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Analysis of Electrochemical Technologies for Wastewater Treatment

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Abstract. Electrochemical technology has demonstrated significant advantages in water pollution treatment by virtue of its efficient redox reaction and flexible control characteristics. This paper systematically discusses the principles and applications of electrocoagulation (EC), electrooxidation (EO) and electro-flotation (EF): electro-flocculation generates hydroxide colloid adsorption of pollutants through the dissolution of the metal anode, and the removal rate of heavy metals (Pb^{2+}, Cd^{2+}, Cu^{2+}) reaches more than 98%; electro-oxidation degrades difficult-to-biodegrade organics with the help of hydroxyl radicals (-OH), and the removal of dyestuff wastewater can reach over 98%. Electro-oxidation with the help of hydroxyl radicals (-OH) to degrade difficult-to-degrade organic matter, the COD and color removal rate of dyestuff wastewater is more than 80%; Electro-flotation using micro-bubbles to achieve high-efficiency separation of emulsified oils and colloidal particles. The synergistic process (e.g., EC-EF) can remove heavy metals and organics simultaneously, and the reduction rate of chromaticity and COD of printing and dyeing wastewater reaches 92.9% and 88.9%, respectively. However, the high cost of electrodes, high energy consumption and scale-up bottlenecks constrain its development. In the future, we need to focus on the development of low-cost electrode materials, multi-technology coupling (e.g., electrochemical-photocatalytic) and intelligent control, in order to promote electrochemical technology in the direction of zero industrial wastewater discharge and resource transformation, and help the sustainable management of water pollution.

Keywords: wastewater, electrochemical technologies, removal efficiency

1. Introduction

With the rapid growth of the global population and the advancement of industrialization leading to environmental pollution, urban and suburban water sources may contain high concentrations of organic and inorganic pollutants, which are often highly toxic, poorly biochemical, and difficult to degrade. The increase in water pollution poses a significant challenge to the environment [1]. If wastewater is discharged directly into rivers without treatment, it will upset the ecological balance and jeopardise the health of plants, animals and humans. The drawbacks of traditional physical, chemical and biological treatment methods are becoming more and more obvious, and it is difficult to meet the treatment requirements. Electrochemical technology is widely used in wastewater treatment due to its high efficiency, flexible reaction, low cost and no secondary pollution [2]. This

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paper discusses the principles of electroflocculation, electrooxidation and electroflotation technologies, their applications and future trends in wastewater and industrial wastewater treatment, providing solutions for sustainable water pollution management and helping to reduce environmental pollution.

2. Electrochemical principles and classification

2.1. Fundamentals

The electrochemical principle removes difficult to degrade and complex pollutants through strong oxidation. At its core is a charge transfer process at the interface between ionic and electronic conductors, which generates several different free radicals through the process of oxidising reactive substances, which then interact with the pollutants to degrade them [3]. A chemical that loses electrons (oxidation) is called a reducing agent, while a chemical that gains electrons (reduction) is called an oxidising agent [4]. In an electrochemical cell consisting of two chambers connected by an external circuit and an ionic conductor, a redox reaction occurs on the cathode and anode plates under the action of an applied electric field for the purpose of removing pollutants.

The essential components of an electrochemical cell are: (1) Electrodes – Typically made of metal or semiconductor materials; cathode – Site of reduction reactions (electron gain); Anode-Site of oxidation reactions (electron loss); (2) Electrolyte – Acts as an ionic conductor, serving as a medium for ion migration; (3) Salt bridge or ionic membrane – Maintains charge balance in the electrolyte and prevents direct mixing of solutions; (4) External circuit – Metallic wires connecting the two electrodes, enabling directional electron transfer to complete the electrochemical reaction cycle [4].

2.2. Electrocoagulation and electroflocculation

The electrocoagulation (EC) process is widely used in wastewater treatment to flocculate and precipitate suspended and dissolved pollutants in an electrolytic solution. The cathode and anode electrodes in an electrolytic cell can be of the same or different materials, where the anode is a dissolved electrode, mainly using aluminum or iron as the pole plate. The reaction mechanism of electrocoagulation is based on a multistep synergistic action: during electrolysis, the anode material (e.g., Fe or Al) undergoes electrochemical dissolution, releasing metal cations (e.g., Fe^{2+}/Al^{3+}) into solution; at the same time, the cathode surface generates, by reduction with water molecules, hydroxyl ions (OH-) and hydrogen gas (H_2). Subsequently, metal cations combine with hydroxyl ions to form highly reactive metal hydroxide colloids (e.g., $Fe(OH)_3$ or $Al(OH)_3$), which destabilise the charged contaminants through charge neutralisation and further trap the contaminants on the surface of the flocs by adsorption and co-precipitation to form easily separable agglomerates. Ultimately, the hydrogen generated at the cathode causes the flocs to float to the surface of the water through electroflotation [5]. The advantages of this process are simple operation, small equipment footprint, no need to add chemicals to avoid secondary pollution, high pollutant removal efficiency, short reaction time, and low investment and operating costs. The disadvantages are the electrode passivation, sludge settling, and the removal of complex pollutants is not good [6].

2.3. Electrochemical oxidation

Electrochemical oxidation is the process of oxidative degradation of pollutants in the context of electrochemical water treatment, where several different hydroxyl radicals and other reactive

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substances are produced by an anodic reaction. Some of the radicals are superoxide (O2−), hydroxyl (HO•), sulfate (SO4•−) and hydroperoxyl (HO2•), and they degrade the organic or organometallic contamination by the chain reaction process. (Advanced oxidation process for the treatment of industrial wastewater: A review on strategies, mechanisms, bottlenecks and prospects) O2•− and HO• are the most critical radicals for water treatment degradation. An advanced oxidation process (AOP) is one of the practical processes for degradation purposes, including ozonation, Fenton's oxidation, and photocatalytic oxidation. They can combat organic compounds in four distinct methods: by removing hydrogen, adding or combining radicals, and transferring electrons [7].

AOPs is a very competitive wastewater treatment technology, with a wide range of adaptability and high treatment efficiency; compared with traditional physical and biological methods, it is easy to operate, with a simple treatment process and a small equipment footprint; compared with the traditional chemical method, there is no need to add additional oxidants, which does not produce secondary pollution, and there is also a bactericidal and disinfectant effect [8]. However, the main drawbacks associated with the technology at this stage are the high cost of making the electrodes, the high consumption of the process, the short service life, etc., and the fact that the operation involves not only high costs, but also the need to implement stringent safety and security programs due to the need to use chemicals with strong reactive properties, such as ozone (O3) and hydrogen peroxide (H2O2)[9].

2.4. Electro-flotation

Electroflotation technology through the application of a DC electric field drive electrode surface hydrolysis reaction, generating micron-sized O_2 / H_2 bubbles, and the use of bubble surface electricity and pollutant particles of electrostatic adsorption and hydrophobic polymerisation, combined with the electric field directional migration of the strong, to achieve the high efficiency of the separation of the sewage in the emulsified oil, colloidal particles and heavy metals away from the separation [10]. Electroflotation process technology for emulsified oil, colloidal particles and heavy metal ions show excellent treatment performance, in the petrochemical, electroplating and other industrial wastewater treatment, with COD removal rates and SS removal rates of up to 90%; no need to add chemicals to avoid secondary pollution [11].

The combined technology of electroflotation and electroflocculation is based on the simultaneous realisation of metal anodic dissolution and microbubble generation in an electrochemical reactor, forming a synergistic mechanism of "flocculation and adsorption-air flotation and separation". The technology makes use of the $Al(OH)_3$/$Fe(OH)_3$ floc generated by electroflocculation to adsorb heavy metals and colloidal pollutants with high efficiency, and at the same time, the electroflotation microgas carries the flocs upward by electrostatic action to remove organic pollutants [12]. In printing and dyeing wastewater treatment, the coupling process has high decolourisation of reactive dyestuffs [13], and when treating oil-containing wastewater, the oil content is greatly reduced and no emulsion-breaking agent is required [14].

3. Applications in wastewater treatment

Electrochemical methods have emerged as a sustainable and efficient approach for wastewater treatment, offering precise control over redox reactions to degrade or recover diverse pollutants. This paper explores their applications in organic and inorganic pollutant removal, and real-world industrial wastewater treatment, and discusses their advantages and limitations.

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3.1. Removal of organic pollutants

Electrochemical oxidation (EO) is highly effective in degrading recalcitrant organic pollutants, including fluorescent agents, dyes, and pharmaceuticals, by generating reactive oxygen species (ROS) such as hydroxyl radicals (•OH) at electrode surfaces.

In a study, electrochemical removal of crystalline violet dye from simulated wastewater was carried out using stainless steel rotating cylindrical anode and the results showed that maximum COD removal of 86.89% and maximum color removal of 88% were achieved under optimum conditions with anode speed = 625 rpm, applied current = 658.568 mA, loaded electrolyte = 0.422 M and treatment time = 90 min [15]. It was found that electro-oxidation enhanced the removal of 14 PPCPs by both direct anodic oxidation and indirect oxidation mediated by activated oxygen [16].

3.2. Removal of inorganic pollutants

Heavy metals (Cu, Pb, and Cd) are efficiently removed via electrodeposition, electroreduction, or adsorption on electrogenerated flocs. Continuous anodic aluminum electrolysis generates $Al^{3}+$ (reaction: $Al \rightarrow Al^{3+} + 3e^{-}$), which hydrolyzes into $Al(OH)_3$ nanoflocs (50-200 nm). These flocs efficiently capture heavy metal ions via surface complexation. A study developed a high-efficiency electrocoagulation reactor (ECR) through an innovative aluminum electrode array configuration (e.g., porous gradient arrangement or three-dimensional mesh structure) for treating synthetic wastewater containing multi-metal ions. Under optimized operational parameters (pH 10, current intensity 1.4 A, reaction time 60 min), the system achieved near-theoretical-limit removal efficiencies of 99.73%, 98.54%, and 98.92% for Pb^{2+}, Cd^{2+}, and Cu^{2+}, respectively [17].

3.3. Complex systems and real wastewater applications

Electrochemical systems are adaptable to industrial wastewater with complex matrices. Boulbaba et al. reported the treatment of textile industrial wastewater by electrochemical processes EC, ECSA, EF and EFSA. All the processes can remove the color and reduce the COD of the solution to over 80% [18]. Demir Delil and Gören systematically investigated the performance of an integrated electrocoagulation-electrooxidation (EC-EO) process for treating real textile wastewater, focusing on the regulatory effects of key operational parameters—including electrode configuration (monopolar/bipolar arrangement), electrode material (Fe/Al anodes), initial pH (3–9), voltage gradient (5–20 V), and electrolysis time (10–60 min)—on COD and color removal. Experimental results demonstrated that under optimized conditions (Al anode-bipolar arrangement, pH 7, 15 V, 40 min), the synergistic effects of electrochemical oxidation (•OH generation) and metal hydroxide flocculation achieved remarkable reductions: color intensity decreased from 395 Pt–Co to 28 Pt–Co (92.9% removal) and COD declined from 1,040 mg/L to 115 mg/L (88.9% removal), without introducing secondary chemical agents [19].

3.4. Advantages and limitations

Electrochemical technologies offer versatile solutions for wastewater treatment, particularly for toxic organics and heavy metals. While energy costs and electrode durability remain challenges, advances in catalytic materials (e.g., non-precious metal oxides) and hybrid systems (e.g., solar-powered EC) promise to enhance sustainability. Future research should focus on cost-effective scale-up and integration with AI-driven process control.

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4. Challenges and future perspectives

Although electrochemical water treatment technology has significant advantages in the efficient removal of pollutants, its large-scale application still faces multiple challenges. The durability and cost of electrode materials are the core bottleneck: although the catalytic activity of precious metal-coated anode is excellent, they are easily passivated and stripped in strong oxidative environments, and the cost is high, which restricts the technical economy; non-precious metal composite electrodes and self-repairing coatings are the direction of breakthrough. System scale and energy consumption optimization need to take into account the efficiency and cost. Laboratory results at the industrial level are prone to uneven current distribution, low mass transfer efficiency and other issues, and the energy consumption of tons of water is far more than biological. It needs to be through the modular multi-stage reactor, three-dimensional porous electrodes and pulses for the combination of renewable energy (e.g., solar power) to achieve reduced consumption and efficiency. Multi-technology synergistic treatment is an inevitable trend to cope with complex wastewater: electrochemical-biological coupling can crack the problem of high energy consumption and high cost during the treatment of nitrophenol pollutants, removing COD (45%) and NO3 - (51%) at the same time, and reducing the biological toxicity, and the low operating cost of this Ag cathode-based system has excellent application potential in the treatment of NP-polluted wastewater [20]. A double-chamber membrane electroflotation reactor was used to recover recyclable chromium (III) from tannery waste effluent wastewater, with a chromium (III) recovery rate of about 98% [21]. And the electrodeposition-adsorption synergistic technology allows simultaneous recovery of heavy metals (Cu^{2+} recovery >94%)[22].

In the future, we should focus on three core elements: developing low-cost and long-life electrode materials, building a multi-process synergistic system (e.g., electrochemical-photocatalytic coupling) and promoting AI-driven precision control, in order to overcome technical bottlenecks and promote the transformation of electrochemical technology towards zero industrial wastewater discharge and resource recycling.

5. Conclusion

Electrochemical technologies (ECTs), distinguished by their high efficiency, operational adaptability, and environmental friendliness, represent a leading approach in advanced wastewater treatment. Research consistently confirms their exceptional performance in eliminating a wide spectrum of pollutants. They effectively degrade persistent organics like dyes and pharmaceuticals, remove heavy metals (e.g., Pb^{2+}, Cd^{2+}, Cu^{2+}) with efficiencies often exceeding 98%, and efficiently separate complex mixtures such as oil-water emulsions (separation >95%). Crucially, their operation typically avoids secondary pollution by minimizing or eliminating chemical additives. Progress through electrode material innovation (e.g., non-precious composites, self-healing coatings) and process optimization (e.g., pulsed power, reactor design, hybrid systems) has enhanced energy efficiency and stability, enabling successful pilot and some full-scale industrial deployments for specific applications. However, significant challenges impede broader large-scale adoption. Key bottlenecks include the high cost and limited lifespan of performant electrodes, difficulties in scaling up reactors leading to issues like uneven current distribution and higher energy consumption compared to biological methods for certain wastes, sensitivity to high-salinity conditions, and a lack of sophisticated intelligent control systems. Future advancement hinges on focused efforts in key areas: (1) Developing affordable, durable, high-performance electrode materials; (2) Creating effective solutions for treating high-salinity and complex industrial effluents; (3) Implementing AI-

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driven process control for optimization; and (4) Promoting synergistic integration with complementary technologies like photocatalysis and biological processes. Successfully tackling these challenges is essential to propel electrochemical technologies towards achieving industrial wastewater zero liquid discharge (ZLD) and resource recovery, solidifying their role in sustainable global water management.

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