on the electrode surface, and exhibits remarkable performance in removing inorganic anions in the field of water treatment.

Taking the removal of bromide from natural water as an example, when GAC is used as the anode material and an anodic voltage of 2–4 V is applied, the surface of the GAC electrode carries a positive charge (**Figure 1**). Under the effect of an electric field force, bromide ions in the solution move toward the anode surface and become enriched there. Compared with simple physical adsorption under zero-voltage conditions, this method significantly improves both the removal efficiency and adsorption capacity of bromide ions. Among the tested voltages, 3 V is the best one, at which the bromide removal rate can reach 46%. In this process, ion enrichment by the electric double layer plays a core role. Meanwhile, a portion of bromide ions is converted into elemental bromine by oxidation on the electrode surface, and GAC still has a large adsorptive capacity for elemental bromine. This further prevents ion desorption, enhances the stability of bromide ion removal, and directly reflects the pivotal role of electric double layer regulation in ion adsorption under potential driving.

2.2.3. Potentially assisted chemical adsorption

An electric field can alter the charge distribution and electronic state of an electrode surface, strengthen the interfacial interactions, and thereby facilitate the complexation and coordinate binding of pollutants. Alternatively, it can achieve pollutant immobilisation through redox mediation effects. A typical example is the reduction of highly toxic Cr(VI) to less toxic, highly adsorbable Cr(III), followed by interfacial adsorption and immobilization.

In heavy metal treatment, an electric field can promote the formation of coordinate bonds between the electrode surface and heavy metal ions. For instance, when a positive polarisation electric field is applied to activated carbon, the external electric field first modulates the surface charge state and electron transfer capacity of the electrode, enabling the formation of stable complexes with Cr(VI). Subsequently, the redox mediation occurs at the interface, reducing Cr(VI) to Cr(III), which then forms precipitates or coordination compounds. This entire process achieves the highly efficient adsorption and immobilisation of the heavy metal.



(a) **(b)**

Figure 1. **(a)** Variation in bromide and total bromine under anodic conditions at different voltages (2 V, 3 V, and 4 V); **(b)** Includes adsorption behaviour under no-voltage conditions. The dashed line corresponds to total bromine, while the solid line corresponds to bromide [17].

Potential-assisted chemisorption has obvious selectivity advantage. An applied electric potential can adjust the ion migration and structural evolution of the electric double layer (EDL): when dealing with wastewater that contains Cr(VI), a properly adjusted potential allows for targeted ion movement within the EDL of nitrogen-doped carbon electrodes. Negatively charged Cr(VI) species are preferentially enriched at the outer Helmholtz plane (OHP) of the electrode or electrolyte interface under the action of an electric field force, achieving the interfacial concentration of Cr(VI) and providing a high-concentration reaction environment for subsequent reduction reactions. In contrast, other inorganic components in the wastewater cannot be effectively enriched in the EDL due to differences in charge properties and ionic radii. Only chromium substances can accumulate at the interface through potential-controlled selective mass transfer in the EDL, so improving the selectivity of the entire Cr(VI) reduction-adsorption process from the mass transfer stage.

The nitrogen atoms on the surface of nitrogen-doped porous carbon (NAC) form local charge-enriched regions under the action of an electric field. This makes the adsorption energy of propylene carbonate significantly lower than that of undoped carbon materials, enabling the specific chemisorption of solvent molecules [19].

2.2.4. Coupled electrochemical conversion and adsorption

Electrochemical conversion combined with adsorption is a technology that lets electrochemical conversion and physical/chemical adsorption work together in one system. Its core mechanism involves sequential processes of adsorptive enrichment followed by electrocatalytic conversion or degradation, achieving efficient removal, transformation, and resource recovery of target substances. This technology has great potential in water treatment, CO_2 valorisation and environmental remediation. It’s also a key technical method to achieve efficient, green, and sustainable pollutant treatment and resource recycling.

In electrochemical water treatment, granular activated carbon (GAC) serves as an ideal cathode material owing to its high specific surface area, tailorable porosity, and excellent adsorptive and reactive properties, which allow it to degrade pollutant particles by generating reactive oxygen species (ROS) such as OH and H_2O_2. Experimental results demonstrate that uncompacted GAC with a high porosity and a density of 0.1997 g/cm^3 yields a •OH concentration of up to 180 ppm, which is considerably higher than the 100 ppm produced by compacted GAC of the same mass. The H_2O_2 yield is less affected by GAC density, while •OH generation is significantly regulated by porosity—this is because a high porosity reduces bubble retention and facilitates the contact between fresh electrolyte and the GAC surface.

Figure 2 shows the mechanism of GAC electrodes in electrochemical conversion-adsorption systems. At the same time, the H_2O_2 and •OH concentrations generated by different GAC configurations [20]. Porosity acts as the key factor that affects the electrochemical water treatment performance of GAC: A high pore structure endows GAC with strong water adsorption ability, better fluid flow performance, and reduced bubble pollution. These advantages can further raise the generation rate of ROS, especially •OH. The optimal configuration was determined to be 1.5 g of loosely placed GAC. This setup balances sufficient reactive surface area and favorable porosity, leading to higher H_2O_2 and •OH yields than all other compressed GAC groups and different mass loadings.

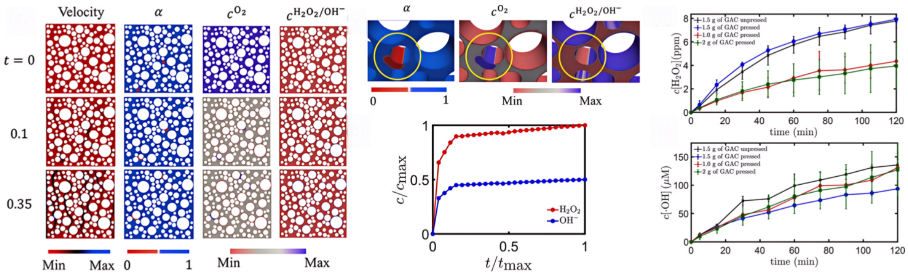


Figure 2. The synergistic process where O_2 is reduced on the GAC surface to form H_2O_2 and ·OH radicals, which degrade organic pollutants into easily adsorbable intermediates, ultimately achieving removal through GAC adsorption [20].

3. Carbon materials for electrochemical adsorption: Types, synthesis, and functionalization

3.1. Traditional porous carbon

3.1.1. Activated carbon (AC)

Activated carbon is a porous carbon material. Its activation treatment creates a rich pore structure and a high specific surface area. Activated carbon has excellent chemical stability. It also facilitates regeneration and possesses strong adsorption capacity. Its raw materials are easy to obtain and its preparation techniques are mature. For these reasons, it is widely applied in electrochemical adsorption scenarios such as water purification and gas adsorption.

The primary sources of raw materials for activated carbon are divided into three categories: coal-based materials, bio-based materials, and synthetic polymers. Coal is a typical example of coal-based materials. Coconut shells, wood, and agricultural waste belong to bio-based materials. Coal-based materials offer high carbon content and low costs. They can produce activated carbon with excellent mechanical strength and abundant micropores. However, the production of coal-based activated carbon causes severe damage to ecosystems. It also generates a large amount of carbon emissions. These emissions further worsen global warming. Compared with coal-based sources, bio-based materials are a more environmentally sustainable option. They come from renewable resources like coconut shells and wood, often as industrial by-products. Activated carbon derived from coconut shells usually has a more concentrated microporous distribution. It also has a high specific surface area. In contrast, wood-based activated carbon can easily form multi-level pore structures after activation [21].

Activation is the pivotal step in forming the pores of activated carbon. It is divided into two categories: physical activation and chemical activation. This step directly determines the pore structure of activated carbon. It also has a direct impact on the electrochemical adsorption properties of activated carbon. Physical activation is achieved through a two-step process involving carbonization under an inert atmosphere followed by oxidation with CO_2/water vapour. Pores are formed by etching at temperatures between 600–1,200 °C. This method is environmentally favourable but requires high-temperature, prolonged processing. The resulting activated carbon typically exhibits a specific surface area of 1,000–2,000 m^2/g, predominantly comprising micropores. Chemical activation employs activators such as KOH, H_3PO_4, or $ZnCl_2$ co-heated with the raw material (450–850 °C). This process concurrently achieves carbonization and activation through dehydration, oxidation, and templating effects, offering advantages of lower activation temperatures and higher efficiency. KOH activation yields microporous-dominant activated carbon with specific surface areas exceeding 3,000 m^2/g. H_3PO_4 activation tends to form structures with well-developed mesopores, while $ZnCl_2$ activation effectively suppresses tar formation and enhances pore volume utilisation [22].

The electrochemical performance of activated carbon is closely related to its pore structure. Large specific surface area and rich micropores can provide enough sites for charge storage. These sites significantly improve the electric double-layer capacitance of activated carbon. The presence of mesopores plays an important role. It can effectively reduce ion transport resistance, and effectively improve the rate performance of activated carbon. Activated carbons prepared from different raw materials can show different electrochemical performances. Coal-derived activated carbon possesses well-developed micropores, so it displays outstanding specific capacitance under low current density. Coconut shell activated carbon has a well-balanced pore structure, so it shows good cycling stability in supercapacitors. After chemical activation, biomass activated carbon forms a graded pore structure and gains better application prospects. It presents good performance in both lithium-ion batteries and supercapacitors. In addition, activation can add functional groups to the surface of activated carbon, such as oxygen-containing and nitrogen-containing groups. These groups enhance pseudocapacitance and improve the electrochemical properties of activated carbon.

3.1.2. Activated carbon fiber (ACF)

Activated carbon fibers belong to a type of porous carbon materials. They are a special kind of porous carbon material with a fibrous morphology. These materials possess a high specific surface area, a controllable pore structure, and excellent interfacial interaction properties. Therefore, activated carbon fibers show outstanding performance in continuous-flow applications, such as the removal of pollutants from water or gas streams.

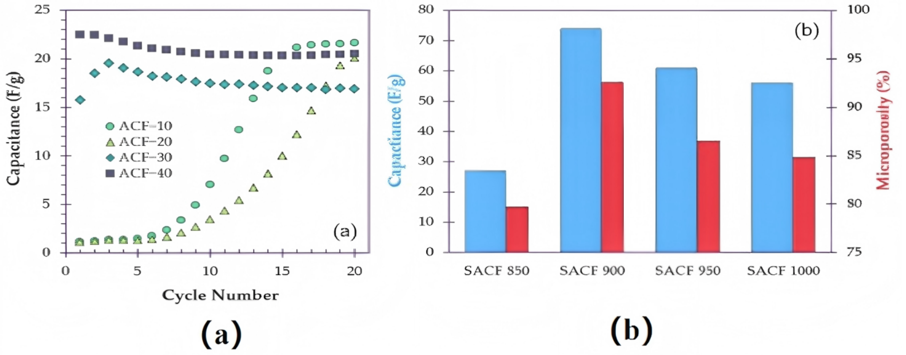
Activated carbon fibres possess high specific surface areas and well-controlled pore structures. Their pore systems are mainly composed of micropores. Most of these micropores are smaller than 2 nm. Meanwhile, mesopores ranging from 2 to 50 nm can also be found in the material. Scientists can adjust the specific surface area of activated carbon fibers by different activation strategies. In general, its value varies between 117 m^2/g and 3,230 m^2/g. The Fe_3O_4-activated lignin-based activated carbon fibre (LCF-Fe) has a specific surface area of 1,466 m^2/g. In this material, micropores take up about 58% of the total pore volume [23]. Asphalt-based activated carbon fiber prepared by physical activation can achieve a maximum surface area of 3,230 m^2/g. Micropores are dominant and contribute up to 99.7% of the pore volume [24]. This micropore-dominated architecture is crucial for maximizing the density of active sites, and it also greatly improves the material's adsorption efficiency.

Activated carbon fibres have a one-dimensional morphology. This unique structure is highly suitable for application in flow systems, and the diameters vary from nanometers to micrometres. Their stacked porous structure can form a porous bed, so that this bed possesses low flow resistance and high mass transfer efficiency [23]. In the present study, activated carbon fibers also display fast adsorption kinetics. Hydroxyl, carboxyl, and aromatic groups on their surface can capture pollutants through electrostatic interactions, and these polar sites also supply numerous active centers to speed up adsorption. Besides, the micrometer-scale short pores inside activated carbon fibers greatly reduce the diffusion resistance of adsorbates. For these reasons, their adsorption rate is 3–5 times that of traditional activated carbon [24]. Activated carbon fibres show excellent mechanical stability and regeneration ability, providing high tensile strength and flexibility. This characteristic allows them to be easily processed into woven fabrics or fixed-bed packing materials. Activated carbon fibres can maintain their structural integrity after multiple adsorption-desorption cycles. They still retain more than 80% of their original adsorption capacity after regeneration.

Scientists use a fixed-bed adsorption column as the main equipment. With this equipment, this device enables activated carbon fibers to efficiently capture low-concentration VOC contaminants in gas flow, such as benzene and toluene. Under 0% relative humidity (RH) conditions, the toluene adsorption capacity of the material reaches 439 mg/g. A constant homogeneous surface diffusion model was applied for simulation analysis. Calculation results reveal that the adsorbent maintains stable continuous operation for up to 946 h until saturation. Its actual adsorption capacity is 1.8 times that of commercial activated carbon. This material can adapt well to different humidity conditions. When RH remains below 50%, its adsorption ability hardly changes. When RH is higher than 70%, the material's adsorption capacity drops significantly. This is because water vapor competes with VOC molecules for pore adsorption sites. Surface hydrophobic modification can solve this problem well [23].

Researchers first process activated carbon fibers into fiber bundles or membrane components. These treated materials can be directly applied to continuous wastewater treatment systems. Activated carbon fibers are able to adsorb specific contaminants selectively. For heavy metal ions like Pb^{2+} and Cr^{6+}, their adsorption capacity is more than 150 mg/g. For dyes such as methylene blue, their adsorption capacity is over 300 mg/g. This carbon fiber material also possesses outstanding regeneration performance. It can be regenerated through acid cleaning or electrochemical desorption methods. After this treatment, its adsorption capacity recovers to more than 85% of its initial value.

Asphalt-derived activated carbon fibers are ideal electrode candidates for flow supercapacitors. They feature excellent electrical conductivity and outstanding energy storage capability. In a 6 M KOH electrolyte system, the specific capacitance of these fibres can reach 427 F/g. After 1,000 charge-discharge cycles, the material still keeps 99.1% of its capacity (**Figure 3**) [24]. Its performance fully meets the core requirements of large-scale energy storage systems, which need high capacity and long service life.



(a) **(b)**

Figure 3. **(a)** Capacitance recovery curve [24]; **(b)** Capacitance values achieved by ACFs activated at different temperatures [24].

3.2. Emerging nano-structured carbon materials

3.2.1. Graphene and graphene oxide (GO/rGO)

Graphene is a two-dimensional material. It consists of a single layer of carbon atoms that form a hexagonal lattice. It has a special two-dimensional honeycomb structure. It is the basic building block for all other graphite materials. For example, it can be wrapped into zero-dimensional fullerenes, rolled into one-dimensional carbon nanotubes, or stacked into three-dimensional graphite. At present, studies on assembling graphene into three-dimensional structures show good potential. This method has become an important strategy in nanotechnology. Graphene has a large surface area, many surface functional groups, and rapid electron transfer ability. These properties make it a good support for adsorption active sites and a catalytic medium. Layer stacking and three-dimensional macroscopic body construction use methods like self-assembly and template-guided approaches. These methods assemble two-dimensional sheets into macroscopic materials with micropores, mesopores, and macropores. This method stops sheets from gathering together and also improves mass transfer efficiency. Si-Yong Qin et al. [25] used graphene oxide powder as nanoconstructing units. They obtained three-dimensional graphene oxide hydrogels by self-assembly through intermolecular interactions. Scientists can control the hydrogel structure by changing the graphene oxide concentration. After vacuum drying to remove water, layered films were successfully prepared. The resulting hydrogel possesses high mechanical strength and can effectively support heavy loads. In addition, the material retains excellent chemical stability under alkaline conditions and shows particularly strong adsorption capacity toward inorganic ions such as chromate. Taken together, these unique properties render the hydrogel highly promising for practical applications in wastewater treatment. Three-dimensional graphene-based macromaterials (3D GBM) carry negative charges on their surface. These charges come from the deprotonation of oxygen-containing groups on graphene oxide flakes. These groups include hydroxyl and carboxyl groups. The number of these groups determines the negative charge density inside the material. This density further affects how well the material can adsorb cationic dyes.

3.2.2. Carbon nanotubes (CNTs)

Carbon nanotubes are hollow cylinders formed by carbon atoms. They are created when curled graphite flakes roll up. Their high aspect ratio gives them a one-dimensional structure. Depending on the arrangement of their layered carbon atoms, carbon nanotubes can be classified into three types [26]. These are single-walled carbon nanotubes (SWCNTs), double-walled carbon nanotubes, and multi-walled carbon nanotubes (MWCNTs). Single-walled carbon nanotubes roll a single-layer graphene sheet into a helical hollow microtube. As for multi-walled carbon nanotubes, they are made of as many as fifty single-layer tubes placed one inside another to form a round tubular structure. Carbon nanotubes have a unique curled structure. They show high rigidity and strength along the axial direction [27–29], but they are prone to compression and deformation in the lateral direction. With a Young’s modulus of 10^{12} pascals, they are the strongest known material and can bear large strain without breaking. These high strength relative to weight allows it to be used for large engineering projects like space elevators.

Single-walled carbon nanotubes have small diameters and long lengths. Carbon nanotubes’ unique structure can greatly boost the mechanical performance of materials. They possess outstanding elasticity and bendability. Meanwhile, their tensile strength and elastic modulus are among the highest found in all known materials. Therefore, they are ideal for reinforcing various materials, including polymer composites. Single-walled carbon nanotubes have higher thermal conductivity than multi-walled materials. Both forms can withstand high temperatures up to 750 °C. A single-walled carbon nanotube consists of only one layer of carbon atoms. Its electrical features depend on structural chirality. It may display metallic or semiconducting properties. Adding a tiny amount of these nanotubes into composite materials can greatly raise electrical conductivity. By contrast, multi-walled carbon nanotubes are more rigid. They are also less likely to break when bent [30].

3.2.3. Carbon nanofibres (CNFs)

Carbon nanofibres are discontinuous fibrous materials formed by stacking nanoscale graphite flakes. Their much higher aspect ratio than conventional fibres makes them important in electrospinning. When lithium-ion batteries experience substantial volumetric changes during cycling, people use carbon nanofibers as the anode to improve battery stability and safety. Qu et al. [31] dispersed silicon particles in carbon nanofibers by magnetic stirring. They used electrospinning to spray the composite and carbonized it to form a three-dimensional silicon/carbon nanofibre film. The electrospun film had uniform thickness, and the carbonized product remained flexible at 900 °C. In addition, the low-cost, highly flexible carbon nanofibers improved the conductivity of silicon nanoparticles, reduced electrode volume changes, and enhanced the reversible capacity and cycling stability of silicon materials.

3.2.4. Graphitic carbonitride (g-C_3N_4)

Graphitic carbon nitride is a nitrogen-rich carbon material characterised by its graphite-like conjugated structure composed of C and N elements [32]. Hydrogen and nitrogen each have one more electron than carbon. This gives the material abundant surface basic sites, electron-rich properties, and hydrogen-bonding molecular interactions. These features further endow it with strong adsorption and catalytic capabilities. Graphitic carbon nitride is synthesised via thermal polycondensation using cyanamide, urea, and guanidine hydrochloride as precursors. Regarding adsorption performance, Zhu et al. [33] demonstrated that g-C_3N_4 utilises three types of surface basic sites: '=N', '=NH', and '-NH_2'. Owing to its surface basic sites and electron-rich properties, g-C_3N_4 can act as a metal-free catalyst for the catalytic decomposition of nitric oxide. Metal ion doping further improves its catalytic activity, and its oxygen tolerance avoids oxygen poisoning in traditional catalysts. g-C_3N_4 can also help identify oxygen activation sites in oxidation reactions and serve as a stable support for metal nanoparticle catalysts [34].

3.3. Biomass-derived carbon

3.3.1. Biochar

Biochar is a carbon-rich material made from biomass like wood, manure, or leaves. Scientists produce it by heating these materials to 400–700 °C in sealed containers without or with little oxygen. With the world focused on protecting the environment, biochar is an important material made from carbon. It can reduce waste pollution, help store carbon, and replace materials that cause heavy pollution. When applied to soil in agriculture, biochar improves cultivation conditions. Pyrolysis of agricultural organic waste not only produces biochar, but also makes two valuable energy products: syngas and bio-oil. This process offers good economic value at a low cost. Valentin et al. [35] found that specific surface functional groups on biochar greatly affect anaerobic digestion. These abundant functional groups play a key role in the system. On one hand, they facilitate direct electron transfer between microorganisms. They also adsorb reaction-inhibiting substances, such as heavy metals and ammonia nitrogen. On the other hand, they accelerate the decomposition of volatile fatty acids.

Electrical conductivity is also a key parameter affecting biochar performance. Current research mainly uses two core methods to improve biochar conductivity effectively: high-temperature treatment and elemental doping. Khater et al. [36] first sun-dried their research materials, such as straw, sawdust, bagasse, and leaves, then chopped them into small pieces. They carbonized these materials at 400 °C, 600 °C, and 800 °C, respectively. The results showed that conductivity increased significantly as the pyrolysis temperature rose from 400 °C to 800 °C, with leaf biochar conductivity increasing from 2.11 dS m^{-1} to 3.46 dS m^{-1}. Pan et al. [37] used diammonium hydrogen phosphate as the nitrogen-phosphorus source. They first treated the material with ultrasound, then modified it at 600 °C. This process formed new functional groups (P=O and $-NH_2$) on the biochar surface. The modified biochar had a larger specific surface area, an optimized pore structure, and much better conductivity than the unmodified samples. As a result, its adsorption efficiency for heavy metal ions improved significantly.

3.3.2. Hierarchical porous carbon

Currently, using natural biomass as a carbon source to prepare porous carbon materials has become a research hotspot in this field. Biomass is a natural organic-inorganic composite system and possesses abundant nanoscale structural domains. During the preparation process, organic components serve as precursors for the formation of the carbon framework. The removal of inorganic components further creates abundant pore structures within the carbon matrix. To further increase the material’s specific surface area, researchers usually need to perform subsequent activation treatment on the prepared carbon material. This method basically conforms to the principles of template-coupled activation methods. The only difference is that the carbon source and template in biomass are naturally integrated, so there is no need to introduce them artificially. Chen et al. [38] used fish scales as both raw material and natural template. The preparation process included carbonization, KOH activation, and acid washing to remove hydroxyapatite, finally obtaining layered porous carbon. The collagen lamellae in fish scales curled up to form macropores. After removing hydroxyapatite, mesopores were left, and the activation process created micropores. Thanks to three pore sizes: micropores, mesopores, and macropores, this material had a specific surface area of 2,273 m^2/g. It also showed excellent ion transport efficiency and high-rate performance.

3.4. Carbon-based composite materials

3.4.1. Carbon/metal oxide composite materials

MnO_2 features high theoretical specific capacitance and a wide potential range. However, MnO_2 has low inherent conductivity. It also undergoes obvious volume changes during repeated charging and discharging. Carbon materials have low electrical resistance, excellent thermal stability, large specific surface area, and porous structures. Therefore, researchers combine MnO_2 with carbon materials. They fabricate porous, thin-film, or layered composite structures, which alleviate the shortcomings of MnO_2. Subramanian et al. [39] studied electrode materials for supercapacitors. They combined manganese dioxide (MnO_2) with carbon nanotubes and graphene-based carbon materials. They form high-capacitance electrodes that can cycle repeatedly, helping to boost the performance of supercapacitors. Bashir et al. [40] studied various metal oxides, including manganese dioxide (MnO_2), ferric oxide (Fe_3O_4), and titanium dioxide (TiO_2). They combined these metal oxides with carbon materials and polymers. The optimization of material morphology and synthetic strategies enables the realization of efficient synergistic effects. This method solved the problems of metal oxides, such as poor conductivity and performance degradation after repeated cycles. It also enabled these composites to be used in more energy storage and conversion scenarios, such as supercapacitors and solar cells.

3.4.2. Carbon/conductive polymer composites

Single-carbon materials or conductive polymers have limitations in storage capacity and surface activity. To overcome this, researchers have combined conductive polymers like polyaniline and polypyrrole with carbon materials to modify their properties. This strategy improves pseudocapacitance and increases the number of functional groups available for surface reactions. Li et al. [41] employed an in-situ polymerization method. In this way, polyaniline is filled into the pores of activated carbon. This maintains the original porous structure and makes ion transport and diffusion easier. The modification creates more active sites that take part in redox reactions for energy storage, improving electrode performance. Therefore, using this composite as an electrode material increases charge storage capacity greatly. It also has accelerated charging and discharging rates. Concurrently, Yan et al. [42] used peanut shells as raw material to produce porous carbon. Then, polyaniline (PANI) nanofibres were grown on this porous carbon. These nanofibers helped form a three-dimensional conductive network. This prepared material has two main functions: it not only stores energy but also absorbs electromagnetic radiation. Furthermore, Wang et al. [43] also conducted relevant research. They fabricated a sandwich-like composite membrane. This composite membrane combined three components: reduced graphene oxide, MXene, and poly (pyridine). The polypyrrole (PPy) layer inside the film shows several key functions. It effectively alleviates the performance loss caused by layer stacking and protects MXene from oxidation. At the same time, this coating improves the capacitance and mechanical stability of the composite. Thus, the PPy layer brings better overall electrochemical performance.

3.4.3. Carbon/metal-organic framework (MOF) composites

Carbon/metal-organic framework (MOF) composites have two primary categories. They are MOF-derived carbon and MOF@carbon variants, respectively. MOFs have designable crystal structures and excellent properties. Scientists make full use of these two advantages to increase the specific surface area and control the pore structure in composite materials precisely. In the preparation process, MOFs can be used as self-sacrificing templates. After high-temperature pyrolysis, MOFs can be formed into corresponding carbon materials. These derived carbons can inherit the porous structure of the original MOFs. Researchers combine these composites with carbon materials such as graphene or carbon nanotubes. After this combination, the composites exhibit large specific surface areas. Their pore dimensions can also be precisely tunable. Researchers can customise the pore structure of these composites. They achieve this by selecting different MOF ligands and metal nodes and need to optimise the composite fabrication process by selecting specific MOF precursors. They also adjust pyrolysis temperatures during the experiment. These two measures together enable the creation of pore networks that are tailored to diverse applications. These special structures provide ample active sites for related reactions. At the same time, they facilitate efficient mass transport in the composite system. In current studies, researchers combine ZIF-8-derived carbon with graphene to solve the problem of slow ion diffusion. This forms a hierarchical porous structure, making ion transport easier and speeding up the diffusion rate. Doping these carbon composites with elements can improve the surface activity of the materials effectively [43].

3.5. Functionalization strategy

3.5.1. Doping with impurity atoms

Most carbon materials used in electrochemical adsorption improve their functions through three main strategies. Researchers often dope carbon materials with heteroatoms such as nitrogen, sulfur, boron, and phosphorus. These atoms possess different electronegativities compared to carbon. Carbon atoms adjacent to heteroatoms often exhibit a partial loss of electron density when interacting with heteroatoms that hold a stronger attraction to electrons. This leads to charge redistribution inside the carbon material, changes local electronic states and spin density, and breaks the electronic inertness of carbon materials, thus forming defect sites and active centers. Hu and other researchers [44] applied this core principle in their work and built catalytic active sites by adding heteroatoms into the carbon structure. After nitrogen doping, pyridinic N, pyrrolic N, and graphitic N are formed. Nearby carbon atoms gain positive charges and adsorb ionic pollutants effectively. In another case, boron doping accepts electrons. It works with nitrogen doping to adjust electronic states. The carbon surface becomes short of electrons. This strengthens its adsorption toward electron-rich polar pollutants. In addition, Phosphorus atoms are relatively more. They distort the carbon structure and donate electrons. The material becomes more hydrophilic. It also shows stronger attraction to ionic substances. Relatively, sulfur doping changes the distribution of electron spin density. More polar adsorption sites appear on the surface. The material adsorbs polar and ionic pollutant intermediates more effectively. Heteroatom doping also improves conductivity and electrochemical stability. It supports efficient and stable electrochemical adsorption.

3.5.2. Surface functional group modification

Carbon electrode materials are often modified with oxygen- or nitrogen-containing functional groups, such as carboxyl (-COOH), hydroxyl (-OH), and amino (-NH_2). These chemical groups effectively raise selective adsorption ability and adjust electrochemical performance. In work by Miao et al. [45], carboxyl groups were introduced onto activated carbon via nitric acid oxidation. These carboxyl groups can form stable hydrogen bonds with phosphate. Compared with raw carbon material, the modified one shows six times higher selectivity for phosphate. Surface modification also optimizes the pore structure and increases the hydrophilicity of carbon materials. Hydrogen-bonding networks are readily formed around oxygen-containing functional groups. This interaction significantly enhances the adsorption affinity toward target species.

Chen's group [46] explored amino-functionalized carbon materials. In acidic environments, amino groups tend to undergo protonation, which endows the electrode surface with a positive charge. Positively charged surfaces generate strong electrostatic interactions with anionic pollutants. In this work, ethylenediamine was grafted onto activated carbon. The amine groups served as hydrogen bond acceptors, forming stable interactions with oxygen-containing moieties in sulfate ions, so improving the selective adsorption of sulfate. Adsorption capacities rose 1.98–2.52 times compared to pristine carbon. Moreover, the modified material exhibited better electrochemical performance and larger specific capacitance. It achieved higher desalination efficiency and effective sulfate desorption. Moreover, it maintained outstanding cycling stability.

3.5.3. Structural engineering

To address the slow mass transport issue—a common feature of conventional carbon materials, carbon materials with special structures are designed with three-dimensional interconnected porous networks and more ordered architectures. These structural features significantly accelerate the transport of both electrons and ions. Recently, this kind of carbon material has become very popular in many areas. It is widely studied for energy storage and catalysis. Researchers can make these 3D connected porous structures in different ways, including the template method and activation methods. The 3D connected structures have micropores, mesopores, and macropores together. This brings two main advantages. First, it gives a larger surface area and improves the adsorption ability of the material. Second, it makes ions move more easily and quickly.

3.6. The relationship between material properties and adsorption mechanisms

The microstructure, surface chemistry, and electronic properties of carbon materials do not exist in isolation; together, they determine the dominant mechanisms and performance limits of the materials in electrochemical adsorption. Understanding the correspondence between these 'material characteristics–adsorption mechanisms' is the foundation for rational material design. **Table 1** below systematically summarizes the core material characteristics discussed in this article and the adsorption mechanisms they primarily contribute to.

Table 1. Core association relating the core material characteristics and adsorption mechanisms.

Key properties of the material	Adsorption mechanism and effects of the influence	Case examples in the text (subsections)	The core reason for performance improvement
High specific surface area and hierarchical porosity	physical adsorption through the electric field and potential-driven ion adsorption	3.1.1 (AC), 3.3.2 (hierarchical porous carbon)	Provide abundant physical adsorption sites and surface area for double-layer formation; mesopores/macropores accelerate mass transfer, while micropores provide high capacity

Table 1. *Cont.*

Key properties of the material	Adsorption mechanism and effects of the influence	Case examples in the text (subsections)	The core reason for performance improvement
Excellent conductivity (e.g., graphene, CNTs)	potential-driven ion adsorption and coupled electrochemical conversion	3.2.1 (GO/rGO), 3.2.2 (CNTs)	Ensure uniform electrode potential distribution, reduce ohmic losses, and achieve efficient double-layer charging; they provide high-speed electron transport channels for Faradaic reactions.
Nitrogen/oxygen and other heteroatom doping	potential-assisted chemical adsorption and selectively enhance performance	3.5.1 (heteroatom doping), 4.1.1 (N-functionalization)	Alter local charge density, creating catalytic or coordination active sites (e.g., pyridinic N for Cr(VI) reduction); increase surface polarity and affinity for specific ions.
Specific surface functional groups (e.g., -COOH, -NH_2, -SH)	potential-assisted chemical adsorption with high selectivity	3.5.2 (functional group modification), 4.1.3, 4.2.3	Immobilize pollutants through specific chemical interactions, such as ion exchange, complexation, and hydrogen bonding; their protonation/deprotonation states are controlled by pH and potential, achieving intelligent adsorption/desorption.
Magnetic/metal oxide composites (e.g., Fe_3O_4)	maintain the mechanism but allow easy separation and may introduce catalytic activity	3.4.1 (C/metal oxides), 4.2.3 (A-m-MWCNTs)	Facilitate magnetic separation after adsorption; metal centers may serve as catalytic sites, promoting redox transformation of pollutants (coupled mechanism)
Ordered mesoporous/3D interconnected structures	potential-driven ion adsorption (kinetic enhancement)	3.5.3 (structural engineering)	Significantly reduce ion transport resistance, allowing adsorption capacity to approach theoretical values even at high rates, particularly suitable for flow-through configurations

4. Removal performance and mechanisms for different pollutants

4.1. Heavy metal ions

4.1.1. Lead ion (Pb^{2+})

Lead ions (Pb^{2+}) represent a typical non-biodegradable heavy metal pollutant. Long-term exposure might damage the human nervous system, liver, and kidneys, etc. Pandey et al. [47] used copper tartrate as a precursor to prepare self-supporting copper carbon nanofibers (Cu-CNF) via hydrogen reduction at 300 °C and acetylene catalytic chemical vapour deposition at 350 °C (**Table 2**). Then they introduced nitrogen functional groups by functionalizing tetraethylpentamine (TEPA). Finally, they prepared x-TEPA-Cu-CNF. Characterization confirmed that 30%-TEPA-Cu-CNF with 30% TEPA loading was the optimal material. It has excellent hydrophilicity, porous structure, and electrochemical activity. Its active area was 73.68 times the geometric electrode area, so it has high ionic conductivity and a fast charge transfer rate. The material design core is the introduction of amino and other nitrogen functional groups through TEPA modification. This combines the mesoporous structure of Cu-CNF with oxygen-containing functional groups (-OH, -COOH). Meanwhile, using the catalytic properties of copper nanoparticles to enhance the material's adsorption capacity for Pb^{2+}. The adsorption behavior of Pb^{2+} followed pseudo-second-order kinetics, and Liu isothermal adsorption model. The former indicates that chemisorption is the rate-limiting step of the entire adsorption process, and the latter suggests that the adsorbent surface energy is uneven, and the adsorption is monolayer saturation adsorption. The adsorption performance was best at pH = 6, and the maximum adsorption capacity was 179 ± 4 mg/g. The adsorption process involves various synergetic mechanisms. First, electrostatic attraction. The material surface is negatively charged under neutral conditions, and electrostatic interaction occurs with positively charged Pb^{2+}. Second, surface complexation. The oxygen-containing functional groups such as -OH and -COOH form stable complexes with Pb^{2+}. Third, pore-filling effects. Due to the small ion radius, Pb^{2+} can enter the mesoporous structure of the material to realize physical adsorption. Fourthly, amino complexation. The introduced $-NH_2$ modified by TEPA formed a stable NH_2-Pb^{2+} complex with Pb^{2+} ions. Furthermore, the material exhibits excellent reusability after regeneration with 1 M NaOH, demonstrating no significant adsorption capacity decay after four cycles.

Table 2. Summary of representative adsorption and removal materials for pollutants.

Material	Pollutant	Performance	Condition	Ref
x-TEPA-Cu-CNF	Pb^{2+}	179 ± 4 mg/g (Adsorption capacity)	pH = 6	Pandey et al. [47]
N-CQDs@α-Fe_2O_3/PANI	Cd^{2+}	/	0.1 M KCl, PBS buffer	Abinaya et al. [48]
AC-NaOH	Cu^{2+}	41.61 mg/g (Adsorption capacity); 99.9% (Removal rate)	pH = 5; Adsorbent dosage: 10 g/L; Duration: 20 min	Abduakhytova et al. [49]
copper plate-foam carbon	Cr(VI)	91.3% (Removal rate)	Voltage: 1.8 V; pH = 4.0; Duration: 30 min; Temperature: 50 °C	Wan et al. [50]
Ti_4O_7@ND-ACC	As(III)/As(V)	The total arsenic removal capacity and As(III) oxidation efficiency is 2.1 and 6.6 times that of the control group, respectively.	Voltage: 1.2 V; pH = 7; flow rate: 1.5 mL/min	Shin et al. [51]
BaO nanoparticles	Congo Red	95% (Degradation rate)	Acidic medium; Duration: 90 min	Gul and Shah [52]
GO nanoplates	Congo Red	166 mg/g (Adsorption capacity); 100% (Removal rate)	Neutral medium; Adsorbent dosage: 4 mg/25 mL	Gul and Shah [52]
K-BC	Tetracycline	491.19 mg/g (Adsorption capacity); 76% (Removal rate)	Temperature: 45 °C	Xu et al. [53]
A-m-MWCNTs	Bisphenol A	43.48 mg/g (Adsorption capacity); 89.51% (Removal rate)	pH = 12; Adsorbent dosage: 1.6 g/L; Time: 45 min; Temperature: 303 K	Bhatia and Datta [54]
MWNTs membrane	Perfluorooctanoic acid (PFOA) and perfluorooctanesulfonic acid (PFOS)	Electro-adsorption capacity: 406 and 506 mg/g for PFOA and PFOS	Polarization potential: +0.6 V; Electrolyte: 1 mM Na_2SO_4; pH = 6.5–7.0	Li et al. [55]
flow-through charged granular activated carbon (GAC) packed column	NO_3^-	40.7 ± 6.0% (Removal rate)	Voltage: 5.0 V	Su et al. [56]
CNT/PAA/$CaCO_3$	PO_4^{3-}	84.1% (Removal rate)	Voltage: 3 V; Flow rate: 1.5 mL/min; Duration: 180 min	Liu et al. [57]

4.1.2. Cadmium ions (Cd^{2+})

Cadmium ions (Cd^{2+}) are medium-to-high toxicity heavy metal ions that are widely present in industrial wastewater, contaminated groundwater, and soil. They readily accumulate through the food chain, posing long-term threats to ecosystems and human health. Abinaya et al. [48] employed a hydrothermal method combined with in situ polymerization to sequentially prepare N-CQDs@α-Fe_2O_3/PANI nanocomposites (**Table 2**). First, nitrogen-doped carbon quantum dots (N-CQDs) were hydrothermally synthesised using glycine and urea as precursors. Then, the binary N-CQDs@α-Fe_2O_3 material was prepared via a hydrothermal composite reaction between the as-prepared

N-CQDs and $FeCl_3 \cdot 6H_2O$. Finally, the target product was obtained through in situ polymerization of aniline to load polyaniline (PANI). The material design leverages synergistic effects among the three components to overcome limitations of individual materials: N-CQDs provide abundant oxygen- and nitrogen-containing functional groups with high specific surface area, enhancing Cd^{2+} chelation capacity; α-Fe_2O_3 exhibits excellent redox activity and structural stability, providing active sites for detection; while PANI endows the material with outstanding conductivity and flexibility, accelerating electron transport and resolving the issues of poor conductivity in α-Fe_2O_3 and insufficient selectivity in N-CQDs. Characterization confirms the composite structure comprises spherical N-CQDs encapsulating α-Fe_2O_3 nanoparticles, dispersed within PANI lamellae, exhibiting favourable crystallinity, hydrophilicity, and electrochemical activity. The electrochemical sensor for Cd^{2+} detection was constructed based on the glassy carbon electrode (GCE) modified with N-CQDs@α-Fe_2O_3/PANI, with 0.1 M KCl as electrolyte and PBS as the buffer solution. Cd^{2+} detection was carried out using square wave voltammetry (SWV). The detection mainly relies on surface complexation combined with electrochemical redox reactions. The composite contains abundant functional groups, including pyridine nitrogen, pyrrole nitrogen, hydroxyl and carboxyl groups, and they were served as active sites. The lone pair electrons form a stable complex with Cd^{2+}, in order to realize the enrichment of Cd^{2+} on the electrode surface. The interaction between PANI and α-Fe_2O_3 accelerates the electron transfer and reduces the charge transfer resistance (Rct = 410 $\Omega \cdot cm^{-2}$). This enables the reversible redox reaction of enriched Cd^{2+} and generates recognizable electrochemical signals. Signal intensity has a good linear relationship with Cd^{2+} concentration, contributing to achieve quantitative detection.

4.1.3. Copper ions (Cu^{2+})

Copper ions (Cu^{2+}), mainly originating from industrial wastewater such as metallurgical and electroplating processes, are a typical bioaccumulative heavy metal pollutant. Excessive intake will cause toxicity to organisms and affect ecosystem balance. It needs to be effectively removed from the water to ensure the safety of water quality. Abduakhytova et al. [49] employed agricultural and forestry waste walnut shells as raw material (**Table 2**). Using NaOH and HNO_3 as electrolytes, they employed electrochemical modification to selectively regulate the surface pore structure and the types and content of oxygen-containing functional groups in walnut shell-based activated carbon (AC). This optimisation yielded modified AC with current densities of 10.33 and 10.58 $mA \cdot cm^{-2}$ for AC-NaOH and AC-HNO_3, respectively, achieving efficient adsorption and recovery of Cu^{2+} from water. NaOH modification significantly increased the activated carbon's specific surface area and micropore fraction while substantially enhancing acidic oxygen-containing functional groups such as hydroxyl and carboxyl groups. HNO_3 modification yielded limited improvements in pore structure with modest increases in oxygen-containing functional groups; however, unmodified activated carbon exhibited a surface area of merely 739.80 m^2/g. Characterization confirmed a substantial increase in the number of adsorption sites on the modified adsorbents' surfaces post-electrochemical modification. Among them, the number of AC-NaOH adsorption centers is 10 times higher than that of the original carbon, while AC-HNO_3 is 7 times higher, providing rich active sites for Cu^{2+} adsorption.

The adsorption system achieves efficient Cu^{2+} removal through electrostatic interaction and chemical bonding. Optimal adsorption conditions were as follows: solution pH = 5.0, adsorbent dosage of 10 g/L, ionic strength 0.01 mol/L Na_2SO_4. During electrostatic adsorption, oxygen-containing functional groups on the surface of activated carbon dissociate at pH = 5.0, making the material's surface negatively charged. This enables electrostatic attraction to adsorb Cu^{2+} ions from the solution. During chemical complexation, Cu^{2+} ions undergo ion exchange reactions with oxygen-containing functional groups such as hydroxyl (-OH) and carboxyl (-COOH) groups on the activated carbon surface, forming stable complexes to achieve chemical adsorption. Concurrently, the modified activated carbon's highly developed microporous and mesoporous structure provides physical enrichment space for Cu^{2+}, enhancing adsorption capacity. The adsorption kinetics conform to a pseudo-second-order model, while the adsorption isotherm fits the Langmuir model. The kinetic model indicates that the overall rate at which Pb^{2+} is adsorbed from the solution onto the solid surface is determined by the chemisorption step, rather than by physical diffusion (such as film diffusion or intra-pore diffusion). While based on the thermodynamic model, the adsorption follows monolayer saturated adsorption on heterogeneous surfaces where active sites with different affinities are present. AC-NaOH exhibits a maximum Cu^{2+} adsorption capacity of 41.61 mg/g, achieving an adsorption efficiency of up to 99.9%, with equilibrium reached within 20 min. The adsorbent can be desorbed and regenerated using 1.0 mol/L H_2SO_4, maintaining high adsorption efficiency after three adsorption-desorption cycles.

4.1.4. Chromium(VI) ions

Chromium ions Cr(VI), mainly from electroplating industrial wastewater, are highly toxic and refractory heavy metal pollutants. Wan et al. [50] explored the removal effect of electrode materials and reaction conditions on Cr (VI) (**Table 2**). Through comparative experiments of four groups of electrode combinations (copper plate-foam carbon, copper plate-carbon paper, stainless steel-foam carbon, stainless steel-carbon paper), the optimal configuration was determined: copper plate as cathode, foam carbon as anode, and saturated calomel electrode as reference electrode, forming a three-electrode electrochemical system, which showed excellent removal performance for Cr(VI). Under the optimal conditions of plate spacing of 2.0 cm, operating voltage of 1.8 V, electrolysis time of 30 min, pH of 4.0, and reaction temperature of 50 °C, the removal rate reached 91.30%. It is based on cathodic electroreduction and precipitation separation. At the cathode, $Cr_2O_7^{2-}$ receives electrons on the copper plate surface, and is reduced to Cr(III) under acidic conditions: $Cr_2O_7^{2-} + 8H^+ + 6e^- \rightarrow 2Cr(OH)_3\downarrow + H_2O$. At the anode, water molecules are oxidized to produce O_2 and H^+: $2H_2O \rightarrow O_2\uparrow + 4H^+ + 4e^-$. Meanwhile, H^+ is consumed during the electrolysis process, and the pH increases. The reduced Cr(III) combines with OH^- to form $Cr(OH)_3$ precipitation, achieving complete removal. As a small amount of copper plate cathode is dissolved, copper hydroxide precipitation is generated, so side reactions occur. DFT calculations confirm that Cu (111) and Fe (111) possess similar adsorption energies for Cr(VI), but that of Cu (111) is lower, so it is easier to desorb and form precipitates, which is the core reason for the higher removal efficiency of the copper plate cathode. The adsorption kinetics follow a pseudo-first-order kinetic model with a correlation coefficient of 0.991, confirming that the reduction reaction is the key step for Cr(VI) removal.

4.1.5. Arsenic (III/V) ions

Arsenic, mainly exists in two oxidation states, trivalent arsenic (As(III)) and pentavalent arsenic (As(V)) in water. They are both highly toxic and carcinogenic pollutants. Among these, As(III) is significantly more toxic than As(V), and it has high water solubility and mobility, making it prone to polluting groundwater. To address arsenic pollution, Shin et al. [51] employed a hydrothermal precipitation and high-temperature reduction method (**Table 2**). Using titanium oxysulphate as a precursor, they prepared TiO_2@ND composite powder by hydrothermal reaction with ND. Then it was reduced at 1000°C under a hydrogen atmosphere to yield the Magnéli phase Ti_4O_7@ND. After mixing with PEDOT: PSS, vacuum filtration, and loading on activated carbon cloth (ACC) substrate to obtain a Magnéli-phase Ti_4O_7@ND-ACC composite anode. TiO_2@ND-ACC and pure ND-ACC were prepared as controls. According to experimental results, the total arsenic removal capacity is 2.1 times that of TiO_2@ND-ACC, while the oxidation efficiency of As(III) to As(V) is 6.6 times higher, far superior to the pure ND-ACC electrode. This system is based on the synergistic effects of electrochemical oxidation and electro adsorption. Under the optimal conditions of operating voltage of 1.2 V, initial solution pH of 7, and flow rate of 1.5 mL/min, As(III) migrates to the Ti_4O_7@ND anode surface due to electrostatic effects. The mixed valence state (Ti^{3+}/Ti^{4+}) and abundant oxygen vacancies in Ti_4O_7 provide active sites, where catalytic oxidation of As(III) to low-toxicity As(V) occurs. ND has a high specific surface area, and through the effect with sp^3/sp^2 carbon structure, it further enhances As(V) adsorption and charge stability. Meanwhile, the OH^- generated by the cathodic reaction migrates to the anode, making the local environment of the anode alkaline, further promoting the binding of As(III) and As(V) to the electrode surface, so enhancing the overall adsorption removal efficiency. Furthermore, after multiple charge and discharge cycles, the removal-desorption performance of the electrode remains stable, indicating that the regeneration and durability of the system are good.

4.1.6. Comparison of heavy metal removal mechanisms and material design strategies

For heavy metals with different valence states, such as Pb^{2+}, Cd^{2+}, Cu^{2+}, a common feature of high-performance materials is that they are functionalized with functional groups such as amino and carboxyl groups, to provide chemical adsorption sites. For highly toxic anionic heavy metals, such as Cr(VI), As(III), the key of material design shifts to the construction of composite electrodes with electrocatalytic reduction ability, which can be removed through a “reduction-fixation” approach. In particular, the key comparison and the difference explanation will be as follows.

1) Adsorption capacity difference: The adsorption capacity of x-TEPA-Cu-CNF for Pb^{2+} (179 mg/g) is much larger than that of AC-NaOH for Cu^{2+} (41.61 mg/g).

This is not only due to the difference in specific surface area, but more importantly, the former introduces a high-density specific amino ligands, while the latter mainly relies on ordinary oxygen-containing groups, which reveals the significant impact of "functional accuracy" on performance.

2) Mechanism pathway selection: Direct adsorption (e.g., Pb^{2+}, Cu^{2+}) vs. indirect reduction adsorption (e.g., Cr(VI)). The choice depends on the chemical form and toxicity of the pollutant: direct adsorption is suitable for metals that exist stably in cationic form; whereas for pollutants existing in oxygen-containing anionic forms, with significantly different toxicities like Cr(VI) and As(III), it is necessary to use Faraday reduction processes to change their form for efficient and safe immobilization.
3) Limitation analysis: Current studies are mostly conducted in single-pollutant systems and lack research on the complex scenarios of multiple heavy metals coexisting and competing in real water; at the same time, most studies focus on adsorption capacity and do not sufficiently evaluate electrode material dissolution and passivation (e.g., copper plate dissolution in Subsection 4.1.4), and regeneration stability during long-term operation.

4.2. Organic pollutants

4.2.1. Congo red dye

Congo Red (CR), a type of aromatic dye, is widely applied in industries such as textile and printing dyeing. It has cytotoxicity and mutagenicity. After polluting water bodies, it will reduce the photosynthetic efficiency, so threatening the survival of aquatic organisms. To protect aquatic life and public health, Gul and Shah [52] employed a chemical precipitation method (**Table 2**). After calcination at 500 °C, BaO nanoparticles were obtained. It has a good crystal form, and the average particle size is 16 nm. Its 3.7 eV bandgap can effectively use light energy to generate active free radicals and realize photocatalytic degradation. Also, Graphene oxide (GO) nanosheets were synthesised by improving the Hummers method as shown in **Figure 4.** The surfaces of the material are rich in oxygen-containing functional groups such as hydroxyl groups, which provide rich active sites for CR adsorption. Using BaO as a photocatalyst, the effect is optimal in acidic media, achieving a 95% degradation rate of CR within 90 min. This is much higher than that in neutral (67%/180 min) and alkaline media (42%/180 min), and is equally superior to $CoFe_2O_4$, NiO, and Fe_2O_3 and other similar photocatalysts. The degradation is driven by the process in which BaO is excited by light to produce electron-hole pairs, and reacts with water and oxygen to generate active species such as •OH and O_2^{-}. Among these, •OH is the core species for degradation, finally mineralizing Congo red into harmless products such as H_2O and CO_2. The degradation process follows pseudo first-order kinetics, with a rate constant of 0.03 min^{-1}. When using GO as an adsorbent, the optimal conditions are a neutral medium and a loading of 4 mg/25 mL, achieving 100% adsorption removal of Congo red with a maximum adsorption capacity of 166 mg/g, far superior to traditional adsorbents such as activated carbon and iron-cobalt oxides. The adsorption mechanism is that the oxygen-containing functional groups on the GO surface form electrostatic interactions and hydrogen bonding with Congo red molecules. At low concentrations, it is monolayer adsorption (according to the Langmuir model), which means there is basically no interaction between surface sites, and the adsorption capacity is limited by the number of available functional groups. And at high concentrations, it is multilayer adsorption (according to the Freundlich model). suggesting that the adsorbed layer of Congo red molecules can continue to adsorb new Congo red molecules through π-π stacking, hydrophobic interactions, or intermolecular hydrogen bonds, forming a second layer and a third layer. On the other hand, the overall adsorption process fits a pseudo-second-order kinetic model with a rate constant of 4.7×10^{-4} g/(mg·min). The adsorption heat dynamically changes with the adsorption process (according to the Temkin model).

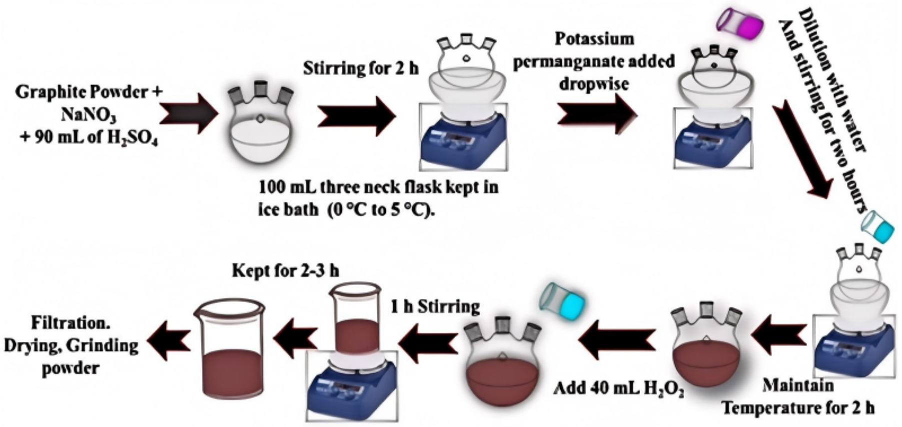


Figure 4. Improved Hummer method for synthesising GO [52].

4.2.2. Tetracycline

Tetracycline (TC), as an antibiotic, is widely used in medical treatment. But because it cannot be degraded in the human body, it will eventually enter the water through material cycles, thus causing antibiotic pollution in the water. So Xu et al. [53] employed agricultural waste wheat straw as raw material to produce original biochar (BC) by pyrolysis at 500 °C under a nitrogen atmosphere (**Table 2**). After mixing the BC with the activator KOH, KOH-activated biochar (K-BC) was obtained by secondary pyrolysis at 700°C. Using original biochar (BC) as a control, characterization confirmed that KOH activation increased the biochar surface area from 53.1 $m^2 \cdot g^{-1}$ to 996.4 $m^2 \cdot g^{-1}$, and its pore volume increased from 0.08 $cm^3 \cdot g^{-1}$ to 0.45 $cm^3 \cdot g^{-1}$. During material preparation, KOH reacted with biochar thermochemically. By etching and hole making, lots of carbon structural defects were created. That is beneficial to provide sufficient sites for tetracycline adsorption. K-BC shows excellent adsorption performance, the theoretical maximum adsorption capacity of tetracycline was 491.19 $mg \cdot g^{-1}$ at 45 °C, much higher than the original biochar. After three times of pyrolysis and regeneration, the removal rate of tetracycline was still more than 76%, showing that its recycling performance was good. The removal mechanism is mainly based on pore filling, π-π interaction, and complexation. The adsorption process conforms to the pseudo-second-order kinetic model. The Langmuir monolayer adsorption model, confirming that the rate is controlled by chemical adsorption. The well-developed microporous and mesoporous structures of K-BC provide lots of physical adsorption sites for tetracycline, to realize rapid pollutant enrichment. KOH activation enhances the aromaticity of biochar, and the π electrons of its graphitic carbon structure strongly interact with the π electrons of tetracycline aromatic rings, which is the main driving force of chemical adsorption. The -OH, C=O, and nitrogen-containing functional groups on the surface of biochar form hydrogen bonds with tetracycline, while some metal ions can be used as bond bridges to enhance the complexation between biochar and tetracycline. Electrostatic interactions have little effect on K-BC adsorption, which further highlights the dominant role of the adsorption mechanisms. Thermodynamic analysis indicates that tetracycline adsorption onto K-BC is a spontaneous, endothermic process accompanied by an increase in system disorder. Elevating environmental temperature significantly enhances adsorption capacity. In other words, the adsorption $\Delta H°$ of tetracycline on K-BC is positive, confirming its endothermic nature, which may be related to the energy input required for the tetracycline molecules to shed their hydration shell before entering the biochar nanopores. At the same time, the $\Delta S°$ of this process is significantly positive, indicating that the increase in disorder at the solid-liquid interface is a key factor driving the spontaneous adsorption ($\Delta G° < 0$). This 'entropy-driven' characteristic is relatively common in the adsorption of hydrophobic organic compounds.

4.2.3. Bisphenol A

Bisphenol A (BPA), an endocrine-disrupting chemical (EDC), is widely used in the synthesis of polycarbonate plastics and epoxy resins. It is commonly found in water containing plastic packaging pollutants. It mainly affects human sexual health. In response, Bhatia and Datta [54] used low-cost multi-walled carbon nanotubes (MWCNTs) as the substrate (**Table 2**). After oxidation with 69% nitric acid, Fe_3O_4 magnetic particles were loaded by Fe^{2+}/Fe^{3+} (1:2) coprecipitation method. Then they wet impregnated 20% Aliquat 336 ethanol solution on the surface of the magnetic MWCNTs (m-MWCNTs), introducing Aliquat 336 amine functional groups to produce A-m-MWCNTs adsorbent.

A-MWCNTs showed excellent adsorption performance to bisphenol A in water. In batch adsorption, the optimal process conditions were as follows: an adsorbent dosage of 1.6 g/L, a contact time of 45 min, a solution pH of 12, and a temperature of 303 K. At this time, the removal rate of 10 mg/L BPA reached 89.51%, with a maximum adsorption capacity of 43.48 mg/g at 303 K. Batch adsorption conformed to the pseudo-second-order kinetic model, confirming that the rate was controlled by chemical adsorption. In column adsorption, the optimal process conditions were as follows: the height of the adsorption bed was 2 cm, the BPA solution flow rate was 2 mL/min, the initial concentration was 20 mg/L, and the temperature was 303 K. At this time, the utilization rate of the adsorbent was the highest. The dynamic adsorption data fitting Thomas model can accurately predict the adsorption behavior of a fixed bed. The system realizes efficient adsorption of BPA by electrostatic attraction and chemical adsorption. Under alkaline conditions with pH > 8, BPA is dissociated into bisphenol salt anions (O^-), and forms strong electrostatic interactions with the quaternary ammonium cations (N^+) of Aliquat 336. BPA molecules also engage in weak hydrogen bonding and van der Waals interactions with oxygen-containing functional groups on the surface of the adsorbent to further enhance adsorption stability. Moreover, Fe_3O_4 has magnetism, which realizes rapid solid-liquid separation through an external magnetic field, facilitating convenient recovery after adsorption. In addition, using a 1 M NaOH solution as a desorption agent, after 5 adsorption-desorption cycles, the removal rate of BPA did not decrease significantly, and magnetism made the separation operation easier. This confirms that A-m-MWCNTs has good regeneration performance and structural stability.

4.2.4. Perfluorinated compounds

Perfluorooctanoic acid (PFOA) and perfluorooctanesulfonic acid (PFOS), belonging to perfluorinated and polyfluoroalkyl substances (PFAS), have been widely used in industrial production and consumer products. They are highly toxic and will cause reproductive toxicity, endocrine disruption, liver and kidney function damage, and so on. Owing to their chemical stability and bioaccumulation, traditional biodegradation is difficult to remove. To address this, Li et al. [55] employed purified multi-walled carbon nanotubes (MWNTs) as the core material (**Table 2**). They used electrodeposition (EPD) to load MWNTs onto titanium plates to prepare MWNTs electrodes. Magnesium nitrate was used as the dispersing agent and deposited for 3 min at 160 V. Finally, they obtained MWNTs thin film electrodes with about 15 μm thick and a uniform, dense surface. The system is based on electrostatic attraction enhancement under electrochemical regulation to achieve efficient adsorption of PFOA and PFOS. The optimal process conditions are 0.6 V polarization potential and an electrolyte concentration of 1 mM Na_2SO_4. In a pH 6.5–7.0 PFOA/PFOS solution, a positive potential of 0.6 V charges the electrode surface positively. This generates strong electrostatic attraction with PFOA and PFOS, which dissociate into anions in water, significantly enhancing the adsorption driving force. Using 1 mM Na_2SO_4 as the supporting electrolyte not only accelerates the mass transfer rate of pollutant ions under an electric field, but also prevents SO_4^{2-} from competing with PFOA/PFOS for adsorption sites at high concentrations. The mesoporous structure of MWNTs provides enough physical adsorption sites for PFOA/PFOS, and its high conductivity ensures uniform potential distribution on the material surface, to achieve full utilisation of adsorption sites. The electroadsorption kinetics conform to the pseudo-second-order model. Compared to the adsorption of powdered MWNTs, the initial adsorption rates for 100 μg/L PFOA/PFOS at 0.6 V increased by 60 times and 41 times, respectively. The Langmuir model was fitted with isotherms, and the maximum electroadsorption capacity of PFOA/PFOS in the concentration range of 50 μg/L–10 mg/L increased by 150 times and 94 times, respectively, reaching 406 mg/g and 506 mg/g, confirming that the process is a monolayer adsorption, and the electrochemical-assisted electrostatic attraction is the core driving force for adsorption enhancement. The MWNTs electrode has excellent regenerability and reusability. After five adsorption-desorption cycles, the PFOA/PFOS adsorption capacities remained at 0.95 mmol/g and 0.83 mmol/g, respectively, and there was no significant change in electrode morphology.

4.2.5. Challenges of organic pollutant removal and the logic of material selection

Based on the nature of pollutants, three dominant strategies are summarized: 1) For ionic dyes (such as Congo red), rely on electrostatic and π-π interactions; 2) For highly electronegative persistent organic pollutants (such as PFAS), rely on electrostatically enhanced adsorption; 3) For neutral antibiotics/endocrine disruptors (such as tetracycline, BPA), rely on physicochemical interactions such as hydrophobic effects and hydrogen bonding, as well as pore filling. Particularly, critical comparison and difference explanation will be presented as below.

1) Performance span analysis: The adsorption capacity of K-BC for tetracycline was very high (491 mg/g), while the adsorption capacity of A-m-MWCNTs for BPA was relatively low (43.48 mg/g). This is due to the match between pollutant molecular size, hydrophobicity, and the pore structure of the material: tetracycline molecules may be easier to enter the well-developed micropores/mesopores of K-BC, while BPA adsorption is more dependent on the specific functional groups of surface modifications.
2) Discussion on the boundary between “adsorption” and “degradation”: Electrochemical adsorption techniques themselves are mainly for “enrichment,” but for degradable organics, future coupling with electrochemical oxidation offers a more thorough treatment, thereby situating the case within a broader technical spectrum.
3) Limitations analysis: Current research on the selective adsorption mechanisms for complex organic pollutants is still insufficient; moreover, many high adsorption capacities are obtained under high-concentration experimental conditions, with weak studies on adsorption behavior, kinetics, and background matrix interference at trace concentrations relevant to environmental contexts.

4.3. Nutrient salts

4.3.1. Nitrates

Nitrates are commonly found in groundwater contaminated by agricultural runoff. Su et al. [56] developed a flow-through charged granular activated carbon (GAC) packed column for removing nitrate from groundwater (**Table 2**). The system uses GAC as the anode and titanium sheet as the cathode. The stainless steel coil within the column realizes GAC electronic transfer. The key to material design lies in using a continuous flow column configuration and GAC with a specific surface area of up to 800 ± 40 m^2/g as the anode. That can not only shorten mass transfer distances but also have adsorption and conductive properties. Under the condition of a battery potential of 5.0 V, GAC can effectively remove 40.7 ± 6.0% of nitrate. In contrast, platinum anodes remove only 4.1 ± 1.5% nitrate, while carbon nanotubes and graphite can hardly remove any detectable nitrate within 2 h. Long term operation until 1800 BV is reached for adsorption saturation, and no by-products such as nitrite or N_2O are generated. The dominant removal mechanism of the systems is mediated by electro adsorption and electrochlorination. The anodic potential makes the surface of GAC positively charged, adsorbing nitrate through electrostatic interactions and thickening the double layer to enhance ion holding capacity. Unabsorbed nitrate is reduced to ammonium ions (NH_4^+) at the cathode, while Cl^- undergoes oxidation at the anode to generate active radicals such as Cl• and HO•. These rapidly oxidise ammonium ions to N_2 without accumulating NO_x. Meanwhile, Cl^- also enhances solution conductivity, further promoting nitrate reduction and adsorption. The N_2 selectivity of this system is close to 100%, with strong resistance to pH interference. It also has a polarity reversal regeneration mode, which can desorb nitrate without acid or alkali, only reversing the polarity of the GAC electrode. After three cycles, the removal capacity has no obvious decline, making it a highly efficient method to remove nitrate pollution.

4.3.2. Phosphate

Phosphorus, commonly found in sewage discharges and agricultural runoff, readily causes eutrophication in water bodies, damaging freshwater and coastal marine ecosystems. In order to achieve efficient removal and resource recovery of phosphates in water, Liu et al. [57] developed a flow-through filtration system based on calcium carbonate-functionalised electrochemical carbon nanotubes (CNT/PAA/$CaCO_3$) (**Table 2**). The material was prepared by vacuum filtration to form a polyacrylic acid (PAA)-modified CNT filter membrane. $CaCO_3$ particles were in situ loaded onto the membrane via an alternating immersion method utilising electrostatic interactions, yielding a CNT/PAA/$CaCO_3$ nano-hybrid anode filter membrane. The porous structure of CNTs enhances convective mass transfer, while PAA's carboxyl groups provide nucleation sites for $CaCO_3$. The flow-through structure significantly improves the electrochemical kinetic efficiency. Under an applied voltage of 3 V and a flow rate of 1.5 mL/min, the recovery rate of phosphate reached 84.1% within 180 min, which is 71.9% higher than that of traditional batch reactors. It has good removal effect on phosphate in the concentration range of 2–20 mg/L. When treating actual domestic sewage, phosphate can be reduced from 1.5 mg/L to 0.4 mg/L. The removal of this system is achieved through electrochemically induced calcium phosphate precipitation and $CaCO_3$ adsorption. H^+ generated by anodic water electrolysis reacts with $CaCO_3$ to release Ca^{2+}, while OH^- generated by cathodic water electrolysis forms a local high pH environment. By combining, Ca^{2+} migrates towards the cathode under the drive of an electric field, forming amorphous calcium phosphate precipitates with phosphate on the cathode surface or in the solution. Furthermore, $CaCO_3$ buffers the solution pH and inhibits H^+/OH^- recombination, thereby enhancing precipitation efficiency. The system efficiently processes low-concentration phosphorous-containing water with a concentration of 2–20 mg/L, and maintain over 70% recovery efficiency for different initial concentrations of phosphates. It also has strong resistance to interference, with the concentration range of Cl^-, NO_3^-, and SO_4^{2-} in water between 1–10 mg/L only reducing the recovery efficiency by merely 2–7%.

4.3.3. Comparative analysis

The removal of nitrate depends on electrochemical reduction, while the removal of phosphate depends on electrochemical-induced precipitation. This difference in mechanisms determines the fundamental difference in system designs and electrode material selections. That is, the former needs a catalytic reduction active center, and the latter needs to provide nucleation points or cation sources. It is also pointed out that the common core challenge of nutrient removal is the significant competitive effect of background electrolytes, such as Cl^-, SO_4^{2-}. The current research can not fully simulate the high ionic strength environment in real water bodies.

4.4. Coexisting substance systems and selectivity

Most of the studies reviewed in this chapter were conducted under laboratory conditions, that is, single pollutant, constant ionic strength, specific background electrolytes, which helps clarify the basic mechanisms. However, real water bodies such as surface water, groundwater, urban and industrial wastewater, have extremely complex substrates, which usually contain multiple coexisting ions, such as Ca^{2+}, Mg^{2+}, Cl^-, SO_4^{2-}, HCO_3^-, natural organic matter (NOM), and other dissolved substances. In carbon-based electrochemical adsorption, these components may significantly affect the removal efficiency and selectivity of target pollutants through competitive adsorption, interface property change, electrode scaling, side reactions, and other mechanisms.

Particularly for the multiple ion co-existence, high concentrations of background ions (such as Ca^{2+}/Mg^{2+} in hard water) can compete with target trace heavy metals (such as Pb^{2+}, Cd^{2+}) for limited surface adsorption sites (including electrostatic sites and specific coordination sites). Also, high ionic strength can compress the double layer thickness and weaken long-range electrostatic interactions, which may be unfavorable for the electroadsorptive enrichment of trace ions (such as PFAS). For instance, Ca^{2+} and Mg^{2+} readily form insoluble salts with phosphates or undergo co-deposition on electrode surfaces, thereby interfering with phosphorus recovery in electrochemical filtration systems. Therefore, mitigating interference from coexisting ions is pivotal to treating water pollution. In another example, although amino groups have specificity for Pb^{2+}, at extremely high Ca^{2+} concentrations, nonspecific electrostatic adsorption sites may be largely occupied. To enhance the selectivity of carbon materials for target pollutants, current research includes methods such as pore size control, surface charge regulation, and specific ligand modification.

First, the pore size control is based on the hydrated ion size and sieving effect. In particular, ions in solution do not exist in a bare form, but are surrounded by water molecules, forming a hydration shell whose effective size is determined by the hydrated ion radius (or Stokes radius). In pore-constrained carbon materials (such as activated carbon or carbon nanotubes), ion transport experiences significant spatial hindrance. Only when the pore size of the material is larger than the hydrated diameter of the ion can the ion effectively enter the interior of the pores and be adsorbed. Therefore, by precisely controlling the pore size distribution of carbon materials (such as preparing micropores or mesopores of specific sizes), size-based molecular/ion sieving can be achieved. For example, hydrated Na^+ with a diameter of approximately 0.66 nm and hydrated Ca^{2+} with a diameter of approximately 0.76 nm exhibit different diffusion and adsorption behaviors in carbon materials with different pore sizes. In another example, mesoporous carbon materials with a pore size of 0.8–1.2 nm can effectively hold Congo red dyes with larger molecular sizes, while allowing small molecules such as Cl^- and

SO_4^{2-} to pass through.

Second, the surface charge regulation is based on the charge density and electrostatic interactions. Specifically, the electrostatic force received by target ions at the electrode/solution interface not only depends on the macro potential of the electrode surface, but is also closely related to the charge density (charge number/hydrated ion volume) of the ion itself. High charge density ions (such as Al^{3+} vs. Na^{+}) generally have stronger adsorption energy in the double layer. In addition, the presence of specific adsorption (short-range interactions with the electrode surface through partial dehydration) and non-specific adsorption (fully hydrated ions existing in the diffuse layer only through long-range electrostatic interactions) further affects the competitive behavior of different ions. The ionic strength and pH of the solution can dynamically adjust the strength and range of this electrostatic selectivity by compressing the thickness of the double layer and changing the sign of the electrode surface charge. By adjusting the pH of the solution, the isoelectric point of the material can be further controlled to carry an opposite charge to the target pollutant, thus achieving adsorption through electrostatic attraction.

Third, the specific ligand modification is based on the ligand chemistry and specific interactions. Beyond ordinary electrostatic interactions, coordination chemistry, hydrogen bonding, hydrophobic interactions, or π-π stacking occur between specific functional groups (such as amino, carboxyl, thiol) introduced through material surface functionalization and target ions. The strength and specificity of these interactions often follow the Hard and Soft Acids and Bases (HSAB) theory. For example, sulfur-containing groups (-SH) with soft basicity exhibit very high selectivity and affinity for soft acidic ions like Hg^{2+} or Pb^{2+}, while oxygen-containing groups (-COOH, -OH) with hard basicity more readily bind with hard acidic ions such as Ca^{2+} and Mg^{2+}. This ‘lock-and-key’ mechanism is the fundamental approach for achieving high selectivity. Therefore, we can introduce ligands on the surface of carbon materials to make it have a specific recognition effect on target pollutants to achieve accurate adsorption of target pollutants. These methods can effectively reduce the interference of coexisting ions, achieving efficient and selective removal of target pollutants in water bodies.

In addition to the competitive effects in actual water medium, NOM such as humic acid and fulvic acid may also cause three main problems: (1) Competitive adsorption: NOM molecules themselves contain rich functional groups (-COOH, -OH), which can occupy active centers on the electrode surface; (2) Hole blockage: Macromolecular NOM may block the micropores and mesopores of carbon materials, reducing the effective specific surface area and increasing mass transfer resistance; (3) Electrode scaling: Irreversible adsorption or polymerization of NOM on the electrode surface can lead to continuous decline of electrode activity and increase of maintenance costs.

To solve the above issues caused by NOM, three potential solutions are proposed, such as: (1) Pretreatment: use processes like coagulation and ultrafiltration to pre-remove some macromolecular NOM; (2) Anti-fouling material design: develop hydrophilic, negatively charged (repulsing negatively charged NOM) or self-cleaning electrode coatings; (3) Operational strategies: use pulse potential, periodic polarity reversal, or chemical cleaning to mitigate NOM fouling.

5. System configuration, operating parameters, and performance evaluation

5.1. System configuration

5.1.1. Flow-through and flow-by

In electrochemical adsorption systems, the system configuration has a great influence on mass transfer efficiency and pressure drop. There are two common structures: Flow-through and Flow-by [58]. These two structures show obvious differences in mass transfer pathways and pressure drop. The fluid moves parallel to the electrode surface. The direction of the electric field is perpendicular to the flow direction. In this case, ions cannot directly reach the adsorption sites on the electrode. They can only diffuse slowly, passing through the thin water flow boundary layer near the electrode surface before being adsorbed. In the flow-through configuration, driven by pressure, the fluid passes vertically through the pores inside the porous electrode. The direction of the electric field is the same as the flow direction. Therefore, ions do not need to diffuse slowly. They can follow the water flow directly enter the electrode interior. This greatly reduces the transfer distance. In addition to mass transfer efficiency, system pressure drop is also an important factor affecting operational energy consumption. In the flow-through configuration, the fluid must penetrate the small pores in the electrode, so the pressure drop produced in the flow process is obviously much higher than in the flow-by configuration. In addition, in order to allow water to pass through the electrode smoothly, the flow-through configuration needs to perforate the electrode current collector. This reduces the effective contact area between the electrode and the current collector, for example, from the original 12.5 cm^2 to about 8 cm^2. In contrast, the Flow-by configuration has a more open flow channel, so the pressure drop is lower. However, the shape of the flow channel in this configuration needs to be optimized during design. For example, using rectangular or circular cross-sections can reduce dead zones where fluid cannot reach, so that the fluid is distributed more uniformly across the entire channel [58].

5.1.2. Membrane capacitive deionization (MCDI)

Traditional capacitive deionization (CDI) technology is limited by a significant co-ion effect. Under the action of an electric field, ions with the same charge as the electrode are repelled from the electrode double layer into the desalination flow channel. This not only wastes the input charge, but also leads to low desalination efficiency and charge efficiency of the entire system [59]. To solve this problem, membrane capacitive deionization (MCDI) has made improvements: a layer of selectively permeable ion exchange membranes (IEMs) is introduced between the electrode and the flow channel. Its core structure is to place an anion exchange membrane (AEM) in front of the anode and a cation exchange membrane (CEM) in front of the cathode. In this way, the electrode chambers and the desalination chamber are physically separated. IEMs have fixed charge groups and generate a strong Donnan exclusion effect, which can effectively prevent co-ions from entering the desalination flow channel. At the same time, they can also ensure that counter-ions with opposite charges to the electrodes move efficiently to the electrode surface. Thus, the co-ion effect is fundamentally suppressed, and the charge efficiency is improved [59,60]. In addition, the introduction of IEMs also enables the system to have the ability to selectively separate different ions. By designing or selecting IEMs with specific pore sizes, different charge densities, and functional groups, MCDI can accomplish some highly selective separation tasks. For example, it can effectively separate lithium from magnesium, or preferentially remove nitrate rather than chloride ions from water [59].

5.1.3. Hybrid systems

Through the coupled design of electrochemical adsorption with processes like electrooxidation, electroreduction, and membrane filtration, electrochemical hybrid systems obviously improve the effect of treating pollutants in water. For example, Kim et al. [61] designed a redox electrodialysis system, combining electrochemical adsorption and electrooxidation technologies. This system can not only remove PFAS from short-chain to long-chain, but also achieve desalination synchronously, and can also decompose the enriched PFAS through electrochemical oxidation. The defluorination effect can reach 76–100%, and this experimental result is intuitive. In terms of the coupling of electrochemical adsorption and electroreduction, Liao et al. [62] discovered that after uranium ions U(IV) are adsorbed onto the electrode surface under the action of an electric field, they are in-situ reduced to water-insoluble U(IV) oxides and deposited. The removal rate can reach up to 99.9%, and the adsorption capacity is 1,340 $mg \cdot g^{-1}$. In addition, the coupling of electrochemical adsorption and membrane filtration is also reflected in the redox electrodialysis system. Kim et al. [61] adopted a nanofiltration membrane (NF) to replace the traditional anion exchange membrane (AEM). This integrated strategy uses an electric field to choose selective ion migration. By combining the strengths of various technologies, it can not only remove per- and polyfluoroalkyl substances efficiently, but also reduce membrane fouling effectively. Furthermore, it maintains stable desalination performance. This provides a practical technical route for water purification.

5.2. Key operational parameters

5.2.1. Applied voltage/current

In the electrochemical adsorption process, applying voltage or current is a key way to regulate the adsorption driving force. Liao et al. [62] prepared a layered 2D/2D niobium phosphate/porous graphene (HGNbP) electrode and systematically explored the effect of voltage on the uranium (U(VI)) adsorption performance. The study found that when the applied voltage reached 0.9 V or higher, the adsorption effect improved significantly. When a voltage of 1.2 V was applied, a 99.9% uranium removal rate could be achieved in only 30 min, and its effect was far superior to that of traditional physicochemical adsorption. At the same time, this voltage range of 0.9~1.2 V could also effectively avoid exceeding the water decomposition potential (≈1.23 V), thus reducing energy waste and the occurrence of side reactions. In addition, the study by Liao et al. [62] also showed that when the current density of the HGNbP-30 electrode increased from 0.8 to 1.5 Ag^{-1}, its capacitance could still remain above 50%. This result suggested that the electrode has good adsorption performance.

5.2.2. Solution chemistry

Solution chemistry parameters play a key role in controlling electrochemical adsorption performance, mainly including pH, ionic strength, and initial concentration. Among these solution chemistry parameters, pH can influence the adsorption process by changing the form of pollutants and the charge state of the electrode surface. Park et al. [63] studied the adsorption behavior of Cd(II) on activated biochar and found that only about 40% of Cd(II) could be adsorbed at pH = 3.5. When the pH increased from 3.5 to 8, the adsorption capacity of Cd(II) also increased accordingly. When the pH was higher than 8, the adsorbent could still remain a relatively good adsorption effect. The reasons for this phenomenon are as follows: under the condition of strong acidity and low pH, the electrode surface is easy to be positively charged, resulting in electrostatic repulsion against Cd^{2+}. Meanwhile, the hydrogen ions in the solution compete with Cd^{2+} for adsorption sites, resulting in poor adsorption effect. With increasing pH, the positive charge on the electrode surface decreases, leading to stronger electrostatic attraction. More adsorption sites become available, and thus increases the adsorption capacity. When the pH is higher than 8, the adsorption effect becomes nearly stable. At this time, in this alkaline environment, $Cd(OH)_2$ precipitation may also form, which further improves the removal effect of Cd(II). The influence of ionic strength on adsorption performance is not fixed and may change significantly at different pH. However, this effect becomes much weaker at higher pH. These trends have been confirmed by experimental results. In addition, the initial concentration of the pollutant also directly affects the saturation adsorption capacity that the adsorbent can finally achieve. Park et al. [63] conducted adsorption isotherm experiments and found that the adsorption of Cd(II) on activated biochar fits the Langmuir model. At a pH of 7.5 and an ionic strength of 0.001 mol/L, the maximum adsorption capacity reached as high as 167.3 mg/g.

5.2.3. Hydraulic conditions

In the electrochemical adsorption system, flow rate and residence time are two key parameters for hydraulic regulation. In a flow-through configuration, a higher flow rate can induce forced convection inside the porous electrode, obviously thinning the diffusion boundary layer. This shortens both the distance and time required for contaminants to migrate from the bulk solution to the adsorption sites on the electrode. For example, Israel Hakizimana et al. [64] conducted a study on an electrochemical system with a porous Ti-ENTA/SnO_2-Sb anode. They found that when the flow rate increased from 0.05 cm/s^{-1} to 0.41 cm/s^{-1}, the pseudo-first-order reaction rate constant (kobs) increased from 0.0829 min^{-1} to 0.2194 min^{-1}. In addition, the mass transfer coefficient (km) also increased accordingly. However, a higher flow velocity is not always better. The residence time, which refers to the effective contact time between the fluid and the electrode, must also be taken into account. In a membrane capacitive deionization system, Hassanvand et al. [65] found through experiments and modeling that, for a feed water with a certain concentration, when the residence time exceeded about 4.4 min, further extending the residence time, the total salt adsorption capacity increased by less than 1%. At the same time, the water recovery rate of the system decreased obviously by 10%.

5.3. Key electrochemical characterization techniques

To deeply understand the material properties and interfacial processes of carbon-based electrochemical adsorption, a series of key electrochemical characterization techniques are indispensable. This section will systematically introduce the basic principles of key characterization technologies, including cyclic voltammetry, electrochemical impedance spectroscopy, and charge efficiency measurement, and explain their practical application value in this research field. These technologies together establish the theoretical and experimental foundation for the evaluation and optimization of electrochemical adsorption systems.

5.3.1. Cyclic voltammetry (CV)

Cyclic voltammetry (CV) is an electrochemical technique. It scans the electrode potential cyclically at a fixed rate and records the corresponding current signal in real time. The obtained current-potential curve (CV curve) can act as a “fingerprint” to reflect the inherent electrochemical properties of electrode materials. In the research of carbon-based electrochemical adsorption, CV is widely applied in the following aspects:

Evaluating capacitive behavior and distinguishing adsorption mechanisms: Ideal non-Faradaic double-layer capacitance behavior (such as potential-driven ion adsorption described in Subsection 2.2.2) shows an approximately rectangular shape on the CV curve. This rectangular shape suggests that rapid electrostatic adsorption/desorption processes occur across the entire potential range. In contrast, when obvious and reversible redox peaks appear on the CV curve, it indicates the existence of Faradaic reactions. These reactions correspond to potential-assisted chemisorption (such as the Cr(VI)/Cr(III) transformation in Subsection 4.1.4) or the pseudocapacitive effect generated by surface functional groups. Thus, CV is the first-choice method for distinguishing between “capacitive adsorption” and “Faradaic process-assisted adsorption.”

Determining electrochemically active surface area and operating potential window: CV can be used to estimate the electrochemical active surface area of electrodes by measuring capacitive current at different scan rates in the non-Faradaic region. Compared with using only the BET specific surface area, this method can more accurately reflect the effective interface area that can be used for charge storage. In addition, CV also helps to determine the safe working potential window. Within this range, water splitting (hydrogen/oxygen evolution) and other harmful side reactions do not occur, which is important for optimizing operating parameters (such as the applied voltage in Subsection 5.2.1).

5.3.2. Electrochemical impedance spectroscopy

Electrochemical impedance spectroscopy (EIS) analyzes the kinetics of interfacial processes by applying a small amplitude sinusoidal AC potential perturbation to an electrochemical system and measuring the relationship between the current response and frequency change. By fitting an equivalent circuit model, multiple key parameters can be quantified from EIS data:

Analyzing interfacial processes and kinetics: A typical Nyquist plot shows a semicircle in the high-frequency region (corresponding to the charge transfer process) and a straight line in the low-frequency region (corresponding to the mass transport process). Charge transfer resistance is a key indicator to evaluate the difficulty of reactions on the electrode surface (such as the reduction of heavy metal ions or the oxidation of organic compounds). For example, in the study of Cd^{2+} sensors in Subsection 4.1.2, a lower Rct value indicates that the N-CQDs@α-Fe_2O_3/PANI composite material has excellent electronic conductivity, ensuring the sensitivity and speed of the detection signal.

Assessing material modification effects and system stability: EIS is a sensitive detection tool. It can be used to evaluate the improvement in conductivity after carbon material functionalization (Subsection 3.5) and composite fabrication (Subsection 3.4). In addition, during the long-term operation of the system, electrode contamination, deactivation of active sites, or pore blockage may all lead to an obvious rise in Rct and mass transport resistance. Thus, EIS can be used to monitor the degradation of electrode performance either online or offline, providing a basis for regeneration cycles.

5.3.3. Charge efficiency and related performance indicators

Charge efficiency is a key indicator for evaluating the energy utilization economy of the electrochemical adsorption process, and it plays a decisive role in assessing the practical application potential of this technology.

Definition and importance of charge efficiency: In electroadsorption processes such as capacitive deionization, charge efficiency is usually defined as the ratio of the moles of ions removed from the solution to the moles of electrons transferred from the external circuit to the electrodes. In an ideal double-layer charging process, the charge efficiency can reach 100%. However, in practical systems, the efficiency is usually much lower. This is mainly caused by the co-ion effect, Faradaic side reactions (such as water electrolysis), or charge leakage. Efficient processes aim to maintain high charge efficiency while achieving high adsorption capacity.

Application in system design and optimization: This concept is directly related to the optimization of system configuration. As described in Subsection 5.1.2, one of the core purposes of introducing ion exchange membranes into membrane capacitive deionization technology is to greatly improve the charge efficiency of the system by suppressing co-ion effects. In performance evaluation (Subsection 5.4) and discussions on energy consumption challenges (Subsection 6.1.3), charge efficiency is an important evaluation index, and its importance is equivalent to that of adsorption capacity and removal rate. One of the goals of optimizing operating parameters (such as voltage and flow rate) is to find the best balance between adsorption performance and charge efficiency. This helps achieve the lowest energy consumption per ton of treated water.

5.3.4. Association with other characterization techniques

The above electrochemical characterization techniques form a strong complementary relationship with the physicochemical characterization methods mentioned earlier in this paper (such as BET measurement of specific surface area, XPS analysis of surface elements and chemical states, and SEM/TEM observation of morphology). Physicochemical characterization mainly reveals the ‘static’ structural properties of materials, while electrochemical characterization methods such as CV and EIS dynamically reflect the interfacial behavior, charge storage, and transport capabilities of materials under ‘working conditions’. Combining these two analytical methods can establish a complete structure-activity relationship from ‘microstructure’ to ‘surface chemistry’ to ‘macroscopic electrochemical performance.’ This is important for deeply understanding the adsorption mechanism (Section 4) and guiding the design of advanced materials (Subsection 6.2.1).

5.3.5. The importance of in situ characterization techniques for understanding interface mechanisms

Traditional characterization techniques (such as cyclic voltammetry and electrochemical impedance spectroscopy) mainly provide macroscopic or statistical information of the system under “before and after operation” or “quasi-equilibrium state”. In order to dynamically reveal the complex evolution of the electrode/solution interface during electrochemical adsorption in real time and in situ at the molecular/atomic scale, in situ characterization techniques have become an indispensable means. Its core importance is reflected in the following aspects:

Directly observe the dynamic processes of the interface: The core mechanism of electrochemical adsorption, such as the real-time formation and evolution of the electric bilayer structure, the valence state changes, and the surface complexation process of pollutants during potential-assisted chemisorption, and the generation and consumption of active species (such as •OH) in coupled electrochemical conversion. These are all rapidly changing dynamic events. In-situ techniques (e.g., in situ spectroscopy, in-situ microscopy) can perform observations while applying working potential/current, capture intermediate states, and identify key steps, providing the most direct experimental evidence for these theoretical mechanisms.

Correlation between material surface chemical properties and real-time performance: This paper highlights the decisive influence of material surface chemistry (such as heteroatom doping and specific functional groups) on adsorption selectivity and mechanism of action. However, the actual working potential of these active sites and the true state of the solution environment (such as the protonation degree of functional groups and the electronic structure of doped atoms) may differ from their static state. In-situ surface-enhanced Raman spectroscopy, in-situ X-ray photoelectron spectroscopy, and other technologies can real-time monitor the changes of material surface chemical states during electrochemical cycles. This helps establish an accurate structure-activity relationship between “dynamic surface properties and adsorption properties,” and provides guidance for more precise material design.

Uncover the mechanism of competitive adsorption and failure: How do competitive ions affect the adsorption path of the target pollutant in complex water bodies? How does the microscopic process of electrode contamination or passivation begin? These issues are directly related to the long-term stability of the system. The in-situ quartz crystal microbalance can monitor the mass changes of the electrode surface in real time and distinguish the adsorption of different substances. In-situ atomic force microscopy can observe the adsorption morphology and nucleation process of pollutant molecules or dirt on the electrode surface. This information is crucial for the development of anti-fouling electrodes and optimizing regeneration strategies.

In conclusion, combining in situ characterization techniques discussed in this paper with the theoretical framework and traditional electrochemical tests can raise our understanding of carbon-based electrochemical adsorption from the level of "black box" or "post-hoc analysis" to a new height of "visualization" and "mechanism empirical evidence". This is not only the key to a deep understanding of existing mechanisms, but also an important foundation for the rational design of next-generation high-performance, high-stability electrode materials and intelligent operating systems for practical applications.

5.4. Performance evaluation metrics

Performance evaluation is a critical step to determine the actual effect of electrochemical adsorption systems in water pollution treatment. Its core indicators comprehensively reflect the adsorption capacity of materials, the economy of the treatment process, and the stability of the system during long-term operation. Adsorption capacity refers to the maximum amount of pollutants that can be adsorbed by a unit mass of adsorbent, and it is the most core indicator for evaluating the performance of the adsorbent itself. Removal efficiency is mainly used to describe the system's capacity to reduce pollutant concentrations to a target level under certain operating conditions. Adsorption kinetics is used to describe the change of the adsorption process over time. This parameter is directly related to the operating cost of the entire process. Cycling stability describes how well an adsorbent can keep its key performance, such as adsorption capacity and removal efficiency, after multiple adsorption–desorption regeneration cycles. For example, Yong et al. [66] developed a micro-mesoporous boron-nitrogen co-doped porous carbon material, and its adsorption capacity for Pb^{2+} could reach 239.6 mg/g. After 15 adsorption–desorption cycles, the material still maintained 83% of its Pb^{2+} adsorption capacity. In another study, Zhou et al. [67] developed a graphite/activated carbon fiber composite electrode. When this electrode was used to treat refined cotton black liquor, its COD removal rate could reach 76%.

6. Challenges and future perspectives

6.1. Current challenges

6.1.1. Material level

Carbon materials, with their advantages of abundant raw materials and controllable costs, have become the core choice for cost-effective electrodes.

The key to the implementation of this technology is the large-scale preparation and synergistic optimization of multiple properties. Such as Activated carbon (AC), it is prepared from coal. Its preparation process is simple, mainly including ball milling, high-temperature activation (800 °C), acid washing purification, and other. Physical mixing with $CoWO_4$ (dispersion, stirring, filtration, drying) is easy to form heterostructures. This process provides a simple and scalable process flow for material preparation [68]. We can synthesize both carbon nanotubes (CNTs) and Mxenes in bulk. Their synthesis uses mature processes such as chemical exfoliation and CVD. Biomass-derived carbon dots can be directly prepared by hydrothermal reaction. It further develops the low-cost, scalable preparation pathways.

The performance of high-performance electrodes depends on the balance among several key parameters. These parameters mainly include adsorption capacity, conductivity, and mechanical strength. After the AC was compounded with $CoWO_4$, the effective specific surface area increased by 1.8 times. At the same time, the charge transfer resistance of the material dropped to 24.8 Ω. This improves the material's adsorption capacity and electron transfer efficiency. The material can achieve a detection limit as low as 0.024 μM. Composite materials of CNTs and metal oxides can improve mechanical strength due to their one-dimensional structure. As a result, they can prevent electrode detachment. MXene-AuNPs improve their own stability through interlayer forces. Their signal decay rate over 32 days is only 3.51%.

Such durability results from the chemical inertness and the composite structure design of carbon materials. The $CoWO_4$-AC electrode showed excellent reproducibility in seven consecutive cycle tests. In addition, its response deviation is very small after 60 days of storage. It reached a recovery rate of 99%–102% in river water samples [68].

6.1.2. Mechanism level

Carbon materials, characterised by high specific surface area and excellent conductivity, find extensive application in electrochemical sensing and catalytic oxidation of pollutants. However, two core challenges persist at the mechanism level.

There is still a serious lack of in situ/operational characterization of complex interfacial processes. A $CoWO_4$-AC heterostructure can be formed between carbon materials and metal oxides. This heterostructure can improve electrochemical performance via synergistic effects. These effects involve dynamic processes such as interfacial electron transfer and pollutant adsorption-oxidation-desorption [68]. However, existing research mainly relies on static characterization techniques such as XPS and XRD. These techniques can only reflect the static chemical state of the interface and fail to track the dynamic evolution process under actual operating conditions. DFT calculations have confirmed the existence of multiple non-covalent interactions between TBPA and $CoWO_4$. These mainly include hydrogen bonding and van der Waals forces. However, due to the lack of in situ experimental validation, it is difficult to reflect the actual interfacial behavior accurately.

In systems containing multiple pollutants, the competitive mechanisms between substances and the selective regulation mechanisms of ions are still under study. In practical application environments, TBPA usually coexists with compounds such as bisphenol A and resorcinol. This causes mutual competition between them in the adsorption and oxidation processes on the surface of carbon materials [68]. Currently, methods for selective regulation of carbon materials are still relatively limited. Existing approaches mainly rely on pore size regulation and surface functional group modification. Current research on the correlation between surface electronic structure and the oxidation characteristics of pollutants is still insufficient. The matching mechanism between the two still needs to be studied in depth. When the oxidation potentials of coexisting pollutants overlap, it can lead to an obvious decrease in selectivity.

6.1.3. System Level

Carbon materials, characterised by high specific surface area and excellent conductivity, find extensive application in electrochemical sensing and catalytic oxidation of pollutants. However, two core challenges persist at the mechanism level, that is, energy consumption and electrode fouling.

Although electrochemical adsorption is considered an energy-saving technology, its actual energy consumption (usually measured as the electricity consumed per unit of water produced or per unit of pollutant removed, kWh/m^3 or kWh/kg of pollutant) heavily depends on the target water quality, system configuration, and operating parameters. Reported energy consumption data in the literature vary widely. For example, capacitive deionization (CDI) technology used for brackish water desalination typically has an energy consumption range of 0.1 to 1.0 kWh/m^3, depending on the influent salinity (e.g., 500–5,000 mg/L NaCl) and recovery rate. For membrane capacitive deionization (MCDI), energy consumption can be further reduced compared to conventional CDI due to improved charge efficiency. When treating low-concentration heavy metals or organic pollutants, electrochemical adsorption systems focused on pollutant enrichment may have energy consumption more reflected in the preparation and regeneration of electrode materials, while the direct electrical consumption may be relatively low, but there is a lack of standardized reporting. To objectively assess its energy efficiency, the typical energy consumption of carbon-based electrochemical adsorption is compared with several mainstream water treatment technologies in **Table 3** below.

Table 3. Overview of energy consumption comparison of different water treatment technologies.

Technology type	**Typical applications**	**Typical energy consumption range (kWh/m^3)**	**Key notes/influencing factors**
Capacitive Deionization (CDI/MCDI)	Brackish water desalination, low-salinity water desalination	0.1–1.0	Energy consumption is approximately linearly related to feedwater salinity; has energy efficiency advantages over RO at low salinity.
Reverse Osmosis (RO)	Seawater desalination, brackish water desalination	Seawater: 3–10 Brackish water: 1–4	Energy consumption is greatly affected by feedwater salinity, pressure, and recovery rate; osmotic pressure must be overcome.
Electrodialysis (ED)	Brackish water desalination, industrial demineralization	0.5–4	Energy consumption is directly related to the amount of ions removed; suitable for medium and low salinity.

Table 3. *Cont.*

Technology type	**Typical applications**	**Typical energy consumption range (kWh/m^3)**	**Key notes/influencing factors**
Advanced Oxidation Processes (AOPs)	Degradation of recalcitrant organics	Several to tens of kWh/m^3 (or kWh/kg pollutant)	Energy consumption highly depends on pollutant type, concentration, oxidant dosage (e.g., H_2O_2), and UV intensity.
Conventional Adsorption (e.g., Activated Carbon)	Broad-spectrum pollutant removal	Most energy consumption occurs in the thermal regeneration stage (~1–3 kWh/kg activated carbon)	Direct water treatment energy consumption is low, but material regeneration (thermal or chemical) is energy-intensive.

From a comparative perspective, it can be seen that for low-salinity brackish water desalination, CDI/MCDI indeed has the potential to compete with or even outperform RO and ED in terms of energy consumption, which supports the discussion in the text regarding its low-energy advantage. However, for high-salinity seawater desalination, RO (especially when combined with energy recovery devices) and ED usually have better energy efficiency. When treating trace contaminants, the absolute electricity consumption of electrochemical adsorption may be very low, but it should be evaluated in combination with its contaminant enrichment efficiency (such as the mass of contaminants removed per unit of energy consumption), and compared with technologies that require molecular destruction, such as advanced oxidation processes, which often require higher energy input to achieve contaminant mineralization.

Various strategies can be used to optimize energy consumption. In process coupling, renewable energy sources such as photovoltaic power generation can be integrated into the system. This enables the system to have dispatchable load characteristics. A study has shown that this method can effectively reduce overall operating costs. According to the energy formula ($E = V \times I \times t/V_{treate}d$), the operating parameters can be accurately adjusted. Thus, the energy consumption of the electrochemical advanced oxidation process is controlled within the range of 0.5–2.5 kWh/m^3 [69].

The electrodes usually suffer from serious fouling and performance degradation in long-term operation. Scaling and organic contamination are the main causes of these problems. Scaling originates from the deposition of ions such as Ca^{2+}, Mg^{2+}, and Fe^{3+}. These ions form substances like $Fe(OH)_3$, $CaCO_3$ and other deposits, creating deposition layers. The deposition layers further block the pores inside the electrodes. Organic contamination can cause humic acid and proteins to adsorb onto the electrode surface. These organic substances can cover the active sites of the electrode by hydrophobic interactions and hydrogen bonding. In turn, this leads to a sharp decline in the electrode's salt adsorption capacity. We can use three effective methods to alleviate these problems. These include material functionalization, regular chemical cleaning, and material pretreatment [70].

Standardized electrode parts and series electrolytic cells can improve performance consistency. Low-cost carbon materials can be used to make modular reactors, which are cost-effective. These systems can lower the operating cost to US$0.503/m^3. This result clearly proves their significant economic advantages [69].

6.1.4. Engineering scaling and system integration

Although carbon-based electrochemical adsorption has shown great potential in laboratory research, its transition from the laboratory to large-scale practical application requires systematically addressing a series of interrelated challenges, including engineering scale-up, long-term stable operation, cost control, and system integration. This section will delve into these core engineering issues.

Expanding the scale of reactor configurations is one of the main challenges faced in the engineering field. Basic laboratory-scale configurations (such as flow-through and flow-channel types) will face various difficulties when scaling up production. The flow-through configurations have higher mass transfer efficiency. However, their scale-up still requires addressing many practical issues. These include ensuring that the internal potential distribution and fluid distribution of large thick electrodes are uniform. At the same time, the system pressure drop needs to be kept within a reasonable range. The flow-channel configuration has lower pressure drop. The channel geometry needs to be optimized (for example, expanding from laboratory rectangular channels to industrial-scale plate-and-frame or tubular stack designs) to avoid the formation of ‘dead zones’. At the same time, the matching relationship between electrode plate area and treated water volume must be accurately calculated. In addition, the ‘stacked’ design is realized by running individual reactors in parallel (to increase treatment capacity) and in series (to improve removal efficiency). This is key to achieving flexible scalability in processing capacity.

In long-term operation of complex real water bodies, electrode fouling (organic matter, biofilm, and colloids blocking pores) and surface passivation (irreversible deposition of metal ions and oxidation of carbon materials) are the primary issues leading to performance degradation and increased maintenance costs. The mechanism lies in the fact that the fouling layer increases mass transfer resistance and interfacial impedance, while passivation reduces active sites. Strategies to address these issues must be multi-faceted:

1) Material level: develop anti-fouling coatings (such as hydrophilic or antibacterial modifications) and electrodes with self-cleaning functions;
2) Operation level: introduce periodic electrochemical cleaning (such as short-term potential reversal, pulse potential) and acid-base chemical regeneration protocols;
3) System level: optimize pretreatment processes (such as multi-media filtration and microfiltration) to reduce the contaminant load in the influent.

Different carbon materials vary greatly in terms of cost, technological maturity, and scalability, which are the core bottlenecks for industrialization. A rational technological path needs to balance between “high performance” and “high cost,” and between “adequate performance” and “excellent economic efficiency.” **Table 4** below systematically compares the techno-economic characteristics of major categories of carbon materials based on the content of Sections 3 and 4:

Table 4. Core comparative analysis on the techno-economic aspects of major categories of carbon materials.

Material category	**Technology maturity (TRL)**	**Relative cost**	**Scalability preparation**	**Key advantages (related subsections)**	**Major challenges of scaling (critical analysis)**
Activated carbon (AC)	High (TRL 8–9), which has been used on a large scale in water treatment.	Low. Raw materials (coal, coconut shell, wood) are abundant, and the production process is mature.	Easy to scale, with mature continuous activation (physical/chemical) production lines.	High specific surface area, very low cost, and mature process (3.1.1).	Electrochemical properties (such as conductivity and capacitance) are generally lower than those of carbon nanomaterials; Performance batch-to-lot variations can be affected by raw materials.
Biochar	Medium to high (TRL 7–8), applied in agriculture/environment.	Extremely low. Using waste biomass as raw material, the cost is mainly pyrolysis energy consumption.	Easy to scale, equipment similar to activated carbon production, but more dispersed raw materials.	Extremely low cost, outstanding environmental benefits (carbon sequestration), and abundant surface functional groups (3.3.1).	Conductivity, pore structure, and performance consistency are highly dependent on precursors and pyrolysis conditions, requiring strict quality control.
Carbon nanotubes (CNTs)/graphene (GO/rGO)	Medium (TRL 4–6), laboratory to pilot scale, high-end fields have been used.	High. Synthesis processes such as CVD are complex, energy consumption is high, and purification and dispersion steps increase costs.	Large-scale preparation, especially high-quality, single-dispersion products, is still challenging, with capacity, uniformity, and cost control issues.	Superior conductivity, mechanical strength, and adjustable surface chemistry for superior performance (3.2.1, 3.2.2).	High raw material and preparation costs are the biggest obstacles; environmental, health, and safety (EHS) concerns about nanomaterials also need to be evaluated.
Carbon nanofibers (CNFs)	Medium (TRL 5–7), which have applications in composites and other fields.	Medium to high. Processes such as electrospinning cost more than AC but may be lower than CNT.	Continuous spinning technology can achieve large-scale production, but the output and rate still need to be improved.	The one-dimensional fiber structure is conducive to the construction of a three-dimensional conductive network and has good flexibility (3.2.3).	Throughput and efficiency in large-scale production, as well as process costs for integration with current collectors.
Hierarchically porous carbon	Medium (TRL 5–7), which is in the transition stage from R&D to application.	Medium. The stencilization method or fine activation process adds complexity and cost.	The removal and recovery of templates and the continuity of complex processes are the difficulties of scale.	Multi-level channels optimize mass transfer and energy storage, and balance performance (3.3.2).	The complexity and repeatability of the preparation process can be controlled, and the cost advantage is not obvious compared to ordinary AC.
Carbon-based composites (e.g., C/MOF, C/polymer)	Low to medium (TRL 3–6) and are mostly laboratory studies.	High. It involves multi-step synthesis and heterogeneous material assembly, and the process is complex.	The scale-up and stability control of multi-step and multi-phase composite processes are a huge challenge.	Function integration to achieve multi-functions such as "adsorption catalysis" and "adsorption sensing" (3.4).	The highest synthesis complexity and high cost; Interface stability in long-term cycles.

The efficient and stable operation of the electrochemical adsorption unit relies on integration with upstream and downstream processes. As an advanced treatment unit, it is necessary to consider how to couple it with biochemical treatment, coagulation, membrane filtration, and other processes, and properly manage the concentrated liquids it produces (such as desorption liquids enriched with pollutants). To achieve low energy consumption and adaptive operation, it is necessary to develop an intelligent control system based on real-time sensors (pH, conductivity, redox potential), using algorithms to dynamically optimize key operating parameters, enabling a shift from constant voltage/constant current modes to more energy-efficient constant concentration effluent and on-demand energy supply modes.

In addition to laboratory-scale preparation, it is also necessary to consider the various challenges faced by large-scale and continuous production processes. At the same time, the cost control of electrode materials (especially functionalized carbon materials and composites) must also be taken into account. The preliminary techno-economic analysis framework includes multiple components. These include the reactor manufacturing cost after scaled-up production, the full lifecycle replacement cost of electrodes, and system maintenance costs. At the same time, it is also necessary to conduct a comparative analysis of investment and operating costs with mature technologies such as reverse osmosis and ion exchange. This helps to objectively identify potential application scenarios where electrochemical adsorption technology has cost competitiveness. For example, softening low-salinity brackish water or selective recovery of trace contaminants. At the same time, it can clarify the current bottlenecks to be overcome, thereby improving the overall economic benefits.

In summary, the strategic choice of materials should closely revolve around the target application scenarios. For large-scale, low-value brackish water desalination or general wastewater treatment, activated carbon and biochar may be the most practical options due to their unparalleled cost advantages and sufficient performance. Research in this area should focus on further improving their performance stability and charge efficiency through green, low-cost modifications. In contrast, for the treatment of extremely toxic or trace pollutants that require selective recovery (such as PFAS or precious metals), the efficiency and selectivity improvements brought by high-performance materials like carbon nanotubes and graphene may be enough to offset some of their cost disadvantages. Research should focus on reducing synthesis costs and developing scalable preparation processes. In the future, exploring the use of inexpensive carbon sources such as biochar as precursors to prepare performance-enhanced carbon materials through green processes, or constructing composite structures of ‘biochar matrix – nanocarbon conductive network’, may be an important direction for achieving a balance of ‘performance-cost-sustainability’. The ‘low-cost’ advantage emphasized in this review needs to be understood and realized within this layered, pragmatic framework for material selection.

6.1.5. Error analysis

When evaluating the performance of carbon-based electrochemical adsorption systems, it is important to note that experimental results may exhibit certain fluctuations and uncertainties. The main sources include:

1) The control precision of operational parameters, as slight variations in voltage or pH can have significant effects on interfacial processes;
2) Batch differences in material properties, especially the heterogeneity of biomass-derived carbon materials;
3) The simplification of the experimental system, as results from laboratory single-pollutant systems may deviate in complex real water bodies due to

competitive adsorption and matrix effects;

4) Performance degradation during long-term operation, such as decreased efficiency caused by deactivation of electrode active sites or contamination.

Future performance reports should quantify these uncertainties as much as possible and conduct long-term stability tests under conditions close to actual applications to provide more reliable data.

6.2. Future research directions

6.2.1. Advanced material design

Carbon materials have excellent electrical conductivity, mechanical stability, and biocompatibility. This makes it important for applications in bioelectronics, energy storage, and other fields. Under the guidance of machine learning, advanced materials can achieve integrated design with intelligent functions. This provides a key way to overcome application limitations.

Carbon materials' performance is closely associated with their microstructure. Traditional experimental methods have certain limitations. It is difficult to comprehensively explore these multidimensional relationships. Machine learning can analyze massive amounts of data to build accurate structure-property prediction models. With the help of these models, the development cycle of materials can be greatly shortened. For example, in the field of electrochemical sensor research, it can quickly optimize the doping ratio of sulfur and phosphorus co-doped graphene. This is used to determine the electrocatalytic reaction solution with the best performance [71]. In neural interface design, the intrinsic relationship between carbon nanotube parameters and interface impedance can be analyzed. This not only helps in fabricating low-impedance electrodes but also enables multi-objective optimization of properties such as conductivity and flexibility [72].

Self-cleaning functionality helps carbon materials resist contamination in complex media. Carbon surfaces tend to adsorb biomolecules or deposits. This adsorption process leads to performance degradation. Surface modification to create specialised structures can impart superhydrophobic properties. For instance, in BSA detection sensors, polydimethylsiloxane combined with sulphur-phosphorus co-doped graphene forms a superhydrophobic interface, reducing biomolecular adsorption [71]. Self-healing capabilities extend carbon materials' applicability in dynamic environments. In flexible electronics, carbon materials are prone to failure under mechanical stress. Dynamic cross-linked networks enable structural and functional repair. For instance, poly(borosiloxane) composites with carbon nanotubes rapidly reconstruct conductive networks to restore electrical conductivity. This capability allows adaptation to tissue movement in applications such as cardiac patches, reducing the risk of immune reactions [72].

6.2.2. Process intensification and mechanism analysis

Process enhancement and mechanism analysis require a dual breakthrough. This is reflected in advanced representation technology and diversified improvement strategies. Novel in-situ spectroscopic techniques present important research value for the dynamic interfacial processes between carbon-based electrodes and pollutants. This technology is listed as a priority research direction in the relevant field. In situ X-ray absorption spectroscopy (XAS) can accurately track changes in the electronic structure and coordination environment of active sites on the electrode surface. This technology can capture in real time the coordination process between heavy metal ions and other substances with the functional groups of carbon materials. Attenuated total reflection Fourier transform infrared spectroscopy (ATR-FTIR) can sensitively detect the structural evolution of pollutant molecules. This technology can reveal the formation mechanisms of interfacial interactions such as hydrogen bonds and electrostatic interactions. Therefore, breaking the limitations of traditional static representations. At the same time, we actively explore various process enhancement strategies. This includes techniques such as photo-electrochemical synergistic effects and magnetic field assistance. On one hand, we combined carbon materials with photocatalysts. This method realizes the synergistic effect of photo-generated carriers and the electric field. Therefore, the adsorption and conversion efficiency of pollutants are remarkably enhanced. On the other hand, magnetic fields can induce directional aggregation of magnetic carbon-based composites. This can improve adsorption kinetics and material recovery. These research findings provide theoretical support for the performance optimization of carbon-based electrochemical adsorption technology. Meanwhile, this also provides corresponding technical support for the technology.

6.2.3. System integration and engineering

System integration and engineering are important aspects of the development of carbon-based electrochemical adsorption technology. It is also a key turning point for this technology to move from the laboratory to practical application. Its core goal lies in developing efficient and compact modular reactors. Based on the structural characteristics of carbon material electrodes, standardized stackable electrode modules can be designed. It can be flexibly configured in series or parallel to adapt to water treatment scenarios of different scales. Notably, computational fluid dynamics is utilized to improve the reactor flow channels and electrode layout. This method can effectively reduce mass transfer resistance and further improve the treatment efficiency per unit volume of the reactor. At the same time, the focus will be on improving the energy recovery system. To achieve energy recovery during the electrochemical adsorption/desorption process, we need to set up the corresponding device. This device is mainly used for energy capture and reuse. In this way, the energy consumption loss of the entire system is reduced. In addition, research must be conducted on actual industrial and agricultural wastewater. It needs to undergo long-term pilot testing to simulate complex water quality environments. At the same time, it is also necessary to simulate the operating conditions of continuous operation. It is necessary to focus on monitoring key indicators such as treatment efficiency and electrode lifespan. At the same time, it is of great necessity to track and monitor parameters such as maintenance costs in order to assess the economic feasibility of this technology through a full life cycle analysis. On this basis, it summarizes the precise process parameters. This provides a reliable design basis for subsequent large-scale engineering applications.

6.2.4. Resource recovery orientation

Shifting from the simple “removal” of pollutants to the “recovery” of resources is an important technological development. This brings carbon-based electrochemical water treatment technology in line with the development of a circular economy. This is also the key direction for the future development of this technology. Its core lies in designing functionalized electrode materials. This type of electrode material combines high-selective adsorption with enrichment capability. At the same time, it is also necessary to have a customized desorption solution. Corresponding research is conducted mainly on high-value metals and nutrient elements in wastewater. High-value metals include Au^{3+}, Ag^{+}, Li^{+}, and nutrients include N, P, K. Modified by precise functional group modification, pore size regulation, and loading of metal nanoparticles on carbon-based electrodes, the electrode materials enjoy an improved specific interaction with the target substance. Finally, it is valuable to achieve efficient adsorption and rapid enrichment of low-concentration target substances. Also, it is necessary to develop mild and efficient desorption solutions. By precisely controlling the electric field parameters in combination with a low-dose green eluent, the stability of the electrode structure and performance can be stabilized. It can effectively desorb the target substances and prevent secondary pollution. The target substance obtained from desorption can be used as an industrial raw material or agricultural fertilizer after simple purification. This process truly realizes turning waste into treasure in the water treatment process. This allows the waste to be efficiently recycled and used. This method combines water environment management with resource recycling. It can bring good environmental benefits during its application. At the same time, it can also create considerable economic value.

7. Conclusion

Carbon-based electrochemical adsorption technology actively and precisely regulates the traditional adsorption process through an electric field, providing an innovative solution for the efficient and selective removal of heavy metals, organic pollutants, and nutrient salts in water. This review systematically explains its core mechanisms—from electric field-enhanced physical adsorption, potential-driven ion adsorption, to potential-assisted chemical adsorption and coupled electrochemical conversion and adsorption—revealing the intrinsic relationship between the characteristics of carbon materials (conductivity, specific surface area/porous structure, surface chemistry) and these mechanisms as well as the ultimate removal performance.

This technology has many outstanding strengths. It features good controllability and reversibility. Researchers can complete adsorption and desorption cycles simply by regulating voltage or current. In addition, this method is eco-friendly. It cuts down the use of chemical reagents and prevents secondary pollution. It also works well in gathering low-concentration and refractory pollutants. This paper summarizes relevant research cases. Targeted carbon materials include functionalized carbon fibers, nanocomposites, and biochar. When experimental conditions are properly optimized, these carbon materials can remove pollutants with remarkable efficiency.

However, promoting this technology from the laboratory to practical engineering applications still requires overcoming several challenges:

1) The performance needs to be verified in complex matrices close to real water (containing multiple coexisting ions and natural organic matter), as well as improving the long-term operational stability and fouling resistance of the systems;
2) In terms of materials, a balance must be found between high performance (such as carbon nanotubes, graphene) and low-cost/scalable feasibility (such as activated carbon, biochar), developing cost-effective electrode materials;
3) At the engineering level, key issues such as reactor scale-up design, system integration, and intelligent control need to be addressed, along with comprehensive techno-economic-environmental lifecycle assessment.

Future studies can focus on several key directions. First, researchers need to develop more advanced in-situ characterization methods. These methods help explore the dynamic reaction mechanisms at material interfaces. Second, it is necessary to reasonably design multi-functional carbon materials. These materials should have good electrical conductivity, proper pore structure, and specific active sites. Third, standard test procedures and energy assessment standards should be set up for complex practical systems. Fourth, pilot experiments and long-term operation tests should be carried out. These efforts can support the large-scale use of carbon-based electrochemical adsorption technology. It also lays a good foundation for its practical application in environmentally friendly water treatment.

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