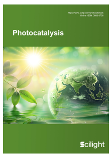
Photocatalysis
https://www.sciltp.com/journals/photocatalysis



Opinion

Defining Key Performing Indicators for Economically Feasible H_2O_2 Production by Means of Photocatalysis

Oleksandr Savateev [1,]*, Chong Wang [1], Zirui You [2] and Zhongxin Chen [2]

[1] Department of Chemistry, The Chinese University of Hong Kong, Hong Kong SAR, China
[2] Guangdong Basic Research Center of Excellence for Aggregate Science, School of Science and Engineering, The Chinese University of Hong Kong (Shenzhen), Shenzhen 518172, China
* Correspondence: oleksandrsavatieiev@cuhk.edu.hk

How To Cite: Savateev, O.; Wang, C.; You, X.; et al. Defining Key Performing Indicators for Economically Feasible H_2O_2 Production by Means of Photocatalysis. *Photocatalysis* **2026**, *2*(2), 4. https://doi.org/10.53941/photocatalysis.2026.100004

Received: 3 March 2026
Revised: 21 April 2026
Accepted: 29 April 2026
Published: 7 May 2026

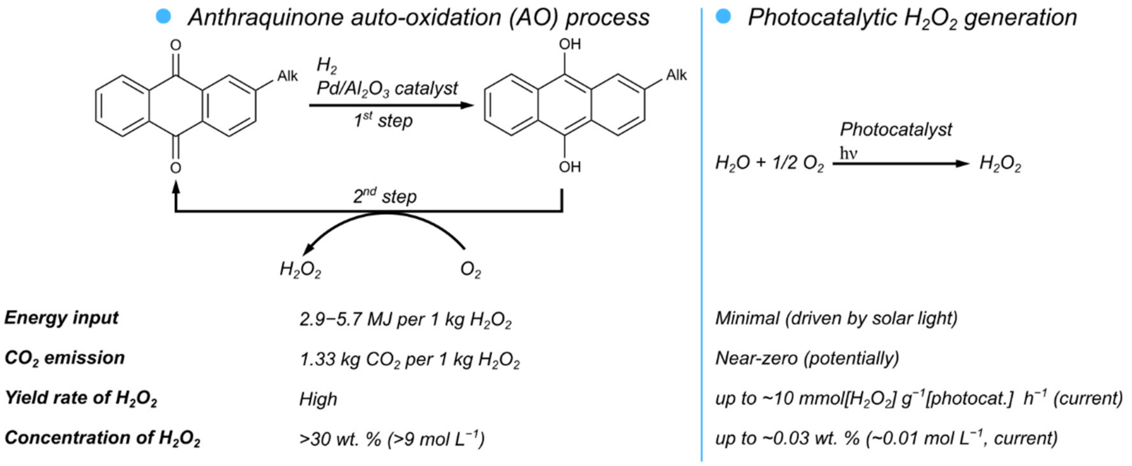
Abstract: Hydrogen peroxide (H_2O_2) is an important chemical commodity. Currently, the anthraquinone auto-oxidation (AO) process is the dominant method for producing hydrogen peroxide worldwide. However, alternative generation methods are being extensively investigated, most notably photocatalytic H_2O_2 synthesis. State-of-the-art heterogeneous photocatalysts can now produce H_2O_2 from water and O_2 with apparent quantum yields (AQYs) of approximately 20% at 420 nm and solar-to-chemical conversion (SCC) efficiencies of several percent. Unlike electrochemical and other emerging methods, photocatalysis can, in principle, deliver H_2O_2 of high purity, i.e., H_2O_2 aqueous solution that is free of electrolytes and other foreign species. However, in the efforts of optimizing the structure of photocatalysts and achieving higher AQY, SCC and the yield rate of H_2O_2 (mol[H_2O_2] g^{-1}[photocatalyst] h^{-1}), the community appears to drift away from another key performing indicator (KPI), which is exceptionally important to make photocatalysis competitive not only to other emerging methods, but also the AO process. This KPI is concentration of H_2O_2 achieved in photocatalysis. This quantity is still in the range of few millimoles per litter (mM). In this opinion article, we articulate importance of this KPI and the viable, in our opinion, strategies of increasing this value by means of heterogeneous photocatalysis.

Keywords: hydrogen peroxide; photocatalysis; solar-to-chemical conversion efficiency; quantum yield; concentration; heterogeneous catalysis

Introduction

Hydrogen peroxide (H_2O_2) is an important chemical commodity, used primarily as a bleaching agent and oxidant. These applications impose specific requirements on its concentration: it must be at least 3 wt.% in aqueous solution. H_2O_2 aqueous solution of such concentration is typically sold in pharmacies and used as a disinfectant. Anthraquinone auto-oxidation (AO) process is the major method of hydrogen peroxide production, which involves two chemical reactions [1]. In the first step, 2-alkylanthraquinone is hydrogenated over Pd/Al_2O_3 catalyst to form 2-alkylanthrahydroquinone (Figure 1). In the second step, 2-alkylanthrahydroquinone reacts spontaneously with O_2, yielding H_2O_2 and recovering 2-alkylanthrahydroquinone. Typically, hydrogen (H_2) for the first step is generated from steam methane reforming, which is an energy intensive process. As a result, production of 1 kg of H_2O_2 requires an input of 2.9–5.7 MJ of energy [2]. Also, it was calculated that production of 1 kg of H_2O_2 emits 1.33 kg of CO_2 (the CO_2 footprint) [3].

Driven by the necessity to develop more sustainable methods for synthesis of this important chemical, direct synthesis of H_2O_2 (DSHP), electrochemical, bioelectrochemical, plasmatic and photocatalytic methods, are being investigated actively. These alternative technologies for H_2O_2 production and their techno-economic feasibility were summarized and discussed by Theofanidis and colleagues [2]. Briefly, direct synthesis of H_2O_2 (DSHP) considers reacting H_2 with O_2 over the noble metal catalyst according to the reaction equation $H_2 + O_2 \rightleftharpoons H_2O_2$. If H_2 for this reaction is generated from the renewable source and using renewable energy, the DSHP could become a more sustainable alternative to the AO process. However, this appealing idea is complicated by a number of other thermodynamically and kinetically favorable reactions, such as $H_2 + 1/2O_2 \rightleftharpoons H_2O$, $H_2O_2 + H_2 \rightleftharpoons 2H_2O$, which, naturally, decrease the selectivity of H_2O_2. In the electrochemical H_2O_2 synthesis, the desired two-electron water oxidation reaction (more thermodynamically challenging) competes with the undesirable four-electron water oxidation reaction (more thermodynamically favorable). A common feature of DSHP, electrochemical and bioelectrochemical methods is that to achieve viable concentration of H_2O_2, for example, 5 wt.% [2], organic solvents, such as decane-1-ol [4], methanol [5], or certain organic additives are required [6]. As a result, an additional step would be necessary to separate H_2O_2 from organic solvent (similar to the AO process) to deliver H_2O_2 to the end users.



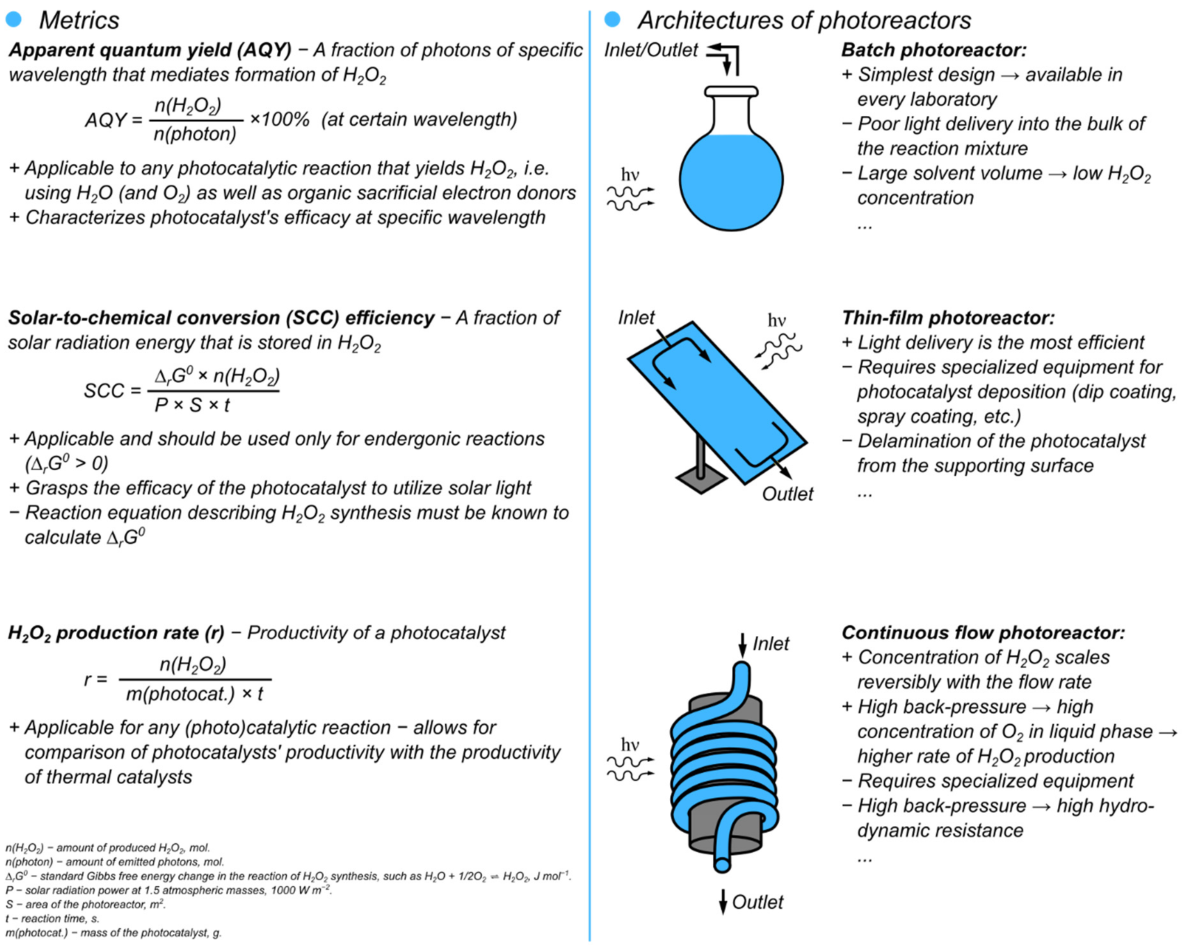
	Anthraquinone auto-oxidation (AO) process	Photocatalytic H_2O_2 generation
Energy input	2.9−5.7 MJ per 1 kg H_2O_2	Minimal (driven by solar light)
CO_2 emission	1.33 kg CO_2 per 1 kg H_2O_2	Near-zero (potentially)
Yield rate of H_2O_2	High	up to ~10 mmol[H_2O_2] g^{-1}[photocat.] h^{-1} (current)
Concentration of H_2O_2	>30 wt. % (>9 mol L^{-1})	up to ~0.03 wt. % (~0.01 mol L^{-1}, current)

Figure 1. Comparison of the AO process and the photocatalytic H_2O_2 generation in terms of energy input, CO_2 footprint, yield rate and concentration of H_2O_2.

Compared to the discussed above DSHP, electrochemical and bioelectrochemical methods, the state-of-the-art photocatalytic systems are free of noble metals [7,8]. While the discussed above methods could utilize solar energy through a series of convertors, a solar panel (and a battery), photocatalysis is driven by the solar light directly. This feature minimizes potential loses of energy upon conversion of the electromagnetic radiation in the UV-vis-nIR range of the spectrum into the electromotive force.

Analysis of the work done in the field of photocatalytic H_2O_2 generation indicates that the community works primarily in two directions: (1) H_2O_2 generated photocatalytically using (organic) sacrificial electron donors, such as alcohols [9], and (2) H_2O_2 generated photocatalytically from water only (or water and O_2). In the first approach, the counterproductive recombination of photogenerated carriers is suppressed by employing sacrificial electron donors [10]. As such, the efficacy of two-electron O_2 reduction to H_2O_2 is maximized. However, from the practicality standpoint of H_2O_2 generation via this approach, it does not solve the problem of reliance on organic solvents and additives, which is similar to DSHP and electrochemical methods, and yields a mixture of H_2O_2 and organic species in water. Unless, oxidation of electron donor and reduction of O_2 are decoupled in time [11] (and space as in "dark" photocatalysis [12–14] which conceptually would be similar to the AO process), photocatalysis, in this scenario, produces a complex mixture of species, which application is limited.

The second photocatalytic approach is definitely more appealing. Provided that the employed photocatalyst is heterogeneous, it may be separated easily from the liquid phase while affording aqueous solution of H_2O_2 which concentration depends on the activity of the employed photocatalyst and the process parameters. Further analysis of published data indicates that the community focuses largely on optimizing the yield rate of H_2O_2 (mol[H_2O_2] g^{-1}[photocatalyst] h^{-1}), apparent quantum yield (AQY, % at certain wavelength) and the solar-to-chemical conversion (SCC, %) efficiency [15]. Figure 2 summarizes these metrics, their advantages and limitations. A growing number of publications apply the SCC metric to reactions characterized by a negative Δ_rG^0 value, such as the spontaneous production of H_2O_2 via O_2 reduction using benzyl alcohol as a sacrificial electron donor, $PhCH_2OH + O_2 \rightleftharpoons PhC(O)H + H_2O_2$. In such spontaneous processes, solar energy is not converted into the potential energy of chemical bonds. We wish to emphasize that the SCC metric should be reserved exclusively for reactions with a positive Δ_rG^0 value—those that are non-spontaneous in the dark—such as the direct synthesis of H_2O_2 from water and oxygen (Figure 2).



● Metrics

Apparent quantum yield (AQY) – A fraction of photons of specific wavelength that mediates formation of H_2O_2

$$AQY = \frac{n(H_2O_2)}{n(photon)} \times 100\% \text{ (at certain wavelength)}$$

+ Applicable to any photocatalytic reaction that yields H_2O_2, i.e. using H_2O (and O_2) as well as organic sacrificial electron donors
+ Characterizes photocatalyst's efficacy at specific wavelength

Solar-to-chemical conversion (SCC) efficiency – A fraction of solar radiation energy that is stored in H_2O_2

$$SCC = \frac{\Delta_rG^0 \times n(H_2O_2)}{P \times S \times t}$$

+ Applicable and should be used only for endergonic reactions ($\Delta_rG^0 > 0$)
+ Grasps the efficacy of the photocatalyst to utilize solar light
– Reaction equation describing H_2O_2 synthesis must be known to calculate Δ_rG^0

H_2O_2 production rate (r) – Productivity of a photocatalyst

$$r = \frac{n(H_2O_2)}{m(photocat.) \times t}$$

+ Applicable for any (photo)catalytic reaction – allows for comparison of photocatalysts' productivity with the productivity of thermal catalysts

$n(H_2O_2)$ – amount of produced H_2O_2, mol.
n(photon) – amount of emitted photons, mol.
Δ_rG^0 – standard Gibbs free energy change in the reaction of H_2O_2 synthesis, such as $H_2O + 1/2O_2 \rightleftharpoons H_2O_2$, J mol^{-1}.
P – solar radiation power at 1.5 atmospheric masses, 1000 W m^{-2}.
S – area of the photoreactor, m^2.
t – reaction time, s.
m(photocat.) – mass of the photocatalyst, g.

● Architectures of photoreactors

Batch photoreactor:
+ Simplest design → available in every laboratory
– Poor light delivery into the bulk of the reaction mixture
– Large solvent volume → low H_2O_2 concentration
…

Thin-film photoreactor:
+ Light delivery is the most efficient
– Requires specialized equipment for photocatalyst deposition (dip coating, spray coating, etc.)
– Delamination of the photocatalyst from the supporting surface
…

Continuous flow photoreactor:
+ Concentration of H_2O_2 scales reversibly with the flow rate
+ High back-pressure → high concentration of O_2 in liquid phase → higher rate of H_2O_2 production
– Requires specialized equipment
– High back-pressure → high hydrodynamic resistance
…

Figure 2. Comparison of performance metrics for photocatalysts, alongside the advantages and limitations of three photoreactor architectures.

Until now, the AQY values greater than few tens percent at 420 nm [7,16], and the SCC of >3% were achieved, which is encouraging [17–19]. These metrics are exceptionally important for developing high-performing photocatalysts. And there is definitely a room for improvement by creating intrinsically more active photocatalysts, which would afford greater AQY and the SCC. Given that H_2O_2 is primarily used as a bleaching agent and oxidant, achieving higher concentration during the photocatalytic experiments is essential for making these methods practical. However, a literature analysis suggests that the final concentration of generated H_2O_2 is often treated as a metric of minor significance, as the research community remains largely focused on competing for higher AQY and SCC values. This trend stems partly from the fundamental nature of research in photocatalyst design; although the photocatalysts target synthesis of a major chemical commodity, current research is generally conducted at Technology Readiness Level (TRL) 1 to 2. Because publishing of research data does not require advancing to higher TRLs, the primary focus remains on catalytic activity—quantified via AQY, SCC and the yield rates—rather than the cumulative concentration of H_2O_2. Consequently, the concentrations achieved via photocatalysis remain significantly lower than those produced by the industrial AO process, and, in many cases, are even lower than those reached through DSHP or photoelectrochemical methods [20].

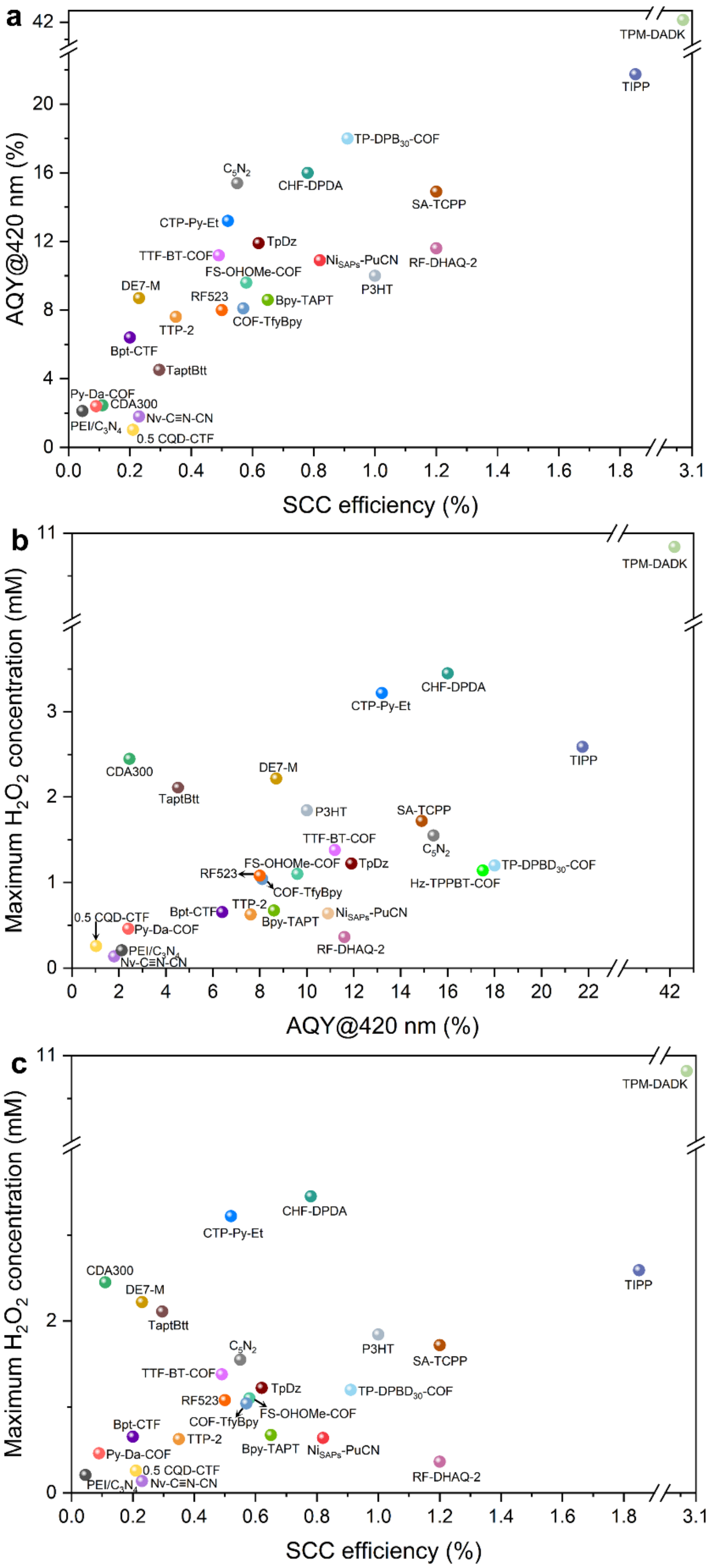


Figure 3. Overview of key performing indicators. (**a**) Dependence of AQY at 420 nm on SCC efficiency. (**b**) Dependence of maximum H_2O_2 concentration on AQY at 420 nm. (**c**) Dependence of maximum H_2O_2 concentration on SCC efficiency. Articles in which H_2O_2 was generated photocatalytically from water and O_2 are considered. TP-DPBD30-COF [15], Hz-TP-BT-COF [16], TPM-DADK [19], FS-OHOMe-COF [21], Nv-C≡N-CN [22], CDA300 [23], COF-TfyBpy [24], RF523 [25], TTP-2 [26], Bpy-TAPT [27], TaptBtt [28], TpDz [29], SA-TCPP [18], CHF-DPDA [7], DE7-M [30], P3HT [31], TTF-BT-COF [32], Py-Da-COF [33], Ni$_{SAPs}$-PuCN [34], PEI/C_3N_4 [35], C_2N_5 [36], RF-DHAQ-2 [17], 0.5 CQD-CTP [37], Bpt-CTP [38], TIPP [39]. This figure is adapted from Ref. [8]. Available under a CC-BY 4.0 license. Copyright 2026 Wang et al.

While AQY, SCC are the parameters intrinsic to the photocatalyst, yield rate and especially concentration of H_2O_2 may be increased by adjusting the process parameters. Figure 2 summarizes some advantages and limitations of three types of photoreactors. Although batch reactors are characterized by design simplicity, they typically achieve concentrations in the millimolar range within a few hours of the reaction mixture exposure to light. Such relatively low concentrations arise from the interplay between standard reaction volumes (10–50 mL) and observed photocatalytic yield rates (0.1−10 mmol[H_2O_2] g^{-1}[photocatalyst] h^{-1}). Using a transition metal free covalent triazine polymer CTP-Py-Et (Figure 3), Wang and colleagues increased concentration of H_2O_2 several times by simple adjustment of reaction volume and the amount of the photocatalyst [8], Minimizing the water volume, or potentially conducting the photocatalytic reaction in moist O_2, could yield H_2O_2 in much higher concentrations. Alternatively, flow technology offers superior control over light delivery and reaction volume, which could also facilitate higher H_2O_2 concentrations. For example, Guo and colleagues increased H_2O_2 concentration by decreasing the flow rate [39].

Nevertheless, challenges of increasing H_2O_2 concentration remain—strong light scattering by the suspended particles of semiconductor photocatalyst, which restricts using dispersions of high optical density. Additionally, the light intensity decreases exponentially as it penetrates deeper into the water-photocatalyst mixture, according to the Beer-Lambert law. Therefore, scaling up the process in batch by simply increasing the volume of the reaction mixture is not efficient—only a fraction of photocatalysts particles, dispersed in the thin layer close to the surface of the reactor, is exposed to light and enables the photoredox reaction, while majority of them remain in the dark, in the bulk of the reaction mixture. This results in low efficacy of the catalyst utilization. Promising approaches to overcome this issue include immobilization of the heterogeneous photocatalyst in the form of thin film, switching to the flow technology and increasing the O_2 concentration by employing backpressure regulators (Figure 2). This can potentially overcome the gas-liquid mass transfer limitation and avoid the additional separation of the catalyst and product (H_2O_2), which would incur extra cost.

We are strongly convinced that to make H_2O_2 production by means of photocatalysis competitive with the AO process and other emerging (potentially more sustainable) methods, efforts should be dedicated to increasing the concentration of H_2O_2 in the reaction mixture. The first target could be to achieve H_2O_2 concentration of 3 wt.% (0.88 mol L^{-1}) by employing water and O_2 as the only reactants. While achieving this goal it is imperative that the photocatalyst maintains its activity over extended operation, is easily recovered from the H_2O_2 solution, and can be reused over multiple cycles without significant performance loss. This would render photocatalysis as a viable method of distributed production of H_2O_2 for its application as the disinfectant.

Author Contributions

O.S.: conceptualization, supervision, investigation, writing—original draft preparation; C.W.: data curation, visualization, investigation; Z.Y.: investigation, writing—reviewing and editing; Z.C.: investigation, writing—reviewing and editing. All authors have read and agreed to the published version of the manuscript.

Funding

This research was funded by the Chinese University of Hong Kong grant number 4933629 and the Faculty of Science of the Chinese University of Hong Kong grant number 5501776. C.W. thanks the RGC Junior Research Fellow Scheme (JRFS) for partial support of this work (JRFS2526-4S07).

Conflicts of Interest

The authors declare no conflict of interest.

Use of AI and AI-Assisted Technologies

No AI tools were utilized for this paper.

References

1. Chen, Q. Development of an anthraquinone process for the production of hydrogen peroxide in a trickle bed reactor—From bench scale to industrial scale. *Chem. Eng. Process. Process Intensif.* **2008**, *47*, 787–792. https://doi.org/10.1016/j.cep.2006.12.012.
2. Theofanidis, S.-A.; Georgiadis, A.G.; Hop, C.J.W.; et al. Alternative H_2O_2 Production Processes: An Outlook on Candidate Technologies beyond the Anthraquinone Process. *ACS Omega* **2025**, *10*, 61076–61095. https://doi.org/10.1021/acsomega.5c07503.

3. Huang, A.; Delima, R.S.; Kim, Y.; et al. Direct H_2O_2 Synthesis, without H_2 Gas. *J. Am. Chem. Soc.* **2022**, *144*, 14548–14554. https://doi.org/10.1021/jacs.2c03158.
4. Akram, A.; Shaw, G.; Lewis, R.J.; et al. The direct synthesis of hydrogen peroxide using a combination of a hydrophobic solvent and water. *Catal. Sci. Technol.* **2020**, *10*, 8203–8212. https://doi.org/10.1039/D0CY01163K.
5. Adams, J.S.; Chemburkar, A.; Priyadarshini, P.; et al. Solvent molecules form surface redox mediators in situ and cocatalyze O_2 reduction on Pd. *Science* **2021**, *371*, 626–632, doi:doi:10.1126/science.abc1339.
6. Xia, C.; Xia, Y.; Zhu, P.; et al. Direct electrosynthesis of pure aqueous H_2O_2 solutions up to 20% by weight using a solid electrolyte. *Science* **2019**, *366*, 226–231, doi:doi:10.1126/science.aay1844.
7. Cheng, H.; Lv, H.; Cheng, J.; et al. Rational Design of Covalent Heptazine Frameworks with Spatially Separated Redox Centers for High-Efficiency Photocatalytic Hydrogen Peroxide Production. *Adv. Mater.* **2022**, *34*, 2107480. https://doi.org/10.1002/adma.202107480.
8. Wang, C.; Lv, J.; Lu, Y.; et al. Harmonizing the Pyrene and Ether Groups in Covalent Triazine Polymers for Highly Effective H_2O_2 Photosynthesis via One-Step Two-Electron Oxygen Reduction. *Adv. Funct. Mater.* **2026**, *36*, e16481. https://doi.org/10.1002/adfm.202516481.
9. Kumar, S.; Bayarkhuu, B.; Ahn, H.; et al. Photocatalytic H_2O_2 production in controlled oxidative environments using covalent triazine frameworks. *Nano Trends* **2023**, *4*, 100023. https://doi.org/10.1016/j.nwnano.2023.100023.
10. Szalad, H.; Galushchinskiy, A.; Jianu, T.; et al. Polymeric triazine/heptazine imide heterostructures enable photocatalytic O_2 reduction to H_2O_2. *Appl. Catal. B Environ. Energy* **2024**, *357*, 124323. https://doi.org/10.1016/j.apcatb.2024.124323.
11. Wang, C.; Zhuang, J.; Xie, Z.; et al. Decoupled Solar Energy Conversion and Charge Storage in a Carbon-Doped Sodium Poly(heptazine imine) for Dark Photocatalysis. *Small Struct.* **2026**, *7*, e202500706. https://doi.org/10.1002/sstr.202500706.
12. Lau, V.W.-h.; Klose, D.; Kasap, H.; et al. Dark Photocatalysis: Storage of Solar Energy in Carbon Nitride for Time-Delayed Hydrogen Generation. *Angew. Chem. Int. Ed.* **2017**, *56*, 510–514. https://doi.org/10.1002/anie.201608553.
13. Ou, H.; Tang, C.; Chen, X.; et al. Solvated Electrons for Photochemistry Syntheses Using Conjugated Carbon Nitride Polymers. *ACS Catal.* **2019**, *9*, 2949–2955. https://doi.org/10.1021/acscatal.9b00314.
14. Savateev, O. Photocharging of Semiconductor Materials: Database, Quantitative Data Analysis, and Application in Organic Synthesis. *Adv. Energy Mater.* **2022**, *12*, 2200352. https://doi.org/10.1002/aenm.202200352.
15. Chen, Y.; Liu, R.; Guo, Y.; et al. Hierarchical assembly of donor–acceptor covalent organic frameworks for photosynthesis of hydrogen peroxide from water and air. *Nat. Synth.* **2024**, *3*, 998–1010. https://doi.org/10.1038/s44160-024-00542-4.
16. Liu, R.; Chen, Y.; Yu, H.; et al. Linkage-engineered donor–acceptor covalent organic frameworks for optimal photosynthesis of hydrogen peroxide from water and air. *Nat. Catal.* **2024**, *7*, 195–206. https://doi.org/10.1038/s41929-023-01102-3.
17. Zhao, C.; Wang, X.; Yin, Y.; et al. Molecular Level Modulation of Anthraquinone-containing Resorcinol-formaldehyde Resin Photocatalysts for H_2O_2 Production with Exceeding 1.2 % Efficiency. *Angew. Chem. Int. Ed.* **2023**, *62*, e202218318. https://doi.org/10.1002/anie.202218318.
18. Zhang, Y.; Pan, C.; Bian, G.; et al. H_2O_2 generation from O_2 and H_2O on a near-infrared absorbing porphyrin supramolecular photocatalyst. *Nat. Energy* **2023**, *8*, 361–371. https://doi.org/10.1038/s41560-023-01218-7.
19. Han, B.; He, H.; Liu, J.; et al. Ketyl radical-mediated exfoliation and electron storage for solar hydrogen peroxide production. *Nat. Commun.* **2025**, *16*, 11046. https://doi.org/10.1038/s41467-025-66852-z.
20. Jeon, T.H.; Kim, B.; Kim, C.; et al. Solar photoelectrochemical synthesis of electrolyte-free H_2O_2 aqueous solution without needing electrical bias and H_2. *Energy Environ. Sci.* **2021**, *14*, 3110–3119. https://doi.org/10.1039/D0EE03567J.
21. Shu, C.; Yang, X.; Liu, L.; et al. Mixed-Linker Strategy for the Construction of Sulfone-Containing D–A–A Covalent Organic Frameworks for Efficient Photocatalytic Hydrogen Peroxide Production. *Angew. Chem. Int. Ed.* **2024**, *63*, e202403926. https://doi.org/10.1002/anie.202403926.
22. Zhang, X.; Ma, P.; Wang, C.; et al. Unraveling the dual defect sites in graphite carbon nitride for ultra-high photocatalytic H_2O_2 evolution. *Energy Environ. Sci.* **2022**, *15*, 830–842. https://doi.org/10.1039/D1EE02369A.
23. Chu, C.; Li, Q.; Miao, W.; et al. Photocatalytic H_2O_2 production driven by cyclodextrin-pyrimidine polymer in a wide pH range without electron donor or oxygen aeration. *Appl. Catal. B Environ.* **2022**, *314*, 121485. https://doi.org/10.1016/j.apcatb.2022.121485.
24. Kou, M.; Wang, Y.; Xu, Y.; et al. Molecularly Engineered Covalent Organic Frameworks for Hydrogen Peroxide Photosynthesis. *Angew. Chem. Int. Ed.* **2022**, *61*, e202200413. https://doi.org/10.1002/anie.202200413.
25. Shiraishi, Y.; Takii, T.; Hagi, T.; et al. Resorcinol–formaldehyde resins as metal-free semiconductor photocatalysts for solar-to-hydrogen peroxide energy conversion. *Nat. Mater.* **2019**, *18*, 985–993. https://doi.org/10.1038/s41563-019-0398-0.
26. Chu, C.; Chen, Z.; Yao, D.; et al. Large-Scale Continuous and In Situ Photosynthesis of Hydrogen Peroxide by Sulfur-Functionalized Polymer Catalyst for Water Treatment. *Angew. Chem. Int. Ed.* **2024**, *63*, e202317214. https://doi.org/10.1002/anie.202317214.
27. Liu, Y.; Han, W.-K.; Chi, W.; et al. Substoichiometric covalent organic frameworks with uncondensed aldehyde for highly efficient hydrogen peroxide photosynthesis in pure water. *Appl. Catal. B Environ.* **2023**, *331*, 122691. https://doi.org/10.1016/j.apcatb.2023.122691.
28. Qin, C.; Wu, X.; Tang, L.; et al. Dual donor-acceptor covalent organic frameworks for hydrogen peroxide photosynthesis. *Nat. Commun.* **2023**, *14*, 5238. https://doi.org/10.1038/s41467-023-40991-7.

29. Liao, Q.; Sun, Q.; Xu, H.; et al. Regulating Relative Nitrogen Locations of Diazine Functionalized Covalent Organic Frameworks for Overall H_2O_2 Photosynthesis. *Angew. Chem. Int. Ed.* **2023**, *62*, e202310556. https://doi.org/10.1002/anie.202310556.
30. Liu, L.; Gao, M.-Y.; Yang, H.; et al. Linear Conjugated Polymers for Solar-Driven Hydrogen Peroxide Production: The Importance of Catalyst Stability. *J. Am. Chem. Soc.* **2021**, *143*, 19287–19293. https://doi.org/10.1021/jacs.1c09979.
31. Shiraishi, Y.; Matsumoto, M.; Ichikawa, S.; et al. Polythiophene-Doped Resorcinol–Formaldehyde Resin Photocatalysts for Solar-to-Hydrogen Peroxide Energy Conversion. *J. Am. Chem. Soc.* **2021**, *143*, 12590–12599. https://doi.org/10.1021/jacs.1c04622.
32. Chang, J.-N.; Li, Q.; Shi, J.-W.; et al. Oxidation-Reduction Molecular Junction Covalent Organic Frameworks for Full Reaction Photosynthesis of H_2O_2. *Angew. Chem. Int. Ed.* **2023**, *62*, e202218868. https://doi.org/10.1002/anie.202218868.
33. Sun, J.; Sekhar Jena, H.; Krishnaraj, C.; et al. Pyrene-Based Covalent Organic Frameworks for Photocatalytic Hydrogen Peroxide Production. *Angew. Chem. Int. Ed.* **2023**, *62*, e202216719. https://doi.org/10.1002/anie.202216719.
34. Zhang, X.; Su, H.; Cui, P.; et al. Developing Ni single-atom sites in carbon nitride for efficient photocatalytic H_2O_2 production. *Nat. Commun.* **2023**, *14*, 7115. https://doi.org/10.1038/s41467-023-42887-y.
35. Zeng, X.; Liu, Y.; Kang, Y.; et al. Simultaneously Tuning Charge Separation and Oxygen Reduction Pathway on Graphitic Carbon Nitride by Polyethylenimine for Boosted Photocatalytic Hydrogen Peroxide Production. *ACS Catal.* **2020**, *10*, 3697–3706. https://doi.org/10.1021/acscatal.9b05247.
36. Ma, J.; Peng, X.; Zhou, Z.; et al. Extended Conjugation Tuning Carbon Nitride for Non-sacrificial H_2O_2 Photosynthesis and Hypoxic Tumor Therapy. *Angew. Chem. Int. Ed.* **2022**, *61*, e202210856. https://doi.org/10.1002/anie.202210856.
37. Yang, Y.; Guo, Q.; Li, Q.; et al. Carbon Quantum Dots Confined into Covalent Triazine Frameworks for Efficient Overall Photocatalytic H_2O_2 Production. *Adv. Funct. Mater.* **2024**, *34*, 2400612. https://doi.org/10.1002/adfm.202400612.
38. Wu, C.; Teng, Z.; Yang, C.; et al. Polarization Engineering of Covalent Triazine Frameworks for Highly Efficient Photosynthesis of Hydrogen Peroxide from Molecular Oxygen and Water. *Adv. Mater.* **2022**, *34*, 2110266. https://doi.org/10.1002/adma.202110266.
39. Guo, Y.; Zhou, Q.; Wang, L.; et al. Enhanced hydrogen peroxide photosynthesis via charge-complementary π-electron sites. *Nat. Commun.* **2025**, *16*, 6297. https://doi.org/10.1038/s41467-025-61452-3.