МЕДИЦИНА, ПЕДАГОГИКА И ТЕХНОЛОГИЯ: ТЕОРИЯ И ПРАКТИКА
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DEVELOPING AN INTEGRATED TREATMENT TECHNOLOGY BASED ON ELECTROCOAGULATION, ELECTROFLOTATION, AND ELECTROOXIDATION

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Annotation

This article develops an integrated electrochemical technology for industrial wastewater treatment based on electrocoagulation, electroflotation, and electrooxidation. The concept is built on mechanistic complementarity: electrocoagulation generates metal hydroxide coagulants in situ to destabilize colloids, emulsions, and dissolved metals; electroflotation intensifies solid liquid separation through fine gas bubbles that rapidly lift and remove formed flocs; electrooxidation then targets the residual dissolved and refractory organic fraction to improve final effluent quality for discharge or reuse. The study systematizes the governing electrochemical rules used for process design, including Faradaic control of coagulant generation, energy intensity accounting, and current density based performance optimization. Key operational variables are analyzed in a unified framework, including current density, hydraulic residence time, electrode material selection, electrolyte conductivity, and pH trajectory, with attention to electrode passivation, sludge management, and energy consumption as scale up constraints. The proposed integrated train is positioned as a compact, controllable, and modular solution suitable for variable industrial matrices where conventional coagulation, biological treatment, or single stage electrochemical methods alone are insufficient.

Keywords

industrial wastewater, integrated electrochemical treatment, electrocoagulation, electroflotation, electrooxidation, boron doped diamond, current density, energy consumption, sludge management, process optimization.

INTRODUCTION

Electrochemical treatment is increasingly positioned as a compact, electrically driven alternative to conventional chemical dosing and multi-stage separation for industrial wastewaters, especially where the influent is variable, inhibitory to biology, or rich in emulsified oils, dyes, and dissolved metals. The rationale for combining electrocoagulation, electroflotation, and electrooxidation into one coordinated train is mechanistic complementarity: electrocoagulation converts dispersed and dissolved pollutant fractions into separable aggregates through in situ generation of metal hydroxo-species; electroflotation intensifies phase separation through fine gas bubble production and attachment to destabilized flocs; electrooxidation then targets the residual dissolved and refractory organics that remain after separation, increasing overall robustness and enabling reuse-oriented effluent quality. Contemporary reviews emphasize that electrocoagulation is not merely "coagulation with electricity," but a controlled Faradaic dosing strategy in which coagulant formation, pH microgradients, and mass transfer jointly determine removal selectivity and energy intensity [1], while electrooxidation with non-active anodes such as boron-doped diamond is distinguished by strong hydroxyl radical generation capacity that supports deep oxidation of persistent organics [7,10].

A coherent integrated technology begins with a quantitative representation of how electrical current translates into reagent generation and pollutant capture. For electrocoagulation with sacrificial aluminum or iron, Faraday's law defines the theoretical mass of anode material dissolved into solution, hence the maximum in situ coagulant dose available for hydrolysis and precipitation.

$$m = I\, t\, M / z\, F$$

Here, m is dissolved anode mass, I is current, t is electrolysis time, M is molar mass of the anode metal, z is electron number, and F is the Faraday constant. The practical significance is that the coagulant dose rate is a programmable function of current, while deviation from theory reflects parasitic reactions, passivation, and nonuniform current distribution. Modern industrial-focused electrocoagulation reviews repeatedly identify current density, conductivity, mixing regime, and electrode composition as primary determinants of current efficiency and effluent quality, rather than nominal voltage alone [1]. In parallel, the specific electrical energy consumption is commonly expressed in volumetric form to enable plant-level benchmarking.

$$E = U\, I\, t / V$$

Here, E is energy in kilowatt-hours per cubic meter, U is cell voltage, and V is treated volume. This metric is highly sensitive to ohmic losses and electrode spacing, which makes reactor geometry and hydrodynamics central design variables for scale-up. A continuous electrocoagulation review in Water reports energy consumption values around 0.7142 kWh per cubic meter for a turbidity removal case using aluminum electrodes, illustrating that low to moderate energy intensities are feasible when conductivity and electrode configuration are favorable [6]. At the same time, other real-matrix studies report higher values depending on wastewater strength, target endpoints, and operating window, underscoring that energy is not an intrinsic property of electrocoagulation but an outcome of electrochemical and transport constraints [4,6].

The mechanistic core of electrocoagulation is a coupled sequence of anodic dissolution and cathodic alkalinization. With aluminum, the anodic reaction generates Al3+ which undergoes rapid hydrolysis to a distribution of monomeric and polymeric hydroxo-complexes and ultimately amorphous Al hydroxide solids that provide strong adsorption and sweep flocculation capacity. With iron, Fe2+ and Fe3+ species similarly hydrolyze and precipitate, with additional redox pathways that can be advantageous for certain pollutants. Cathodic water reduction simultaneously produces hydroxide ions and hydrogen gas, creating local pH gradients that accelerate hydroxide precipitation and colloid destabilization. In industrial waters containing emulsified oils or dyes, destabilization occurs through a combination of charge neutralization, double-layer compression at elevated ionic strength, adsorption to freshly formed hydroxide surfaces, and enmeshment within sweeping precipitates. A synthesis review on industrial wastewater electrocoagulation highlights broad applicability across complex matrices and frames in situ coagulant generation as the defining feature of the technology’s selectivity and compactness [1].

RESULTS

Electroflotation is most powerful when it is not treated as an independent unit but as the separation engine that harvests electrocoagulation products quickly and consistently. Gas bubbles generated electrochemically at electrodes provide attachment sites and buoyant lift for destabilized flocs, oils, and low-density solids. From a process physics perspective, the central variables are bubble size distribution, bubble number density, residence time, and collision-attachment efficiency, all of which are linked to current density, electrode surface morphology, and electrolyte composition. Experimental analysis of electroflotation bubble diameters demonstrates systematic dependence on pH, current density, electrolyte concentration, and electrode configuration, confirming that bubble-mediated separation can be engineered rather than assumed [5]. When electrocoagulation and electroflotation are co-located in the same reactor or operated sequentially without long delays, the system benefits from immediate removal of flocculated material, reducing re-dispersion and minimizing further electrode fouling. This synergy also reduces footprint compared with gravity clarification, which is particularly relevant for industrial sites with space constraints.

Electrooxidation supplies the final barrier for dissolved and refractory organics that escape capture-based removal. The mechanistic distinction most consistently emphasized in the electrooxidation literature is the role of anode material in determining the dominant oxidizing species and mineralization potential. Non-active anodes such as boron-doped diamond operate at high oxygen evolution overpotentials and can generate high surface concentrations of hydroxyl radicals that oxidize organics in a largely nonselective manner, enabling deep conversion that is often described as electrochemical incineration [10]. Foundational evidence and mechanistic interpretations in the BDD literature explicitly link performance to hydroxyl radical accumulation and the formation of highly reactive intermediates at the anode surface [10]. Recent reviews on BDD-based and related non-active anodes reinforce the same mechanistic framework and emphasize material synthesis, stability, and scale-up considerations for industrial deployment [2,3]. Applications in dye-containing wastewater continue to report strong dependence of removal on current density, pH, electrolysis time, and supporting electrolyte, reflecting the combined influence of radical generation rates and mass transfer limits in the boundary layer adjacent to the anode [7].

A technically defensible integrated technology therefore uses electrocoagulation and electroflotation as the primary bulk-removal stage and electrooxidation as the polishing stage, with control logic derived from mechanistic endpoints. The first stage targets rapid removal of suspended solids, colloids, emulsified oils, and metal species that can be precipitated or adsorbed. The second stage targets residual COD, chromophoric compounds, and persistent organics that remain dissolved or weakly associated with solids. A practical rule emerging from modern industrial electrocoagulation reviews is that optimizing current density and treatment time should be performed against charge utilization and separation performance, not against maximum removal alone, because excessively high current density accelerates electrode consumption, gas evolution, and heating, often increasing specific energy without proportional gains in effluent quality [1]. A parallel rule in electrooxidation design is that the marginal benefit of additional electrolysis time diminishes once mass transfer becomes limiting or easily oxidizable fractions are depleted, shifting the process toward energy-intensive oxidation of intermediates; mechanistic attention to mineralization kinetics and current efficiency is therefore essential [3,10].

For process development under OAK-style expectations, the most persuasive methodological strategy is to treat the integrated system as a coupled set of charge-balance and mass-transfer problems. In electrocoagulation and electroflotation, the objective is to maximize pollutant removal per unit charge through improved current distribution, electrode spacing, and mixing, while maintaining a pH window that favors hydroxide formation and stable floc properties. In electrooxidation, the objective is to maximize oxidant generation and effective contact with target organics by controlling current density, hydrodynamics, and electrolyte composition, while suppressing parasitic oxygen evolution and minimizing problematic by-product formation. Recent discussions of electrochemical remediation on BDD underscore both the promise for challenging contaminants and the need for careful process control and materials selection to achieve stable performance [8].

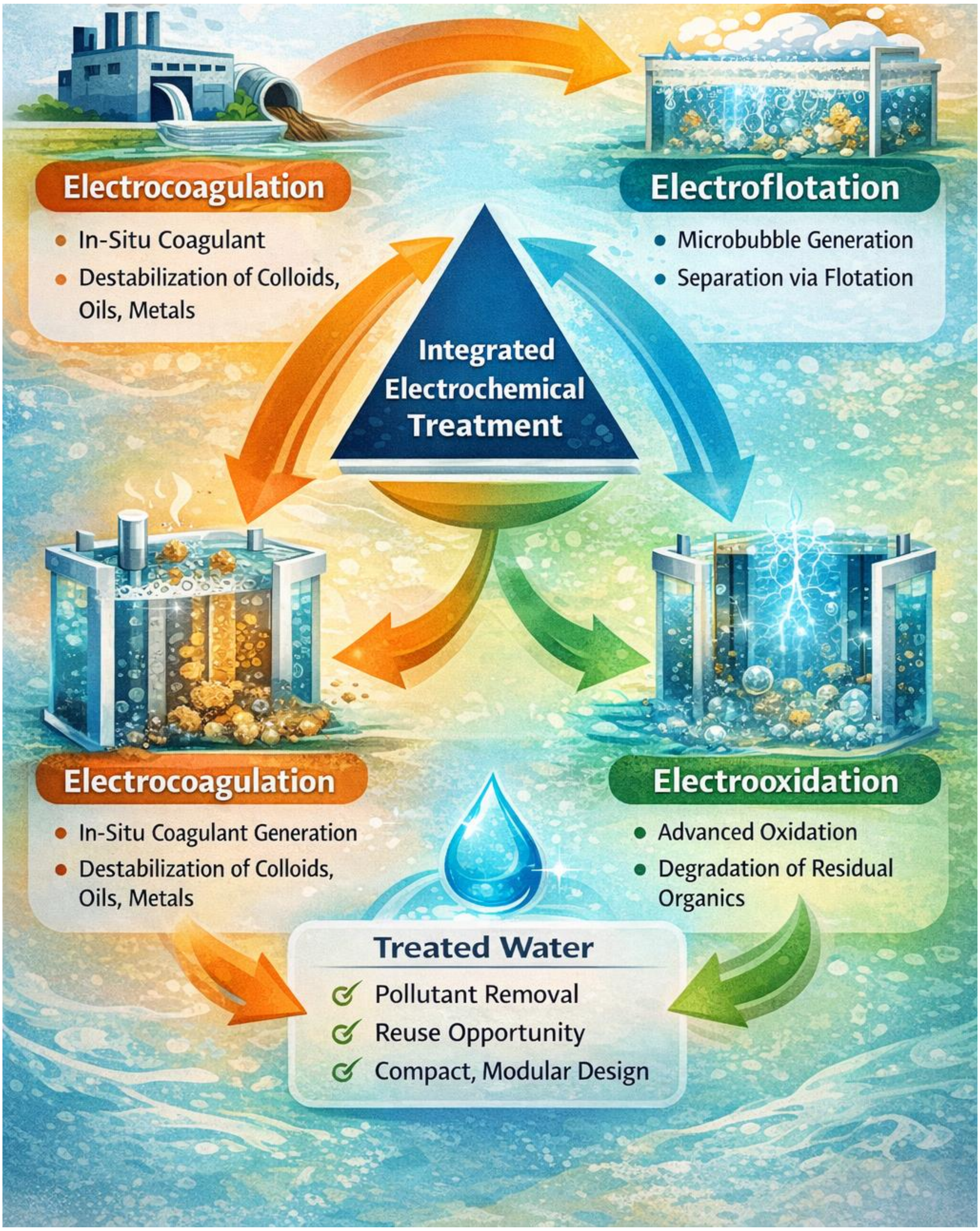
Quantitative performance claims must be handled with matrix specificity. Industrial wastewaters can differ by orders of magnitude in conductivity, COD, metal loading, and surfactant content, so no single removal percentage is universally meaningful. Still, representative literature does provide credible ranges that support the integrated logic. A continuous electrocoagulation review reports turbidity removal around 82.29 percent with energy consumption around 0.7142 kWh per cubic meter for an aluminum electrode configuration, illustrating that bulk clarification targets can be met with moderate energy under appropriate conditions [6]. Electrooxidation studies using BDD for dye wastewater describe systematic parameter effects and demonstrate that strong removal can be achieved when the operating window supports sufficient radical flux and reaction time, with modeling approaches increasingly used to map parameter-response surfaces for design [7]. These results align with the mechanistic argument that capture-dominant removal is efficient for particulate and adsorbable fractions, while oxidation-dominant removal is required for dissolved refractory fractions.

A rigorous discussion of the integrated concept must also address scale-up risks that are mechanistically rooted. Electrode passivation, surface scaling, and organic fouling reduce effective area and alter local current density, decreasing current efficiency for both coagulant generation and radical production. Gas holdup can change conductivity pathways, increase ohmic drop, and modify mixing patterns. Sludge generation is intrinsic to electrocoagulation because pollutants are transferred into a solid phase; the integrated strategy improves this constraint by using electrooxidation to reduce residual dissolved organics without increasing sludge, but it does not eliminate the need for sludge handling. The design implication is that the integrated system should target sludge minimization by removing the maximum pollutant load with the minimum anode dissolution consistent with stable floc formation, and then apply electrooxidation only to the residual fraction where destruction is more rational than capture. Modern electrocoagulation reviews explicitly frame operational challenges around electrode consumption, passivation, and optimization of electrical parameters, reinforcing that successful technology development is as much electrochemical engineering as it is water chemistry [1].

In conclusion, developing a complex treatment technology based on electrocoagulation, electroflotation, and electrooxidation is scientifically justified by clear mechanistic complementarity and by design controllability through electrical inputs. Electrocoagulation supplies programmable in situ coagulant generation and destabilization, electroflotation supplies intensified separation via engineered microbubbles, and electrooxidation supplies advanced oxidation capacity for persistent dissolved organics, particularly when non-active anodes such as boron-doped diamond are used. The most defensible development pathway is charge-efficient bulk removal followed by targeted oxidation polishing, guided by Faradaic dosing, energy-intensity accounting, and mass-transfer-aware reactor engineering. The combined approach is well aligned with current research trends that emphasize compactness, modularity, and reuse-oriented effluent quality in industrial water management [1,3,6,10].

DISCUSSION

Electrocoagulation, electroflotation, and electrooxidation form a scientifically coherent triad for industrial wastewater treatment because they address different physicochemical forms of pollution using electrically controllable mechanisms. Industrial wastewaters frequently contain simultaneous mixtures of dissolved metals, colloids, emulsified oils, suspended solids, dyes, surfactants, and high chemical oxygen demand fractions, so treatment performance depends on whether a technology can convert dispersed and dissolved species into separable phases and then destroy the remaining refractory dissolved organics.



1-photo. Developing an integrated treatment technology based on electrocoagulation, electroflotation, and electrooxidation

A combined electrochemical train is therefore not an additive convenience but a mechanistically layered strategy that converts electrical charge into coagulant generation, separation intensification, and advanced oxidation in sequence. The global relevance is reinforced by large-scale wastewater production and incomplete treatment coverage, with an influential global assessment estimating 359.4 billion cubic meters of wastewater generated annually and about 52 percent treated, emphasizing that intensified and modular processes can contribute where conventional infrastructure is strained or mismatched to industrial matrices [4].

Electrocoagulation is best defined as Faradaic coagulant dosing coupled to in situ hydrolysis and precipitation. It relies on sacrificial anodes, most commonly aluminum or iron, whose dissolution under applied current releases metal ions that undergo rapid hydrolysis to produce a distribution of hydroxo complexes and amorphous hydroxide solids. These freshly formed solids are highly effective sorbents and sweep flocculants that destabilize colloids, adsorb dissolved organics, and capture metals through co-precipitation and surface complexation. The scientific basis begins with Faraday’s law, which links applied charge to the theoretical coagulant mass generated.

$$m = I\ t\ M / z\ F$$

In this relationship, m is the dissolved anode mass, I is current, t is electrolysis time, M is molar mass, z is electron number for the anode dissolution reaction, and F is the Faraday constant. This law is central to technology development because it enables dosing by design rather than by empirical chemical addition, while real systems deviate from the theoretical dose due to parasitic reactions, electrode passivation, and nonuniform current distribution. Recent industrial wastewater reviews emphasize that pH, current density, electrode material, and operating time govern removal efficiency and current efficiency, making these variables primary control levers for scalable process design [1].

The mechanistic pathway in electrocoagulation has a characteristic structure. Anodic dissolution generates Al three plus or Fe two plus, while cathodic water reduction generates hydroxide ions and hydrogen gas. The local cathodic alkalinity accelerates hydroxide precipitation and supports rapid floc formation even when bulk pH is not strongly alkaline. The resulting hydroxide phases destabilize colloids through charge neutralization, adsorption, and bridging, and remove metals through precipitation and co-precipitation pathways. The scientific consensus in electrocoagulation literature is that removal is governed by speciation and interfacial chemistry, so the same current can produce very different outcomes in different matrices depending on complexing ligands, ionic strength, and the fraction of pollutants present as truly dissolved versus colloidal or emulsified forms [1]. This is why robust development work treats electrocoagulation not as a single recipe but as a speciation-aware unit operation that must be matched to the wastewater class.

Energy and electrode consumption determine whether electrocoagulation can move from laboratory results to industrial adoption. The standard energy accounting expresses electricity intensity as:

$E = U I t / V$

Here, E is energy per treated volume, U is cell voltage, I is current, t is electrolysis time, and V is treated volume. The implication is that energy rises with voltage and time, and voltage rises with ohmic losses that scale with electrode spacing and inverse conductivity. A well-cited industrial electrocoagulation review reports low energy consumption values around 0.63 kilowatt-hours per cubic meter for iron and 0.70 kilowatt-hours per cubic meter for aluminum in a specific electrode connection mode, illustrating the feasibility of moderate energy operation when geometry and conductivity are favorable [5]. More recent studies on intensified and multi-electrode configurations report broader energy ranges, such as 0.041 to 9.13 kilowatt-hours per cubic meter depending on configuration and loading, which underscores the need for reactor engineering and operating window selection rather than reliance on nominal removal percentages alone [2]. The scientific lesson is that electrocoagulation should be optimized for pollutant removal per unit charge and for stable separability, because excessive current density can shift charge utilization toward gas evolution and heating without proportional gains in effluent quality.

Electroflotation is the separation accelerator that makes electrocoagulation products recoverable with high reliability and compact footprint. Its defining feature is microbubble generation through water electrolysis, producing hydrogen at the cathode and oxygen at the anode in appropriate configurations. Fine bubbles provide high interfacial area and collision frequency, enabling attachment to flocs, oils, and suspended particles, which reduces apparent density and lifts aggregates to the surface for skimming. The critical scientific insight is that electroflotation is not merely aeration; it is bubble engineering. Bubble size distribution and number density control collision-attachment probability and rise velocity, thereby controlling separation rate and solids capture. Experimental work on electroflotation shows that bubble diameter and its distribution respond systematically to operating parameters such as pH, current density, electrolyte concentration, and electrode geometry, confirming that flotation performance can be tuned electrochemically rather than treated as an uncontrolled side effect [3]. In a combined system, electrocoagulation prepares the pollutant phase into buoyant, bubble-attachable flocs, and electroflotation provides rapid phase disengagement, reducing the time solids remain in the reactor and lowering risks of re-dispersion and electrode fouling.

Electrooxidation provides the destructive pathway for dissolved and refractory organics that evade capture-based processes. Its theoretical foundation is the generation of highly reactive oxidizing species at the anode, and its practical performance is governed by anode material. A prominent mechanistic framework distinguishes non-active anodes, typified by boron-doped diamond, which can sustain high surface concentrations of hydroxyl radicals and thereby enable deep oxidation and, in favorable conditions, mineralization. The concept of electrochemical incineration on boron-doped diamond has been articulated and evidenced in foundational literature, which attributes the strong oxidation capacity to electro-generated hydroxyl radicals at high anodic potentials and to direct electron-transfer pathways under certain regimes [6]. Subsequent and more recent reviews continue to position boron-doped diamond and related non-active materials as high-performance anodes for persistent organic contaminants, while emphasizing that current density, electrolyte composition, and hydrodynamics determine whether oxidant generation translates into bulk removal or is lost to parasitic oxygen evolution [6].

Technology development for electrooxidation therefore treats the reactor as a coupled kinetics and mass transfer system. The rate of oxidation depends on oxidant flux at the anode surface and on transport of organics into the reactive boundary layer. As readily oxidizable fractions are depleted, marginal removal per additional charge often declines, so rational process design targets electrooxidation to the residual fraction after electrocoagulation and electroflotation have removed solids, emulsions, and adsorbable organics. This sequencing is the essence of a complex treatment technology: bulk conversion and separation first, polishing destruction second. The approach is supported by application studies of boron-doped diamond electrooxidation for dye-containing wastewaters that report strong dependence of removal outcomes on current density and operating conditions, consistent with radical generation and mass transfer control [7].

The combined electrocoagulation electroflotation electrooxidation strategy can be developed as a controllable train by defining mechanistic performance indicators at each stage. The electrocoagulation stage should be controlled by charge dose, pH trajectory, and separability of flocs, with the goal of maximizing removal per coulomb while maintaining stable solid-liquid separation. The electroflotation stage should be controlled by gas generation rate, bubble size behavior, and surface solids recovery, with the goal of minimizing hydraulic residence time required for clarification. The electrooxidation stage should be controlled by energy intensity, current efficiency, and residual dissolved organic indicators such as chemical oxygen demand and color for chromophoric wastewaters, with the goal of achieving reuse-relevant effluent quality without excessive charge consumption.

In sum, electrocoagulation supplies programmable in situ coagulant generation and phase conversion, electroflotation supplies intensified separation through engineered microbubbles, and electrooxidation supplies advanced oxidation for dissolved refractory organics, especially when non-active anodes such as boron-doped diamond are used. The combined technology is scientifically defensible because it matches mechanisms to pollutant forms and it is industrially attractive because control is electrical, modular, and responsive to influent variability. The most rigorous development pathway is to ground design in Faradaic dosing, energy-intensity benchmarking, bubble-mediated separation physics, and anode-material-dependent oxidation theory, while validating performance on real wastewater matrices under realistic loading fluctuations.

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