TECHNICAL SCIENCE RESEARCH IN UZBEKISTAN
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DEVELOPMENT OF TECHNOLOGY FOR ELECTROCHEMICAL INDUSTRIAL WASTEWATER TREATMENT

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Annotation. The treatment of industrial wastewater has become a critical environmental and economic challenge due to the increasing volume of pollutants discharged into water bodies. Among various technologies, electrochemical methods offer significant advantages due to their efficiency, versatility, and low environmental impact. These methods, including electroflotation, electrooxidation, and electrocoagulation, have gained considerable attention as sustainable solutions for wastewater treatment in industrial sectors. This article explores the development of electrochemical technologies for industrial wastewater treatment, with a focus on their application, mechanisms, advantages, and challenges in real-world scenarios.

Keywords. Electrochemical methods, wastewater treatment, electroflotation, electrooxidation, electrocoagulation, industrial effluent, environmental sustainability, hybrid systems.

INTRODUCTION

The motivation for this research stems from the limitations of traditional methods-activated sludge processes often achieve only 50-70% COD removal for recalcitrant industrial streams, while physicochemical coagulation-flocculation generates large volumes of hazardous sludge (0.5-1.5 kg/m³ treated) and requires continuous chemical dosing. Electrochemical alternatives, rooted in fundamental electrochemistry, utilize controlled potential or current to drive reactions such as anodic oxidation, cathodic reduction, and electrocoagulation. Key theories include Faraday's laws governing mass transport via electrolysis ($m = (I\ t\ M)/(n\ F)$), the Butler-Volmer kinetics for electrode processes, and the Nernst equation for equilibrium potentials. In Uzbekistan's context, where industrial water reuse remains below 15% and regulatory pressure intensifies under the National Environmental Action Plan aligned with SDG 6, innovative electrochemical systems promise enhanced pollutant removal, energy efficiency, and resource recovery. This study aims to develop and optimize a hybrid

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electrochemical technology integrating electrocoagulation and advanced electrooxidation, targeting >90% removal of COD, color, and heavy metals from real textile and tanning wastewater, while achieving energy consumption below 10 kWh/m³.

METHODS

The experimental methodology employed a laboratory-scale rectangular batch reactor (5-10 L capacity) constructed from acrylic, with modular electrode configurations to facilitate testing various materials. Anodes included dimensionally stable anodes (DSA) of RuO_2-IrO_2-TiO_2 coated on titanium (for chlorine-mediated oxidation), boron-doped diamond (BDD) on silicon or niobium substrates (for hydroxyl radical generation), and sacrificial aluminum plates (for electrocoagulation). Cathodes were stainless steel (AISI 316L) or titanium to support hydrogen evolution and pH elevation. Power was supplied by a DC potentiostat/galvanostat (0-30 V, 0-10 A) with constant current or potential modes. Wastewater samples were collected from operating textile dyeing and leather processing facilities in the Tashkent and Fergana regions, pre-filtered (mesh 0.5 mm) to remove large solids, and characterized for initial parameters: pH 4.5-9.5, conductivity 8-25 mS/cm, COD 1200-2800 mg/L (dichromate method), color 600-1200 Pt-Co units (spectrophotometric), TSS 250-600 mg/L, Cr(total) 3-12 mg/L, and phenols 10-50 mg/L.

Process optimization followed a multi-stage approach. First, electrocoagulation used Al anodes at current densities of 5-30 mA/cm², electrolysis times 20-90 min, and inter-electrode gaps of 1-3 cm, with NaCl (0.5-3 g/L) as supporting electrolyte when needed. Post-coagulation, supernatants underwent electrooxidation with BDD or MMO anodes at 20-150 mA/cm² for 60-180 min. Key operational variables-current density (j), pH, NaCl concentration, and treatment time-were optimized using response surface methodology (RSM) via Box-Behnken design (Design-Expert software, v.13), with 3 factors at 3 levels yielding 17 experimental runs plus replicates. Response variables included COD removal (%), color removal (%), and specific energy consumption (kWh/kg COD removed). Analytical methods adhered to standard procedures: COD by closed reflux dichromate (APHA 5220 B), heavy metals by atomic absorption spectrometry (PerkinElmer AAnalyst 400), color by ADMI tristimulus filter method, and pH/ORP via calibrated electrodes. Electrode stability

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was assessed through cyclic voltammetry and long-term chronoamperometry (>200 h). Statistical significance was evaluated by ANOVA ($p < 0.05$).

RESULTS

Electrocoagulation with aluminum anodes achieved rapid TSS removal (95-99%) and partial COD reduction (40-65%) within 30-45 min at 15-25 mA/cm², primarily through Al^{3+} hydrolysis forming $Al(OH)_3$ flocs that adsorb colloids and dyes.

Optimal conditions (pH 7.0-7.5, j = 20 mA/cm², t = 40 min) reduced color by 70-85% and Cr by 80-92% via coprecipitation and reduction. Subsequent electrooxidation on BDD anodes markedly enhanced organic degradation, with COD removal reaching 88-96% after 120 min at 80 mA/cm² in the presence of 1.5 g/L NaCl, generating in-situ oxidants including •OH ($E° = 2.80$ V) and ClO^-/HClO. Color was virtually eliminated (>98%), with residual COD <150 mg/L, well below discharge standards (O'z DSt 950:2011 limit 150 mg/L for COD in surface waters). Heavy metal polishing yielded final concentrations: Cr <0.05 mg/L, Cd <0.005 mg/L, Pb <0.1 mg/L.

RSM modeling produced highly significant quadratic models ($R^2 = 0.96$-0.98, Adj $R^2 > 0.94$, lack-of-fit $p > 0.05$), with current density exerting the strongest positive effect on removal efficiencies (F-value >50, $p < 0.0001$), followed by NaCl concentration and treatment time. Energy consumption averaged 4.8-7.2 kWh/m³ (or 6-12 kWh/kg COD), competitive with literature values for similar hybrid systems. BDD electrodes demonstrated superior stability, with <5% activity loss after 250 h, compared to graphite alternatives that passivated rapidly. Pseudo-first-order kinetics described organic degradation ($k = 0.015$-0.085 min^{-1}), with rate constants increasing linearly with applied current up to mass transfer limitations.

DISCUSSION

The development of electrochemical technologies for treating industrial wastewater represents a critical advancement in environmental engineering, particularly in regions facing severe water pollution and scarcity, such as Uzbekistan. Industrial effluents from sectors including textiles, metallurgy, leather tanning, and chemical manufacturing introduce complex mixtures of pollutants-heavy metals (Cr, Cd, Pb, Ni), synthetic dyes, phenols, surfactants, and persistent organic

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compounds-that resist conventional biological treatment due to high toxicity and low biodegradability. According to national environmental monitoring data, industrial discharges in Uzbekistan contribute to approximately 25-35% of surface water pollution in major river basins like the Amu Darya and Syr Darya, with COD levels frequently exceeding 1000-3000 mg/L and heavy metal concentrations surpassing maximum allowable limits (MACs) by 10-100 times (e.g., Cr(VI) up to 5-15 mg/L against MAC of 0.05 mg/L per O'z DSt 950:2011). Electrochemical processes offer distinct advantages through direct and indirect redox mechanisms, minimal sludge generation, and adaptability to variable wastewater compositions, making them suitable for on-site or decentralized applications.

The superior performance of the hybrid system arises from synergistic mechanisms: electrocoagulation effectively preconditions the wastewater by aggregating particulates and reducing turbidity, thereby minimizing electrode fouling during oxidation and enhancing mass transfer of organics to the anode surface. BDD's wide potential window (>3 V) enables non-selective •OH-mediated mineralization, bypassing limitations of conventional anodes where oxygen evolution competes (OER overpotential ~0.4-0.6 V). Indirect oxidation via active chlorine species augments degradation in chloride-rich effluents, common in Uzbek textile wastewaters (Cl^- 500-3000 mg/L). Compared to standalone electrocoagulation (COD removal ~60%) or electrooxidation alone (prone to passivation), the integrated approach achieves higher overall efficiency with 30-45% lower energy demand.

Challenges include electrode scaling in high-hardness waters (mitigated by polarity reversal every 10-15 min) and initial capital costs for BDD (~$400-600/m²), offset by extended lifespan (>5 years at industrial scale) and reduced sludge disposal (0.05-0.15 kg/m³ vs. 0.8-1.2 kg/m³ in chemical coagulation). Economic feasibility analysis indicates a payback period of 2.5-4 years for a 500 m³/day plant, assuming electricity at $0.08-0.12/kWh and water reuse value. Scalability was confirmed in 100 L semi-continuous trials, maintaining >90% removal with flow-through configuration and recirculation. These results align with and extend findings by Uzbek researchers on electrochemical

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dye degradation and heavy metal removal, confirming the technology's viability for local industrial conditions.

CONCLUSION

The developed hybrid electrochemical technology-combining sacrificial electrocoagulation with BDD-based advanced electrooxidation-offers a robust, efficient solution for treating complex industrial wastewaters in Uzbekistan. Achieving 90-96% COD/color removal, near-complete heavy metal elimination, and energy use of 5-8 kWh/m³, it outperforms conventional methods while minimizing secondary pollution. Implementation could significantly enhance water reuse in water-stressed regions, support compliance with stringent MACs, and contribute to sustainable industrial development. Future work should focus on pilot-scale demonstrations, solar-powered integration, and nanomaterial-modified electrodes for further efficiency gains.

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