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Perspective

Rethinking Photo-Assisted Advanced Oxidation Processes toward Sustainable Water Treatment

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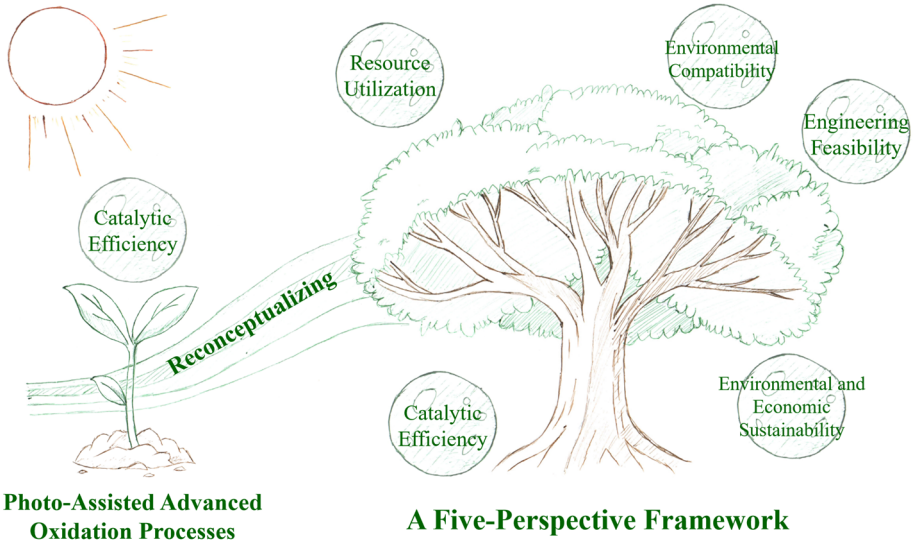
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Abstract: Photo-assisted advanced oxidation processes (AOPs) have emerged as promising strategies for sustainable water treatment, yet their development remains largely driven by catalytic activity, with degradation efficiency and reactive oxygen species generation often serving as the primary performance metrics. Here, we argue that this activity-centered paradigm is insufficient for translating laboratory advances into practical and sustainable water treatment. We propose a shift from activity optimization toward sustainability optimization, in which photo-assisted AOPs are examined from five complementary perspectives: catalytic efficiency, resource utilization, environmental compatibility, engineering feasibility, and environmental and economic sustainability. Particular emphasis is placed on improving the utilization efficiency of sunlight, oxidants, and reactive oxygen species rather than simply maximizing their generation. We further highlight the need to examine realistic water matrices, scalable catalyst design, and to weigh environmental and economic sustainability alongside them. Moving beyond activity, we argue, can provide a more meaningful framework for guiding the next generation of photo-assisted AOPs toward practical, efficient, and sustainable water treatment.

Highlights

- Photo-assisted AOPs: From activity optimization to sustainability optimization.
- A five-perspective framework reframes how photo-assisted AOPs are judged.
- No weighted index: From maximizing one metric to meeting every requirement.



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1. Introduction

The rapid rise of emerging contaminants—pharmaceuticals, personal care products, antibiotics, and persistent industrial chemicals—has created serious challenges for conventional water treatment [1–3]. Many of these compounds resist biological degradation and are discharged continuously into natural waters, raising growing concerns about ecological safety and human health [4,5]. Among the available options, advanced oxidation processes (AOPs) have drawn wide attention for their ability to generate highly reactive oxygen species (ROS), which drive the non-selective oxidation and mineralization of recalcitrant organic pollutants [6–9]. In recent years, coupling light irradiation with AOPs has pushed the field further, using solar energy to promote charge separation, activate oxidants, and steer ROS generation [9,10]. As a result, a range of photo-assisted AOPs—photocatalysis, photo-Fenton chemistry, photo-assisted persulfate activation, photoelectrocatalysis, and photo-ozonation—have taken shape as promising routes to sustainable water purification [11,12].

This fast-growing field has seen real progress in catalyst design, interfacial engineering, and the study of reaction mechanisms. Materials of increasing sophistication—heterojunction semiconductors [13–15], single-atom catalysts [16–18], high-entropy compounds [19,20], plasmonic nanostructures [21]—have been developed to maximize ROS production and speed up pollutant degradation. Catalytic performance is therefore usually judged by metrics such as degradation efficiency, apparent rate constants, mineralization, or ROS yield [22,23]. These indicators do capture catalytic activity, yet over time they have become the dominant, and often the only, basis on which new photo-assisted AOPs are judged. Still, an activity-driven paradigm calls for a harder look. High degradation efficiency measured under ideal laboratory conditions does not automatically carry over to practical, sustainable treatment [24]. Excessive oxidant use, high energy demand, complicated catalyst synthesis, weak long-term stability, and poor performance in real water matrices remain stubborn barriers to scale-up [6,25]. More to the point, many studies keep pushing catalytic activity without asking whether the extra gain is worth the added environmental, economic, and operational cost. That gap suggests the field may be optimizing the wrong target.

Here we argue that the field should move from chasing maximum catalytic activity to sustainability optimization. Instead of asking how to generate more reactive oxygen species, future work should ask how to use sunlight, oxidants, and catalytic materials more efficiently to remove pollutants sustainably. We believe that redefining how photo-assisted AOPs are evaluated—shifting from activity-centered metrics toward a broader sustainability-oriented assessment—offers a more useful framework for catalyst design, technology development, and, ultimately, engineering deployment.

2. The Activity-Oriented Paradigm: An Incomplete Definition of Progress

Over the past decade, research on photo-assisted advanced oxidation processes (photo-assisted AOPs) has grown rapidly [11]. Advances in photocatalysis, semiconductor engineering, and oxidation chemistry have driven the development of countless catalytic systems, almost all aimed at accelerating ROS generation and improving pollutant degradation. This activity-centered mindset has sunk deep into the field, shaping not only how catalysts are designed but also what counts as progress. In most papers, a new catalyst is judged better if it shows higher degradation efficiency, a higher apparent rate constant, faster ROS generation, or improved mineralization than earlier reports.

Scientifically, this focus on activity makes sense. Higher rates usually mean better charge separation, more efficient oxidant activation, and faster interfacial kinetics [26]. Not surprisingly, a great deal of effort has gone into ever more elaborate catalytic materials—defect-engineered semiconductors, heterojunction architectures, plasmonic nanostructures, single-atom catalysts, high-entropy compounds. These efforts have deepened our mechanistic understanding of photo-assisted processes and, without question, raised the performance ceiling of lab-scale systems. Yet one important question has been largely ignored: does higher catalytic activity really make for a better water-treatment technology? Increasingly, the answer is no. For one thing, activity has become the dominant—often the only—criterion used to judge a catalyst. Studies typically line up degradation efficiency, pseudo-first-order rate constants, total organic carbon (TOC) removal, and ROS yield [22]. Useful as these metrics are for describing reactivity, they say little about whether a technology is practical, affordable, or environmentally sound. Consequently, small gains in degradation kinetics are often hailed as major advances, even when they come at the cost of far greater energy, oxidant, synthetic complexity, or material use.

Consider, for instance, the common practice of boosting degradation by raising persulfate dose, hydrogen peroxide concentration, catalyst loading, or light intensity [27,28]. These tactics do raise ROS production, but they rarely take into account that every extra unit of oxidant or energy adds to operating cost and environmental load [29]. The field has become adept at maximizing radical generation, while paying less attention to how efficiently those radicals actually degrade pollutants. Pursuing higher activity without accounting for resource efficiency may deliver technologies that perform well in the lab but struggle at scale. A second problem is the gap between laboratory

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tests and real use. Most photo-assisted AOP studies work with ultrapure water, a single model pollutant, and tightly controlled conditions. Such setups are essential for mechanistic study but rarely reflect the complexity of real wastewater. In actual water matrices, dissolved organic matter, inorganic ions, natural colloids, and competing contaminants all affect light penetration, surface chemistry, oxidant activation, and ROS lifetime [30–32]. Catalysts that perform exceptionally well under ideal conditions can therefore lose much of that performance in practice. Despite being a well-known issue, systematic testing under environmentally relevant conditions is still the exception rather than the rule.

At its core, the current paradigm rests on an unstated assumption: more activity means a better technology. That was reasonable early on, when raising catalytic efficiency was the main scientific hurdle. Today, however, many systems already achieve near-complete degradation of model pollutants under optimized lab conditions. Against that backdrop, squeezing out another 5–10% in degradation efficiency brings diminishing returns—especially if it demands more complex synthesis, more chemicals, or more energy. More importantly, an environmental technology should be judged not just by catalytic performance but by its overall contribution to sustainable water treatment [33–35]. The aim of photo-assisted AOPs is to remove contaminants while using as little energy, chemicals, and material as possible, and while keeping long-term stability and environmental compatibility. These broader perspectives are still largely missing from how the field evaluates itself. The question for the next generation of photo-assisted AOPs is therefore no longer how to make catalysts more active, but how to make photo-assisted oxidation more sustainable. Answering it demands a shift in how we define success—away from maximizing catalytic activity and toward resource utilization, environmental compatibility, engineering feasibility, and environmental and economic sustainability.

3. From Activity Optimization to Sustainability Optimization: A New Framework for Photo-Assisted AOPs

If the goal of photo-assisted AOPs is to deliver practical, sustainable water treatment, then the yardsticks we use to measure progress must change with it. Rather than chasing incremental gains in degradation kinetics, future work should focus on using energy, oxidants, and catalytic materials efficiently across the whole treatment process. Put differently, the field needs to move from activity optimization to sustainability optimization, in which catalytic performance is examined together with resource utilization, environmental compatibility, engineering feasibility, and environmental and economic sustainability (Figure 1). This shift does not mean catalytic activity no longer matters. On the contrary, high activity remains the bedrock of efficient oxidation. But it should no longer be treated as the end goal. One perspective cannot capture everything that matters, sustainability is better served by viewing a technology from several angles at once, of which catalytic efficiency is one. We therefore propose examining future photo-assisted AOPs through an integrated, sustainability-oriented framework built on five complementary perspectives: catalytic efficiency, resource utilization, environmental compatibility, engineering feasibility, and environmental and economic sustainability. These perspectives were assembled by considering, beyond degradation activity, which further aspects of a photo-assisted AOP bear on its sustainability. Taken together, they define technological success more completely than activity alone.

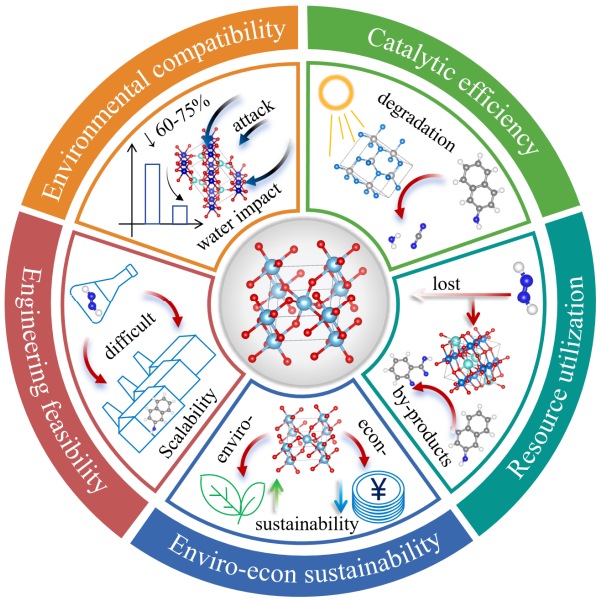


Figure 1. A five-perspective, sustainability-oriented evaluation framework for photo-assisted AOPs. Catalytic efficiency remains necessary but is no longer sufficient. Resource utilization, environmental compatibility, engineering feasibility, and environmental and economic sustainability are examined together.

3.1. Catalytic Efficiency: Foundational, but not the Destination

Catalytic activity will remain an essential indicator, since it reflects a material's intrinsic ability to activate oxidants and convert pollutants. Metrics such as degradation kinetics, mineralization, charge-separation efficiency, and ROS generation are still valuable for understanding mechanisms and guiding design [36,37]. What sets one material apart from another is the charge separation it achieves, the electronic structure of its active sites, and the match between its light absorption and the oxidant it activates. Going forward, however, catalyst development should consider not only catalytic activity

but also resource utilization, environmental compatibility, engineering feasibility, and environmental and economic sustainability, instead of pursuing the highest possible activity at any cost. That reframing pushes researchers to view catalytic efficiency more prudently and holistically.

3.2. Resource Utilization: Efficiency as a Central Criterion

Resource utilization asks what becomes of the resources that a photo-assisted AOP consumes—light, oxidants, catalysts, and the energy that drives them. Current research rarely poses this question: degradation is usually improved by raising oxidant dose, catalyst loading, or light intensity, and how efficiently those inputs are used is seldom measured. Many report catalytic efficiency alone while overlooking the more than one-order-of-magnitude differences in oxidant dosage that underlie it [38,39]. Two facets of resource utilization can be distinguished. The first is how much of the input is actually utilized, and how much is lost: solar energy that is not absorbed, an oxidant that remains unconsumed, or a catalyst that loses activity are all losses of input, and they differ greatly between systems that report comparable degradation. What governs the first facet is how long the reactive species survive and how readily they reach the pollutants, so the response is to bring the oxidant, the light and the pollutant into contact—a question of how the catalytic material is arranged and distributed. The second facet is how much of the utilized input is converted into the intended outcome rather than into by-products: oxidant consumed in side reactions, or radicals lost to scavenging and recombination, do not contribute to pollutant removal. Here the governing factor is by-product formation, and the response has two sides—controlling the reaction conditions, since many side reactions arise from unstable conditions, and designing catalytic pathways that sharpen selectivity. The two facets together cover the fate of the entire input. Five quantities are commonly used along these lines—solar-energy utilization, energy consumption, oxidant utilization, catalyst productivity and lifetime, and the volume of water treated per unit of energy input—and ROS utilization efficiency is a case in point, being the share of generated ROS that goes directly into pollutant degradation rather than being lost to scavenging or radical recombination. Which of these factors dominates depends on the operating mode: where light must first penetrate the water, poor light transmission limits utilization, whereas in radical-dominated systems the loss arises instead from scavenging and non-selective reaction. This shift would reshape catalyst design: from making more radicals to using them better. In addition, emerging technologies such as solar-driven natural water treatment systems and bio-photocatalytic coupled systems improve the intended outcome without additional engineered inputs, and thus greatly increase resource utilization efficiency. This suggests that, beyond improving the utilization efficiency of engineered inputs, improving the utilization efficiency of natural resources is also a highly promising direction.

3.3. Environmental Compatibility: Real-Water Robustness over Idealized Lab Tests

Environmental compatibility asks how a process behaves under the conditions of real waters rather than of laboratory model solutions. Photo-assisted AOPs are meant for complex environmental waters, not ultrapure lab solutions. Real waters carry natural organic matter, inorganic ions, suspended solids, and mixed contaminants, and their conditions vary as well: temperature, rainfall, and runoff that carries pollutants differ from one site and season to another. Testing catalytic performance in realistic matrices therefore addresses both the composition of the water and the conditions under which it is treated. Typically, catalytic efficiency in real waters declines by about 60–75%, and in certain matrices by more than 90% [30,40–42]. The impact of real water matrices is therefore not negligible, and environmental compatibility requires urgent attention. Catalysts that hold up under those conditions will matter far more in practice than ones that excel only in simplified lab systems. Environmental robustness, in short, belongs in the core set of criteria by which catalysts are judged. At the macroscopic level, robustness asks whether a catalyst can maintain its catalytic efficiency over long-term operation. At the microscopic level, whether its structure remains stable and its active sites resist poisoning. The specific difficulty differs with the type of process: in photocatalysis, for instance, the water itself may transmit little light, while in radical-dominated systems such as photo-Fenton, treating a trace contaminant raises the question of selectivity, because radicals react with little discrimination.

3.4. Engineering Feasibility: Scalability as a Design Guide

As catalyst structures grow more elaborate, their synthesis often involves many steps, costly precursors, or low-yield routes. These choices may lift activity but can also hurt scalability and cost-effectiveness [43–45]. Engineering feasibility asks whether a process can be scaled up and deployed under real operating conditions, which places synthesis and operation—not only catalytic performance—within view. Structural sophistication must therefore be weighed against manufacturability. Compatibility with continuous-flow reactors, in particular, requires that the form of the catalyst and the configuration of the reactor be designed for each other. Simpler synthesis, scalable production, and long-term operational stability deserve more attention [46]. In the end, the best catalyst is not necessarily the one with the

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highest lab activity, but the one that can actually be deployed for sustainable water treatment.

3.5. Environmental and Economic Sustainability: Life-Cycle Techno-Economic-Environmental Assessment

Environmental and economic sustainability asks what a process means for the environment and for the economy: it refers specifically to environmental impact and economic viability. Environmental impact can be assessed, for example, by life-cycle assessment (LCA), which quantifies impacts across a technology's full life cycle, and by carbon-footprint evaluation. Economic performance can be assessed, for example, by techno-economic analysis (TEA). However, over the past decade, only about 1.0% of studies in this field have focused on LCA/TEA and related environmental and economic indicators [47–49]. On a positive note, this share has been growing rapidly year by year. Such assessment is best built into catalyst development from the start, so that it accompanies material design rather than following it. For laboratory-scale studies, environmental impact and economic performance can also be approached quantitatively through simpler quantities—for example, metal leaching and ecotoxicity, or the additional carbon emissions associated with reagent use—while economic performance can be considered for both synthesis and reaction by converting high-temperature and mechanical inputs into an equivalent electricity demand. In addition, the economic cost at the material development stage should also be taken into account. For example, emerging methods such as machine learning can rapidly screen materials and thereby substantially reduce development costs, which is an important reflection of considering economic viability. These analyses require researchers to consider not only catalytic performance gains but also whether additional environmental and economic costs arise from more sophisticated materials. Just as important, embedding sustainability metrics in development encourages innovation that serves both scientific ambition and societal need.

Taken together, these points suggest that the future competitiveness of photo-assisted AOPs will hinge not on the highest degradation efficiency under ideal conditions, but on how efficiently sunlight, oxidants, catalytic materials, and money are turned into environmental benefit. The next generation of photo-assisted oxidation technologies should be designed and judged through a sustainability-oriented framework that joins catalytic activity with resource utilization, environmental compatibility, engineering feasibility, and environmental and economic sustainability. Only such a shift can carry photo-assisted AOPs from efficient lab curiosities to genuinely sustainable water-treatment technologies.

4. Perspective

As photo-assisted advanced oxidation matures, the field is reaching a turning point. For nearly two decades, steady gains in catalyst design, oxidant activation, and ROS generation have deepened our fundamental grasp of photo-assisted oxidation chemistry and established photo-assisted AOPs as a leading strategy against emerging contaminants. Yet maturity also means reconsidering the questions we ask and the metrics we use to define success. For the next generation of photo-assisted AOPs, the central challenge is no longer how to make more ROS or faster kinetics, but how to extract the most environmental benefit from each unit of sunlight, oxidant, catalyst, and money spent. As these technologies move from demonstration to deployment, sustainability has to become a design goal, not an afterthought. This transition calls for a matching shift in research philosophy. Instead of rating catalysts mainly by degradation efficiency or rate, future work should weave resource utilization, engineering feasibility, environmental compatibility, and environmental and economic sustainability into both development and assessment. A view across these several perspectives aligns innovation more closely with the practical demands of sustainable water treatment and speeds the move from lab discovery to scalable technology. More broadly, this shift reaches beyond photo-assisted AOPs. Many emerging environmental technologies—photocatalysis, photoelectrocatalysis, electrochemical oxidation, and other advanced oxidation processes—are still judged mainly by activity-based metrics. The framework proposed here therefore reflects a wider evolution in environmental catalysis: from maximizing reaction performance to sustainability optimization.

In the end, the competitiveness of photo-assisted AOPs will not be decided by which catalyst makes the most radicals or the fastest degradation under ideal lab conditions. It will be decided by which technology delivers the least environmental impact and the lowest cost with the least energy, chemical, and material use under real operating conditions. Moving beyond activity does not make catalytic performance less important; it changes what counts as progress in photo-assisted advanced oxidation. Activity will always be the foundation of catalyst development, but it should not be the final destination. As environmental problems grow more complex and sustainability becomes a defining priority, future innovations must be judged not only by how fast pollutants vanish, but by how efficiently energy, chemicals, and materials are turned into lasting benefit. The next real breakthrough in photo-assisted AOPs may come less from generating more reactive oxygen species than from building a sustainability-oriented paradigm that connects fundamental catalysis with practical water treatment. The future of photo-assisted advanced oxidation, in other words, will belong to the technologies

that meet these broader requirements while remaining highly active.

Author Contributions

Z.W.: Conceptualization, writing—reviewing and editing; B.W.: Conceptualization, supervision, writing—reviewing and editing; A.R.P.-S.: Conceptualization, supervision, writing—reviewing and editing. All authors have read and agreed to the published version of the manuscript.

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No primary research results, software or code have been included, and no new data were generated or analyzed as part of this comment.

Conflicts of Interest

The authors declare no conflict of interest.

Use of AI and AI-Assisted Technologies

During the preparation of this work, the authors used ChatGPT to polish the English language. After using this tool, the authors reviewed and edited the content as needed and assume full responsibility for the content of the published article.

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