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Catalytic and Advanced Oxidation Technologies for Emerging Contaminant Removal: Challenges, Progress and the Road Ahead

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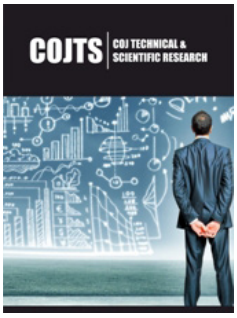

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Abstract

Water contamination by emerging pollutants-pharmaceuticals, microplastics, nitrates and endocrine disruptors-represents one of the most pressing environmental challenges of our era. Conventional water treatment systems were not designed to handle these complex compounds, which persist in aquatic ecosystems even at trace concentrations with documented biological effects. This opinion article argues that catalytic and Advanced Oxidation Processes (AOPs), particularly those employing non-noble bimetallic catalysts, photo electrocatalysis and engineered nanomaterials, are no longer experimental curiosities but technologically mature approaches ready for broader deployment. Drawing on over two decades of research, we discuss the strategic value of catalyst design, selectivity control and process intensification, and call for stronger bridges between fundamental research and environmental policy.

Keywords: Advanced oxidation processes; Bimetallic catalysts; Emerging contaminants; Microplastics; Water treatment; Green hydrogen; Photo electrocatalysis

The Invisible Threat in our Water

Every day, millions of people consume water containing compounds that should not be there: Residual antibiotics from agricultural runoff, anti-inflammatory drugs excreted and inadequately removed in wastewater plants, nitrates leaching from fertilized soils and microplastic fragments from ubiquitous synthetic materials. The tragic irony is that modern analytical chemistry has made these contaminants visible precisely as regulatory frameworks struggle to keep pace. We can now detect pharmaceutical compounds at nanogram-per-liter concentrations; the question is whether we have the technological and political will to remove them. The term ‘emerging contaminants’ is itself misleading. Many of these substances have been present in water sources for decades; what has emerged is our awareness of them [1]. Nitrates have contaminated groundwater in agricultural regions like the Argentine Litoral for generations, linked to methemoglobinemia in infants and increasingly associated with colorectal cancer risk in adults. Microplastics, now detected in human blood, placenta and lung tissue, entered aquatic systems long before they entered the regulatory agenda [2,3]. The urgency is real and incremental improvements to century-old chlorination-based treatment will not suffice.

Why Catalysis? The Case for Advanced Treatment

Advanced oxidation processes exploit the extraordinary reactivity of hydroxyl radicals (·OH) and other reactive oxygen species to mineralize recalcitrant organic compounds that resist biological degradation. Fenton and photo-Fenton reactions, catalytic ozonization and photo electrocatalysis have demonstrated efficacy against pharmaceuticals, dyes, pesticides and personal care products under laboratory and pilot-scale conditions. The underlying chemistry is well understood; the engineering challenge lies in translating performance from batch reactors and clean model solutions to continuous-flow systems operating on real, complex matrices. Our group's work on Fenton-like oxidation using copper-loaded resins demonstrated that non-noble metal heterogeneous catalysts can achieve phenol degradation efficiencies exceeding 90% under mild conditions, with catalyst stability suitable for repeated use [4]. This matters enormously for scalability: Noble metals such as platinum and palladium are effective but economically prohibitive for large-scale deployment. The synthesis of Cu/Al_2O_3 and Cu-resin systems represents a deliberate design philosophy-robust, low-cost, regenerable catalysts that can be integrated into existing infrastructure [4,5].

For inorganic contaminants like nitrates, the strategy differs but the design philosophy is the same. Bimetallic Pd/In catalysts selectively reduce nitrate to dinitrogen rather than the unwanted byproduct ammonium, addressing a key selectivity challenge that long hindered catalytic denitrification [6]. Using formic acid as a green reductant further aligns the process with circular economy principles, avoiding the use of pressurized hydrogen gas [7]. These are not merely incremental improvements; they represent a conceptual shift toward catalysts designed with environmental impact-not just conversion rate-as the primary objective.

Microplastics: The Frontier No One Wanted to Reach

If pharmaceuticals in water are a policy challenge, microplastics are a civilizational one. They are everywhere-Arctic ice, deep ocean trenches, alpine lakes and municipal tap water. Conventional filtration retains larger particles but fails against microplastics below 1μm and nano-scale fragments remain almost entirely unaddressed by standard treatment trains. Photocatalysis has emerged as the most promising degradation approach because it can, in principle, mineralize plastic fragments rather than merely concentrate or transfer the problem [2,3]. Our recent reviews synthesize the state of knowledge across degradation mechanisms, catalyst materials and operational parameters [2,3]. TiO_2-based photocatalysts under UV irradiation have shown the most consistent activity against polyethylene and polystyrene fragments, but visible-light-active materials doped with nitrogen, carbon, or transition metals are rapidly closing the efficiency gap. The key bottleneck is no longer chemical feasibility but reactor design: How to maximize light penetration and catalyst-particle contact in turbid, real-world water. Solving this engineering problem is the field's most important near-term objective.

Photo Electrocatalysis and the Green Hydrogen Synergy

Perhaps the most intellectually exciting development in our field is the convergence of water remediation and renewable energy generation within a single photoelectrochemical device. Semiconductor electrodes illuminated by solar radiation can simultaneously oxidize organic contaminants at the photoanode and reduce protons to hydrogen at the cathode-producing clean fuel while treating wastewater [8,9]. This dual functionality transforms the economics of water treatment: Rather than a pure cost centre, the process becomes an energy-generating asset. Our work on Pd: In-doped TiO_2 electrodes demonstrated simultaneous paracetamol oxidation and hydrogen evolution under photoelectrochemical conditions [8]. Complementary studies on $NiMo/TiO_2$ catalysts modified with copper showed enhanced bifunctional performance for green hydrogen production and pharmaceutical pollutant removal [9]. These results suggest that the artificial separation between environmental catalysis and energy research is conceptually outdated. The materials challenges are shared; the synthesis strategies are converging. Researchers who continue to work within disciplinary silos risk missing the most productive territory.

From Laboratory to Litoral: Bridging Research and Reality

The Argentine Litoral region presents a particularly instructive case study in the complexity of real-world water quality management. The Paraná River basin sustains agriculture, industry, urban populations and extraordinary biodiversity-and receives inputs from all of them. Nitrates from intensive agriculture, pharmaceuticals from urban wastewater, and emerging industrial effluents create a multi-contaminant matrix that single-target treatment strategies cannot address. Our ongoing research on integrated ecotoxicological and biotechnological assessment of urban wastewater within a circular economy framework directly addresses this complexity [10]. The detection of quinolone antibiotics in water using modified electrochemical sensors-another line of work from our group [11]-illustrates the complementary role of analytical innovation. You cannot manage what you cannot measure. Sensitive, affordable, field-deployable sensors for pharmaceutical contaminants are a precondition for effective monitoring programs, particularly in lower-income regions where laboratory infrastructure is limited. The development of Prussian blue-modified graphite electrodes for antibiotic detection represents exactly the kind of low-cost analytical innovation that environmental monitoring in developing regions requires.

A Call to Action: What Needs to Change

The scientific evidence for catalytic and advanced oxidation technologies is compelling. What lags behind is the ecosystem supporting their deployment: Regulatory standards that include emerging contaminants as monitored and controlled parameters; funding mechanisms that bridge the gap between TRL 4 laboratory proof-of-concept and TRL 7 pilot demonstration; and interdisciplinary training that equips environmental engineers with the materials science literacy to evaluate next-generation catalysts critically.

Equally important is the integration of circular economy thinking into water treatment design from the outset. Catalysts should be designed for regeneration and end-of-life recovery. Processes should be evaluated not just for contaminant removal efficiency but for energy consumption, sludge generation and secondary pollution risk. The development of chitosan/alginate bio composite adsorbents for heavy metal removal exemplifies this philosophy: Bio-based, biodegradable materials that remove copper and other metals while generating minimal secondary waste [12]. We are not short of solutions. We are short of will, coordination and investment in the translation infrastructure that converts scientific knowledge into operating treatment systems. Journals like COJ Technical & Scientific Research play a role in this process by providing accessible platforms for disseminating advances across disciplines and geographies. The next decade will determine whether the remarkable progress made in catalytic water treatment becomes standard practice or remains confined to the literature.

Conclusion

Emerging contaminants in water are a defining environmental challenge of this century. Catalytic remediation-from bimetallic reduction of nitrates to photo electrocatalytic degradation of pharmaceuticals and microplastics-has matured from fundamental curiosity to a portfolio of deployable technologies. The field's frontier now lies at the intersection of sustainability (green reductants, solar energy, bio-based materials), multifunctionality (simultaneous remediation and energy production) and system integration (sensors, reactors, policy frameworks). Researchers, engineers, policymakers and communities must engage with this challenge together. The chemistry is ready. The question is whether we are.

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