

**PILOT TESTING OF ELECTROCHEMICAL WASTEWATER TREATMENT
UNDER INDUSTRIAL CONDITIONS: SLUDGE MANAGEMENT AND
ENVIRONMENTAL-ECONOMIC EFFICIENCY ASSESSMENT****Zoirov Sirojiddin Sahomiddin o'g'li**

Termiz davlat muhandislik va agrotexnologiyalar universiteti magistranti

sirojiddinzoirov5@gmail.com

Abstract. Electrochemical treatment has moved from laboratory demonstrations toward pilot and industrial deployments because it offers modular control, rapid response to influent variability, and the ability to couple separation and destruction mechanisms in compact systems. This article presents an engineering and evaluation framework for piloting electrochemical treatment under industrial conditions, with particular focus on sludge generation and management, energy and electrode consumption, and environmental-economic performance. The approach integrates electrocoagulation and electroflotation for bulk removal of colloids, emulsions, and metals, followed by electrooxidation for polishing of residual dissolved and refractory organics. Core performance indicators include removal per unit charge, specific energy consumption, electrode consumption, sludge yield and dewaterability, and simplified life cycle and techno-economic metrics suitable for decision-making. Evidence from recent literature demonstrates that costs and energy intensity vary widely with wastewater composition and reactor design, with reported treatment costs around 2.06 USD per cubic meter for an electrocoagulation case in soluble coffee industry wastewater and broad energy ranges across industrial matrices, highlighting the need for structured pilots that quantify operational envelopes and uncertainty. The article concludes with a pilot protocol and decision criteria for scale-up that prioritize energy efficiency, stable compliance, and responsible sludge handling.

Keywords. industrial pilot testing, electrocoagulation, electroflotation, electrooxidation, sludge management, specific energy consumption, electrode consumption, techno-economic assessment, life cycle assessment, scale-up

INTRODUCTION

Industrial wastewater management is increasingly constrained by stricter discharge requirements, water reuse targets, fluctuating production cycles, and the rising cost of energy and chemicals. Electrochemical treatment is attractive in this context because it can generate reactive species in situ and can be controlled by electrical inputs rather than bulk chemical dosing. The most practical industrial concept

is not a single electrochemical step but an integrated train in which electrocoagulation and electroflotation remove the bulk fraction of suspended solids, emulsified oils, color bodies, and metals, while electrooxidation polishes the remaining dissolved and refractory organics. This staged logic is consistent with modern evidence that electrocoagulation is effective for mixed industrial matrices but is highly sensitive to operating conditions, and that electrooxidation can address persistent organics but requires careful control of energy intensity and reactor design.

The global relevance of improved wastewater treatment is underscored by country-level assessments estimating global wastewater production at 359.4 billion cubic meters per year, with about 63 percent collected and 52 percent treated, meaning a large fraction is still released untreated into the environment [turn0search3]. For industrial settings, the need is not only higher removal efficiency but also predictable and economically defensible operation under real conditions, including fluctuating conductivity, variable pollutant loading, and intermittent shocks. Therefore, industrial pilots must move beyond reporting removal percentages and demonstrate stable performance, energy demand, sludge behavior, maintainability, and overall environmental-economic balance.

METHODS

Pilot objectives and scope were defined around three evaluation pillars: process performance under variability, sludge generation and management feasibility, and environmental-economic efficiency suitable for scale-up decisions. The proposed pilot design is structured as an integrated electrochemical train with three functional blocks: electrocoagulation for in situ coagulant generation and destabilization, electroflotation for rapid phase separation, and electrooxidation for polishing. A pilot may operate as a single modular skid with separated chambers or as a two-stage setup where electrocoagulation and electroflotation are coupled in a primary reactor followed by a polishing electrooxidation cell.

Key operating variables include current density, hydraulic residence time, electrode material and connection mode, inter-electrode spacing, mixing or cross-flow velocity, and conductivity management. Influent characterization includes COD, BOD when relevant, color, turbidity, oil and grease, total suspended solids, key metals, pH, conductivity, and alkalinity. For electrooxidation, additional monitoring includes chloride and bromide when present, because halide chemistry can influence oxidation pathways and by-product risks.

The primary quantitative indicators were selected to separate true process gains from mere increases in electrical input. Specific electrical energy consumption was calculated using:

$$E = U I t / V$$

where E is kilowatt-hours per cubic meter, U is volts, I is amperes, t is hours, and V is cubic meters treated. For electrocoagulation, theoretical anode dissolution was tracked by Faraday's law:

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

where m is the dissolved anode mass, M is molar mass, z is electron number, and F is Faraday constant. Sludge yield was quantified as kilograms of dry solids per cubic meter treated, with parallel reporting of sludge volume index or settleability, dewaterability indicators such as capillary suction time when available, and metal content when the wastewater includes heavy metals. A pilot decision requires this sludge accounting because electrocoagulation transfers pollutants into a solid phase, and disposal or reuse routes often dominate operating cost and environmental footprint.

Environmental-economic efficiency was assessed using a combined techno-economic assessment and simplified life cycle assessment logic. The techno-economic component includes electricity cost, electrode consumption, chemical additions if any, labor and maintenance, and sludge handling cost. Literature demonstrates that electrocoagulation treatment costs can be reported at the level of USD per cubic meter, with one recent study reporting an average cost of 2.06 USD per cubic meter including energy, electrode wear, and sludge disposal for soluble coffee industry wastewater using iron electrodes [turn0search0]. The life cycle component prioritizes hotspots such as electricity generation mix, electrode manufacturing burdens, and sludge disposal impacts, consistent with recent work applying life cycle assessment to electrochemical oxidation and electrochemical treatment sustainability [turn0search5, turn0search21, turn0search1].

RESULTS

Pilot performance should be reported as stable operating envelopes rather than single-point maxima. In the integrated train, electrocoagulation typically provides rapid reductions in turbidity, suspended solids, and a significant fraction of COD when the COD is associated with colloids, emulsions, or adsorbable organics. Electroflotation accelerates the physical separation of these destabilized aggregates, reducing the need for large clarifiers and improving resilience against fluctuating flow. Electrooxidation improves final effluent stability by oxidizing remaining dissolved and

refractory organics, particularly in streams where color bodies and complex aromatic compounds persist after separation.



1- photo. Pilot testing of electrochemical wastewater treatment under industrial conditions: sludge management and environmental-economic efficiency assessment

Energy consumption is a central outcome. Because E scales with voltage, current, and time, pilots must demonstrate how removal changes with charge dose and how voltage evolves with scaling, gas holdup, and electrode aging. Literature consistently shows wide ranges in reported energy and cost across matrices, implying that a pilot must be designed to map the realistic window for the specific industrial effluent rather than relying on generalized benchmarks. The soluble coffee industry case reporting 2.06 USD per cubic meter provides a reference magnitude for an industrially relevant cost that includes sludge disposal, and it highlights that sludge costs cannot be ignored [turn0search0]. For electrooxidation, scale-up work combining modeling and life cycle assessment demonstrates that design and operating conditions strongly influence environmental profile and therefore must be optimized at pilot scale before full deployment [turn0search1]. A separate prospective life cycle assessment for electrochemical oxidation emphasizes that indirect burdens from energy and electrode preparation can be significant, reinforcing that energy intensity and electrode lifetime are key determinants of sustainability at industrial scale [turn0search5].

Sludge generation is intrinsic to electrocoagulation and must be treated as a design output. Sludge yield is influenced by anode material, current density, pH trajectory, ionic strength, and pollutant composition. High anode dissolution increases removal but can produce excessive sludge and increase disposal cost. Therefore, optimal operation is defined by removal per unit charge and by sludge quality, not by maximum removal percentage. Sludge quality is evaluated through settleability, dewaterability, and contaminant content, particularly metals. In many industrial contexts, the feasibility of sludge handling is a go or no-go criterion for electrocoagulation scale-up. The pilot should therefore quantify not only mass but also the operational behavior of sludge in thickening and dewatering, and it should document whether sludge can be stabilized or whether it qualifies as hazardous waste.

DISCUSSION

Industrial pilot testing has a different purpose than laboratory optimization. A laboratory study can hold conditions constant and report best-case removals, while an industrial pilot must prove controllability, maintainability, and predictable cost under disturbances. The most common pilot failure modes are not low instantaneous removal but instability: electrode passivation, voltage drift, scaling, short-circuiting due to solids accumulation, inconsistent flotation separation, and unexpected sludge behavior. A robust pilot design therefore emphasizes three control principles.

First, operate with charge-based control rather than time-based control. Because both coagulant generation and oxidant flux are charge-driven, dosing should be

expressed as ampere-hours per cubic meter, enabling consistent performance under flow changes and enabling direct linking of removal to energy consumption and electrode consumption.

Second, treat reactor hydraulics and solids separation as part of the electrochemical design. Electroflotation is most valuable when it stabilizes separation quickly and prevents recirculation of solids that cause passivation. Bubble generation and hydrodynamics must be tuned so that flocs are removed rather than re-dispersed. This improves both treatment performance and electrode lifetime.

Third, define a sludge strategy before scale-up. Electrocoagulation moves pollutants into sludge, so the pilot must establish a realistic route such as dewatering and disposal, co-processing, or resource recovery where feasible. Costs reported in industrial cases explicitly include sludge disposal, demonstrating that sludge economics materially affect overall feasibility [turn0search0]. When heavy metals are present, regulatory classification of sludge determines disposal route and cost and must be part of the pilot's compliance design.

Environmental-economic efficiency should be presented as a transparent balance rather than a single number. Techno-economic assessment provides the operational cost structure, while life cycle assessment highlights hidden burdens associated with electricity and electrode production. Recent literature applying life cycle assessment and scale-up modeling to electrochemical advanced oxidation demonstrates that operating conditions and reactor design significantly shift environmental impact profiles, meaning that the cleanest solution is not necessarily the one with the highest removal but the one with the lowest impact per unit of compliance or per unit of reusable water produced. In practice, this supports an integrated train where electrocoagulation and electroflotation remove the bulk load efficiently and electrooxidation is reserved for polishing, minimizing the charge required for deep oxidation.

A rigorous industrial pilot should also define performance in relation to discharge or reuse endpoints. If the goal is reuse, conductivity management, residual oxidants, and by-product control become important; if the goal is discharge, robust compliance with COD, metals, and turbidity limits becomes primary. The pilot should run long enough to capture electrode aging and scaling behavior and should include planned stress tests such as higher pollutant loading, lower conductivity, and pH shifts.

CONCLUSION

An electrochemical treatment technology can be considered ready for industrial scale-up only when pilot testing demonstrates stable compliance, predictable energy

intensity, manageable electrode consumption, and a feasible sludge management route under realistic variability. The integrated electrocoagulation-electroflotation-electrooxidation concept is technically justified because it matches mechanisms to pollutant forms: capture and separation for colloids, emulsions, and metals, followed by oxidative polishing for residual dissolved and refractory organics. Industrial pilot protocols should report removal per unit charge, specific energy consumption, electrode consumption, sludge yield and dewaterability, and environmental-economic indicators aligned with life cycle and techno-economic assessment logic. Recent literature illustrates that costs such as 2.06 USD per cubic meter can be achieved in specific industrial electrocoagulation cases when energy, electrode wear, and sludge disposal are accounted for, and that life cycle assessment outcomes depend strongly on reactor design and operating conditions in electrochemical oxidation systems, reinforcing the necessity of structured pilots before scale-up [turn0search0, turn0search1, turn0search5]. With disciplined pilot design and transparent accounting, electrochemical treatment can deliver compact and modular industrial solutions that support both regulatory compliance and water reuse.

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