

Research Progress on Electrochemical Recycled Activated Carbon

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ABSTRACT

Activated carbon (AC) is widely used in water treatment and environmental pollution control due to its excellent adsorption properties. However, the regeneration of saturated AC remains a critical challenge. As an efficient and environmentally friendly regeneration technology, electrochemical regeneration drives redox reactions through applied electric fields to degrade adsorbed pollutants and restore AC's adsorption capacity. This paper reviews the mechanisms of electrochemical AC regeneration, including direct electron transfer, $\cdot\text{OH}$ radical oxidation, and electrochemical desorption. It explores how key parameters such as electrode materials, current density, electrolyte type, and pH value affect regeneration efficiency. Research demonstrates that electrochemical regeneration offers advantages like low energy consumption, minimal secondary pollution, and high regeneration rates, making it particularly suitable for regenerating saturated AC with high-concentration organic pollutants. Future research should focus on optimizing reactor designs, developing stable electrode materials, and exploring application potential in complex real-world wastewater systems.

KEYWORDS

Activated carbon; Electrochemical regeneration; Adsorbent regeneration; Wastewater treatment

1. INTRODUCTION

Activated carbon adsorption is a widely used method for removing pollutants from water [1]. Due to its highly porous structure and functional surface groups, activated carbon exhibits high adsorption capacity. Additionally, it demonstrates strong affinity for a wide range of components even at low concentrations, such as organic substances and heavy metal ions [2]. Currently, industries including petroleum and natural gas, pharmaceuticals, and wastewater treatment are increasingly incorporating activated carbon into their production processes. With the continuous growth in global demand for activated carbon, environmental protection standards, product quality requirements, and regulations on liquid/gas emissions have become progressively stricter. Since 2012, global consumption has grown by nearly 10% annually, reaching 4.28 million tons [3]. While activated carbon has proven highly effective, its service life is limited. Once it reaches its adsorption limit, it ceases to produce effective adsorption performance. The spent activated carbon is then replaced with new material, which is subsequently disposed of through landfilling—a method that may lead to toxic pollutant leaching into the environment [4]. Regenerating spent activated carbon offers a more economical and environmentally friendly solution, enabling multiple adsorption cycles and reuse.

Activated carbon regeneration technology is a crucial environmental solution that restores adsorption capacity through various methods, thereby extending service life and reducing waste. Key regeneration approaches include thermal regeneration, chemical regeneration, and biological regeneration. Thermal regeneration consumes significant energy but proves ineffective against heat-

resistant pollutants, with 5-15% carbon loss observed [5]. Chemical regeneration may cause secondary pollution and involves costly reagent selection and disposal [6]. Biological regeneration requires prolonged cycles and specific microbial growth conditions. Notably, these technologies often overlook secondary contamination risks during pollutant removal. Their processes primarily focus on desorbing contaminants from solid phases into alternative media (e.g., gases, liquids, or solid waste), rather than achieving fundamental pollutant elimination or harmless treatment.

To comprehensively evaluate and apply activated carbon regeneration technology, we need to conduct in-depth research on pollutant desorption treatment methods. This ensures the regeneration process not only restores activated carbon's adsorption capacity but also achieves safe pollutant management and environmentally friendly processing. To overcome these limitations, researchers have turned to an emerging technique called electrochemical regeneration. In this method, saturated activated carbon is placed between two electrodes with opposite charges. When current is applied, the desorption and degradation of adsorbed pollutants can be observed. R.M.NARBAITZ et al. [7] were the first to study this technology, using a 1L electrochemical reactor to regenerate 1.2g of phenol-saturated granular activated carbon. After five hours of treatment, the GAC regeneration efficiency reached 95%, with minimal carbon loss—only 2% of adsorption capacity was lost per cycle during continuous regeneration. These results outperform other regeneration methods in terms of adsorption capacity and long-term performance, making them worthy of further investigation in this field [8].

In conclusion, this paper aims to comprehensively explore the electrochemical regeneration mechanism, influencing factors and advantages and disadvantages of the technology. By doing so, we seek to fundamentally grasp the core aspects of this regeneration technology, deepen our understanding of electrochemical regeneration techniques, provide a solid theoretical foundation for further in-depth research, and promote the continuous progress and development of activated carbon regeneration technology.

2. MECHANISM OF ELECTROCHEMICAL REGENERATION

Electrochemical regeneration technology involves placing activated carbon contaminated with pollutants in a specially designed electrochemical reactor. By applying an external electric field, this process triggers a series of chemical or physical changes in the adsorbate, effectively removing contaminants while restoring the carbon's original adsorption capacity. The regeneration mechanism primarily involves two stages: First, desorption occurs on the carbon surface, producing adsorbent particles free from contaminants. Subsequently, under electrochemical action, the electrodes and polarized carbon particles catalyze pollutant degradation, completely removing them from the system [9].

Electrochemical reactions include: 1) Direct anodic oxidation. Pollutants first migrate and adsorb onto the anode surface, where direct electron transfer occurs to produce oxidized compounds [10]. Direct oxidation is not considered a key oxidation mechanism for treating wastewater contaminated with organic compounds due to its extremely slow kinetics and low degradation rates of organic matter [11]. 2) Indirect anodic oxidation. This process involves generating reactive substances through electricity, such as active chlorine, ozone, hydrogen peroxide, and hydroxyl radicals. Specifically, water oxidation at the anode surface produces hydroxyl radicals that immediately react with pollutants nearby to remove them [12]. Additionally, free radicals generated during electrochemical processes can be chemically or physically adsorbed onto the anode surface, converting into high-valent oxidation states. These high-valent substances then react with organic pollutants to form oxygen-containing products. 3) Indirect cathodic oxidation. First, the double-electron reduction of dissolved oxygen occurs at the cathode to form H_2O_2 . If granular activated carbon is placed between the electrodes, it enhances the generation rate of hydrogen peroxide and other oxidizing agents [13]. The granular activated carbon serves as a catalyst, promoting further

reduction of hydrogen peroxide at the cathode to produce highly oxidized hydroxyl radicals. The generated hydroxyl radicals can oxidize pollutants desorbed from the activated carbon surface, achieving the purpose of carbon regeneration.

3. FACTORS AFFECTING ELECTROCHEMICAL REGENERATION

3.1. Electrochemical Reactor

3.1.1. Fixed-bed type

The fixed-bed method involves securing activated carbon adsorbent particles on or between the working anode and cathode. Researchers have adopted this configuration due to its controllability, enhanced current efficiency, and superior surface-to-volume ratio. The most common approach positions the adsorbent in contact with the anode or cathode to prevent short circuits that could reduce current flow and degrade performance. Nadia Gadi et al. [14] employed a cathode fixation method by embedding activated carbon particles within stainless steel mesh for caffeine degradation. Results demonstrated 100% caffeine degradation rate and 76% mineralization rate in wastewater treatment. During regeneration, complete caffeine desorption was achieved, with the first cycle yielding 50% regeneration efficiency. Wei Zhou et al. [15] developed a composite cathode combining granular activated carbon and stainless steel mesh. After 12 hours of electrochemical treatment, the activated carbon achieved 88.7% regeneration efficiency, maintaining 52.3% efficiency even after 10 adsorption-regeneration cycles.

3.1.2. Fluidized bed type

An electrochemical fluidized bed is a device where solid particles (such as catalysts and electrode materials) are uniformly stacked in a perforated container to form a bed layer. When a fluid (e.g., electrolyte solution) flows downward through the bed, the solid particles exhibit a liquid-like boiling phenomenon under fluid influence, known as fluidization. This configuration is termed an electrochemical fluidized bed. Yingzhen Li et al. [16] developed a fluidized bed system that enables electrodes to undergo rapid and efficient regeneration in high fluoride concentration aqueous solutions when subjected to -1.6V voltage. The fluoride removal rate showed no significant decline after multiple cycles of electro-enhanced adsorption and regeneration. M.H. Zhou et al. [17] implemented a fluidized bed electrochemical process using activated carbon loaded with p-nitrophenol. Under optimal conditions, the activated carbon achieved 90% regeneration efficiency within 1.5 hours, with no noticeable deterioration observed after five consecutive adsorption-regeneration cycles. Zhou Lei et al. [18] attributed the high regeneration efficiency to activated carbon particles' proximity to the anode, where hydroxyl radicals could oxidize adsorbed substances. By increasing the electrolyte flow rate in the fluidized reactor, pollutant removal rates rose from 85.4% to 96.8% after 1.5 hours of operation. Zhang et al. [19] demonstrated that activated carbon particles in fluidized electrochemical cells exhibited 10% higher regeneration efficiency compared to those fixed on cathode surfaces.

3.2. Regeneration Site

The electrochemical regeneration position refers to the location of materials to be regenerated (such as activated carbon and metal ions) within an electrolytic cell during the regeneration process, specifically whether they are situated in the anode or cathode region. This positioning significantly impacts the effectiveness of electrochemical regeneration. Research indicates that cathodic regeneration of granular activated carbon (even when in contact with the cathode) demonstrates higher efficiency than anodic regeneration [20]. Danilo H.S. Santos et al. [21] found that electrochemical treatment effectively restores activated carbon's adsorption capacity, achieving maximum efficiencies of approximately 79% and 84% under anode and cathode currents of 0.1 A for

carbon fiber cloth-AC electrodes, respectively. Additionally, through adsorption-regeneration cycles at the cathode, the material exhibited excellent stability, maintaining a regeneration rate around 80% after eight consecutive cycles. Zhang et al. [22] discovered that cathodic regeneration efficiency for saturated activated carbon adsorbing phenol was 20% higher than anodic regeneration. Berenguer R et al. [23] similarly observed elevated regeneration efficiency at the cathode. It is believed that substantial charge accumulation at the anode enhances the attraction between phenol and activated carbon, while the opposite occurs at the cathode where the concentration gradient of adsorbate opposes the potential gradient, leading to competition between diffusion and migration. Garcia-Oton M et al. [24] found reduced oxygen-containing groups on activated carbon surfaces at the cathode region, whereas increased numbers were observed at the anode. However, the increase in surface oxygen groups may lead to micropore clogging [25].

3.3. Electrode Materials

Cathode materials must be capable of generating H_2O_2 according to reactor requirements, meaning they should effectively reduce O_2 to produce H_2O_2 and thereby degrade desorbed pollutants into CO_2 and H_2O . Commonly used electrode materials include stainless steel, graphite, and glassy carbon. Xiao et al. [26] investigated the regeneration efficiency of Rhodamine B-saturated activated carbon in an electrochemical regeneration system using 9, 10-anthraquinone-2-sulfonic acid/poly-pyrrole-modified graphite sheets. They determined optimal conditions as 155mA current density, 0.13M electrolyte concentration, and 7h regeneration time. After 8 regeneration cycles, the activated carbon achieved a 76.6% regeneration efficiency. Ferrandez-Gomez et al. [27] conducted adsorption tests on saturated bisphenol A (BPA)-contaminated activated carbon using Pt/Ti, RuO_2/Ti , and IrO_2/Ti anodes. The Pt/Ti anode showed 96% regeneration efficiency after 3 hours of operation, with no significant differences observed between anode pairs. They concluded that RuO_2/Ti and IrO_2/Ti could serve as cost-effective alternatives to Pt/Ti. Leyla Gazigil et al. [28] optimized alternating current electrochemical regeneration conditions for activated carbon using laboratory-produced Sn/Sb/Ni-Ti anodes with Pt/Ti cathodes. Results demonstrated 6 effective regeneration cycles: 98.78% efficiency during the first cycle and 68.55% removal efficiency in the final cycle. The carbon-PTFE electrode developed by Yu Jue Wang et al. [29] enables the cathode to rapidly generate H_2O_2 under electrofenton conditions, with the generated H_2O_2 being effectively utilized to initiate Fenton oxidation reactions with Fe^{2+} , thereby promoting the oxidative removal of target pollutants. Tusekile Alfredy et al. [30] employed a loading method to immobilize alumina onto activated carbon, achieving effective paraquat removal through electrochemical oxidation. The composite electrode demonstrates high reusability, maintaining significant regeneration efficiency even after multiple cycles.

3.4. Current Density

Current density significantly influences the regeneration efficiency of activated carbon. As current intensity increases, the production rate of oxidative free radicals rises, accelerating degradation rates. Enhanced electrochemical mass transfer dynamics facilitate free radicals' entry into the micropores of adsorbent materials. Simultaneously, elevated current density promotes desorption of organic adsorbates and accelerates their migration to the liquid phase. Chih-Huang Weng et al. [31] investigated the regeneration performance of field-collected spent granular activated carbon from wastewater treatment plants using electrochemical methods. Through intermittent methylene blue (MB) adsorption experiments, they evaluated electrochemical regeneration capabilities and found that increased current density boosts regeneration efficiency. Huiping Zhang et al. [32] conducted studies on phenol-saturated activated carbon regeneration in electrochemical reactors, revealing a slight improvement in regeneration efficiency with increasing regeneration current.

At lower applied current densities, the presence of less strongly oxidizing substances like hydrogen peroxide can reduce the efficiency of phenol oxidation degradation. However, excessively high

current densities may slow down or even halt phenol degradation. This occurs because hydrogen peroxide production on the cathode plate reaches saturation at elevated current levels, with no further increase in output when the applied current density continues to rise. Additionally, high potentials may induce side reactions such as oxygen deposition and water formation.

3.5. Electrolyte

In the treatment of organic wastewater (including phenol-containing wastewater), solutions typically exhibit poor conductivity, making direct electrochemical catalytic treatment impractical. Therefore, it is necessary to introduce support electrolytes with excellent conductivity, high stability, and strong water solubility. The selection of electrolytes significantly impacts the electrochemical catalytic oxidation of organic compounds, as different electrolytes play distinct roles during experiments. Commonly used electrolytes include sodium chlorides such as sodium chloride. R.M. Narbaitz et al. [33] observed that increasing NaCl concentration from 0.1% to 1.0% (w/w) linearly enhances activated carbon regeneration efficiency. A drawback of using sodium chloride as an electrolyte is its tendency to chlorinate organic compounds, potentially increasing toxicity. In such cases, degradation of formed compounds requires extended treatment time. G. Asgari et al. [34] found that variations in electrolyte concentration directly affect ion exchange rates and reduce electrostatic resistance between electrodes and electrolytes, thereby improving system performance through enhanced electrochemical reactions (e.g., oxygen reduction to hydrogen). However, alternative electrolytes like sodium bicarbonate lead to decreased activated carbon regeneration efficiency. This occurs because bicarbonate ions act as free radical scavengers in the solution, hindering the oxidation rate of organic pollutants.

3.6. Regeneration Time

For organic adsorbents, extending regeneration time can enhance the production of oxidative free radicals such as hydroxyl radicals, which facilitates the oxidative degradation of organic matter and promotes the desorption of degradation products into the electrolyte. However, prolonged regeneration time may adversely affect the adsorbent. Berenguer R et al. [35] employed electrochemical regeneration of phenol-adsorbed granular activated carbon, observing increasing regeneration efficiency and pore recovery rate during the initial 3-hour phase. However, as time progressed, accumulated oxidative byproducts gradually hindered further regeneration. Belgin Karabacakog˘lu et al. [36] demonstrated that while electrochemical regeneration achieved sustained efficiency increases from 30 to 60 minutes for Cr⁶⁺-adsorbed activated carbon, efficiency began to decline after 120 minutes. Consequently, 60 minutes was identified as the optimal regeneration duration. Narbaitz R M et al. [37] emphasized that excessive regeneration time could lead to electrode surface accumulation of reaction products, resulting in electrode passivation. These findings indicate that different activated carbons require tailored regeneration times, necessitating comprehensive evaluation of both regeneration efficiency and economic considerations in practical applications.

3.7. pH

Within electrochemical cells, the pH value significantly influences pollutant adsorption efficiency, the types of compounds generated through electrogeneration, electroadsorption and desorption processes, as well as oxidation reaction rates. The prevailing view is that higher pH values tend to promote desorption processes, while lower pH values accelerate oxidation reactions. Found that cathode regeneration in NaOH medium facilitates phenolate desorption. At the anode, appropriate acidity helps suppress electrochemical side reactions and enhances electrochemical oxidation. Alkaline conditions favor HClO formation, which indirectly strengthens oxidation. pH selection during regeneration depends on the type of adsorbate. Generally, alkaline conditions are more suitable for organic adsorbates, as most degradation products of organic adsorbates exhibit higher water

solubility under alkaline conditions or their functional groups can undergo hydrolysis with oxygen-containing groups in adsorbent materials, thereby enhancing desorption. For heavy metal adsorbates, acidity proves more advantageous, as increased H^+ ions weaken metal adsorption forces, facilitating desorption.

4. CONCLUSION

In conclusion, this study investigated the influencing factors in the electrochemical regeneration process of activated carbon. Key parameters such as reactor type, cathode material, current density, pH value, electrolyte type and concentration, and regeneration time were analyzed. By optimizing these control conditions, the efficiency of activated carbon regeneration can be significantly enhanced. The optimized electrochemical regeneration process not only promotes desorption but also enables direct oxidation of pollutants at the electrode surface.

Electrochemical regeneration, as an innovative liquid-phase regeneration technology, demonstrates unique advantages and holds promising applications in the era of increasingly widespread use of adsorbent materials. Therefore, in-depth research on electrochemical regeneration is of significant value. Current studies predominantly focus on desorption treatment of single adsorbate substances, yet practical applications involve activated carbon's simultaneous adsorption of diverse and complex material types. Future efforts should address existing technical bottlenecks to achieve sustainable regeneration and recycling of activated carbon, thereby enhancing resource utilization efficiency, reducing costs, and protecting the environment.

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