nature reviews clean technology

https://doi.org/10.1038/s44359-025-00037-1

Review article

Photo-assisted technologies for environmental remediation

Bo Weng[1,2]✉, Meng Zhang[1,2], Yingzheng Lin[1,2], Jiacheng Yang[1,2], Jiangquan Lv[3], Ning Han[4], Jiafang Xie[1,2]✉, Hongpeng Jia[1,2]✉, Bao-Lian Su[5], Maarten Roeffaers[6], Johan Hofkens[7], Yongfa Zhu[8], Shaobin Wang[9], Wonyong Choi[10] & Yu-Ming Zheng[1,2]✉

Abstract

Industrial processes can lead to air and water pollution, particularly from organic contaminants such as toluene and antibiotics, posing threats to human health. Photo-assisted chemical oxidation technologies leverage light energy to mineralize these contaminants. In this Review, we discuss the mechanisms and efficiencies of photo-assisted advanced oxidation processes for wastewater treatment and photothermal technologies for air purification. The integration of solar energy enhances degradation efficiency and reduces energy consumption, enabling more efficient remediation methods. We evaluate the technological aspects of photo-assisted technologies, such as photo-Fenton, photo-persulfate activation, photo-ozonation and photoelectrochemical oxidation, emphasizing their potential for practical applications. Finally, we discuss the challenges in scaling up photo-assisted technologies for specific environmental remediation needs. Photo-assisted technologies have demonstrated effectiveness in environmental remediation, although large-scale applications remain constrained by high costs. Future potential applications of photo-assisted technologies will require that technology selection be tailored to specific pollution scenarios and engineering processes optimized to minimize costs.

Sections

---

[1]State Key Laboratory of Advanced Environmental Technology, Institute of Urban Environment, Chinese Academy of Sciences, Xiamen, China. [2]University of Chinese Academy of Sciences, Beijing, China. [3]College of Electronics and Information Science, Fujian Jiangxia University, Fuzhou, China. [4]Department of Electrical and Computer Engineering, University of Toronto, Toronto, Canada. [5]Laboratory of Living Materials at the State Key Laboratory of Advanced Technology for Materials Synthesis and Processing, Wuhan University of Technology, Wuhan, China. [6]cMACS, Department of Microbial and Molecular Systems, KU Leuven, Leuven, Belgium. [7]Department of Chemistry, KU Leuven, Leuven, Belgium. [8]Department of Chemistry, Tsinghua University, Beijing, China. [9]School of Chemical Engineering, University of Adelaide, Adelaide, South Australia, Australia. [10]Department of Energy Engineering, Korea Institute of Energy Technology (KENTECH), Naju, South Korea. ✉e-mail: bweng@iue.ac.cn; jfxie@iue.ac.cn; hpjia@iue.ac.cn; ymzheng@iue.ac.cn

Key points

- Photo-assisted advanced oxidation processes efficiently treat wastewater, whereas photothermal technologies are used in air purification.
- The integration of solar energy can enhance efficiency of remediation processes and reduce energy consumption.
- Solar energy interacts with chemical oxidation processes, which results in the formation of reactive oxygen species that accelerate the degradation of pollutants.
- Wastewater treatments, such as the Fenton oxidation process, consume a high quantity of H_2O_2 and are kinetically slow. Integrating solar energy accelerates the process.
- Using compound parabolic collectors and raceway pond reactors optimizes light harvesting and enables remediation at concentrations of milligrams per litre and below.
- Combining different advanced oxidation technologies can help to reduce energy consumption and widen the range of contaminants that can be mineralized.

Introduction

Environmental pollution of water and air can adversely affect health and ecosystems[1,2]. Remediation technologies, such as chemical oxidation[3–6], adsorption and filtration[7,8], have been developed to eliminate organic pollutants. Among these technologies, advanced oxidation processes (AOPs)[9–11] and thermal catalytic oxidation[12–15] are used because of their versatility and ability to achieve complete mineralization of pollutants, avoiding the generation of secondary pollutants[16]. However, these methods can be costly, highlighting the need for more efficient and cost-effective solutions[17].

Integrating solar energy into remediation technologies can enhance their efficiency and sustainability[4]. Solar energy can interact with chemical oxidation processes to promote the generation of reactive oxygen species (ROS)[18–20]. This accelerates pollutant degradation and reduces reliance on external energy sources[19]. For example, in photo-Fenton activation, a typical photo-assisted AOP, the integration of light enhances the AOP efficiency by generating more hydroxyl radicals and enabling the complete mineralization of contaminants with minimal energy input[21]. Other photobased technologies are also used in water and air purification[19].

Despite their potential, several challenges hinder the effectiveness and widespread adoption of light-driven remediation technologies in practical environmental applications. The primary challenge lies in the limited light absorption by catalysts and/or oxidants. This limitation arises from two main factors: suboptimal absorption spectra of the materials, which restrict their activity to a narrow portion of the solar spectrum, and interference caused by impurities in the photo-assisted catalytic reaction systems, which reflect or absorb light[22,23]. The stability of catalysts is also a concern[24,25], with many going through degradation or deactivation over time, which reduces their effectiveness and leads to ion leakage[24]. Furthermore, the presence of competing substances, including heavy metals, and other co-existing pollutants in polluted media can interfere with the catalytic process, diminishing the availability of the light-induced reactive species needed for effective remediations[26]. This competition often requires higher catalyst dosages or prolonged reaction times, both of which can negatively affect the overall efficiency and practicality of the remediation technology[27]. Another critical yet often overlooked aspect is the economic viability and sustainability of light-driven remediation technologies[28,29], particularly for large-scale applications where the costs of catalyst production and energy consumption must be carefully balanced to ensure overall efficiency. Addressing these issues is crucial for advancing the use of light-driven technologies in practical environmental remediation.

In this Review, we introduce the applications of photo-assisted technologies to water and air purification (Fig. 1). We outline different photo-assisted advanced oxidation processes, including photo-Fenton, photo-persulfate activation, photo-ozonation and photoelectrochemical oxidation, for water purification, and highlight their mechanisms and efficiencies. Semiconductor-based photocatalysis is excluded from this Review as we aim to present light as an auxiliary method rather than the primary technical approach. Applications and benefits of photo-assisted thermal technologies for air purification, particularly for volatile organic compound (VOC) treatment, are also discussed. Finally, we evaluate the technology development stage and economic costs of these photo-assisted technologies to assess their practical applicability.

Water purification

For water purification, oxidation processes such as Fenton oxidation involve high chemical consumption of H_2O_2, contributing to operational costs[30]. These methods, although effective, underscore the necessity for more efficient solutions to reduce the quantity of H_2O_2 oxidants and the overall cost of the system. Strategies aiming at reducing cost by harnessing the power of light have been proposed to address this challenge[31,32] (Fig. 2). By integrating photochemical techniques such as ultraviolet (UV)-assisted catalysis, the efficiency of antibiotics degradation can be enhanced[33]. This approach reduces overall energy requirements and makes use of renewable energy sources[34]. The incorporation of advanced light-harvesting materials and technologies can optimize the use of natural sunlight, thereby minimizing dependency on fossil-fuel based energy sources[35].

Photo-assisted Fenton oxidation

The Fenton process generates strong oxidizing species (Fig. 2a), $^{\bullet}OH$ and Fe(IV)=O, through reactions between Fe(II) and H_2O_2 (ref. 36) (equation (1)). However, the inherent slow reduction kinetics of Fe(III) ($k = 0.01–0.001\ M^{-1}s^{-1}$) limit the steady and high-efficiency operation of the Fenton process[37] (equation (2)). Introducing external renewable energy into the Fenton process – known as the photo-Fenton process – is a strategy to accelerate the reaction. Under UV light irradiation, the photoactive $Fe(OH)^{2+}$ in the Fenton reaction promotes the reduction of Fe(III) and produces additional $^{\bullet}OH$ (refs. 38,39) (equation (3)). The photolysis of H_2O_2 also contributes to the extra production of $^{\bullet}OH$ (equation (4)). Thus, with the assistance of light, both the rate of the Fe(II)/Fe(III) redox cycle and the yield of produced active species in the Fenton reaction are improved, promoting pollutant decomposition[39].

$$Fe^{2+} + H_2O_2 \rightarrow Fe^{3+} + HO^{\bullet} + OH^{-} \quad k \approx 40 - 80\ M^{-1}\,s^{-1} \tag{1}$$

$$Fe^{3+} + H_2O_2 \rightarrow Fe^{2+} + HO_2^{\bullet} + H^{+} \quad k \approx 0.001 - 0.01\ M^{-1}\,s^{-1} \tag{2}$$

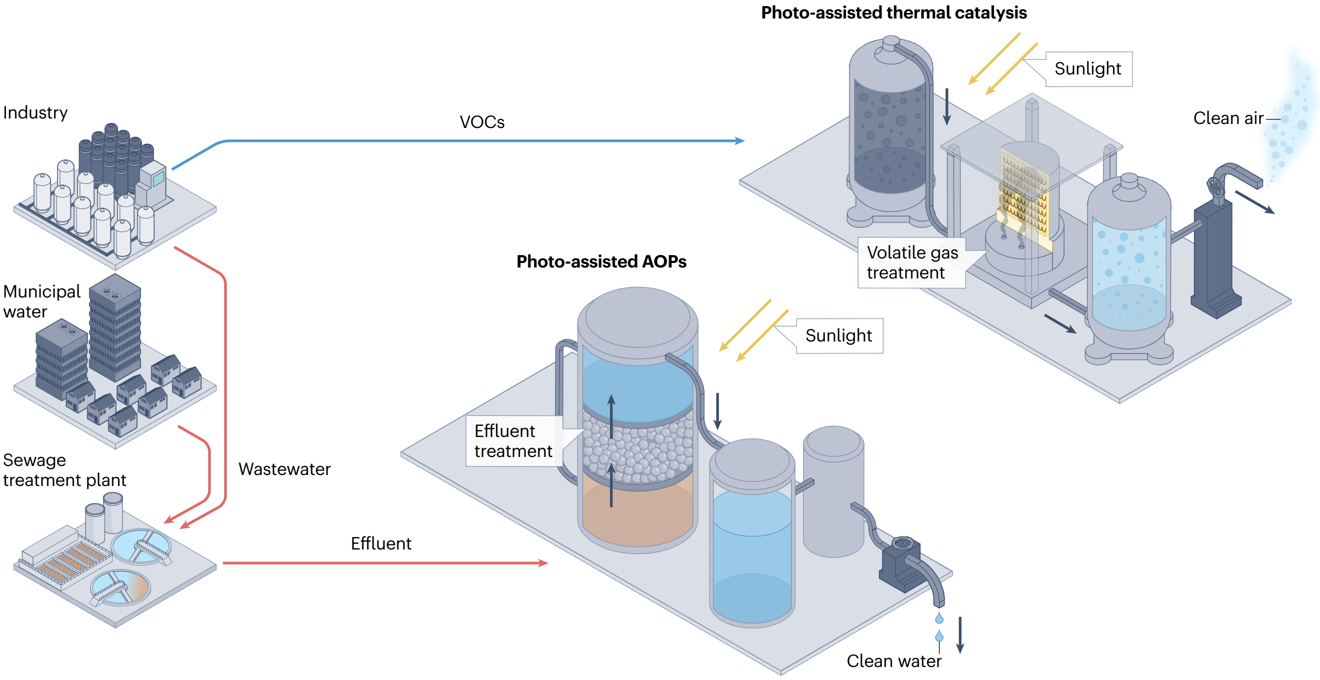

Fig. 1 | Photo-assisted technologies for water and air purification. Photo-assisted advanced oxidation processes (AOPs) and photo-assisted thermal catalysis can be used for wastewater and air treatment. The wastewater from industries and municipal water usage is collected and transferred into a sewage treatment plant for treatment. The effluent containing refractory organic pollutants is purified using photo-assisted AOPs. Volatile organic compounds (VOCs) generated from industry can be purified through photo-assisted thermal technologies.

$$\mathrm{Fe(OH)^{2+}} + h\nu \rightarrow \mathrm{Fe^{2+}} + {}^{\bullet}\mathrm{OH} \tag{3}$$

$$\mathrm{H_2O_2} + h\nu \rightarrow 2\ {}^{\bullet}\mathrm{OH} \tag{4}$$

Another issue in traditional Fenton processes (both homogeneous and heterogeneous) is a narrow pH operating window[40,41]. Fe(III) tends to hydrolyse at $\mathrm{pH} > 3$, reducing the concentration of the active metal in the system[42]. To address this issue, organic chelating ligands can be introduced in homogeneous Fenton systems, or catalysts can be added to heterogeneous Fenton systems[43,44]. Regardless of whether it is a homogeneous or heterogeneous system, the introduction of light can enhance the catalytic degradation efficiency of the Fenton process[45]. Light can aid the complete mineralization of organic compounds and the rapid reduction of Fe(III) by decomposing the partially oxidized by-products, such as iron complexes (for example, oxalates), through a ligand-to-metal charge transfer mechanism[46]. Organic chelate ligands containing several carboxyl groups (for example, nitrilotriacetic acid and ethylene diamine tetra-acetic acid) have been added to the photo-Fenton reaction to ensure operational stability at near-neutral pH[44–48]. Diversifying the chemical structure, functional groups and steric configuration of organic ligands (for example, nitrogen-containing groups, phosphonic acid groups, cyclic tetradentate ligands) can further functionalize the photo-Fenton reaction by selectively producing active species and extending the photoresponse wavelength to the visible or near-infrared range[49,50].

Heterogeneous Fenton systems show enhanced contaminant removal performance under light. The removal efficiency can increase by 2 to 13 times, depending on the physicochemical properties of the Fenton photocatalysts[51]. The underlying mechanisms include the semiconducting behaviour of Fe(III) oxides, direct activation of surface hydroxyl species and H_2O_2, and the leakage of Fe(II) and Fe(III) cations, combining features of heterogeneous and homogeneous chemistry[52]. In the homogeneous photo-Fenton process, the production of active species is heavily influenced by the photoresponsive properties of Fe^{3+} aggregates[53]. Consequently, the structure of hydrolysed Fe^{3+} species has been correlated with the generation of active species under varying reaction conditions, such as pH and Fe^{3+} concentration[53,54]. Alternatively, manipulating the spin state of active metal atoms in heterogeneous catalysts presents an efficient strategy to direct active species generation in the photo-Fenton reaction. The spin states of metal atoms are strongly influenced by the electronic properties of the support materials[55,56]. Furthermore, the design of heterogeneous photocatalysts capable of in situ generation of H_2O_2 (201 $\mu\mathrm{mol\,g^{-1}\,h^{-1}}$) – known as the photo-self-Fenton reaction – can reduce the need for external H_2O_2 (ref. 56).

Conventional homogeneous Fenton oxidation is used as a pretreatment process before biochemical treatment or as an advanced treatment following conventional wastewater treatment plants to remove emerging contaminants[57]. Compared with the conventional homogeneous Fenton reaction, the homogeneous photo-Fenton reaction demonstrates a higher yield of active species, which leads to an enhanced mineralization rate relative to the Fenton process[58].

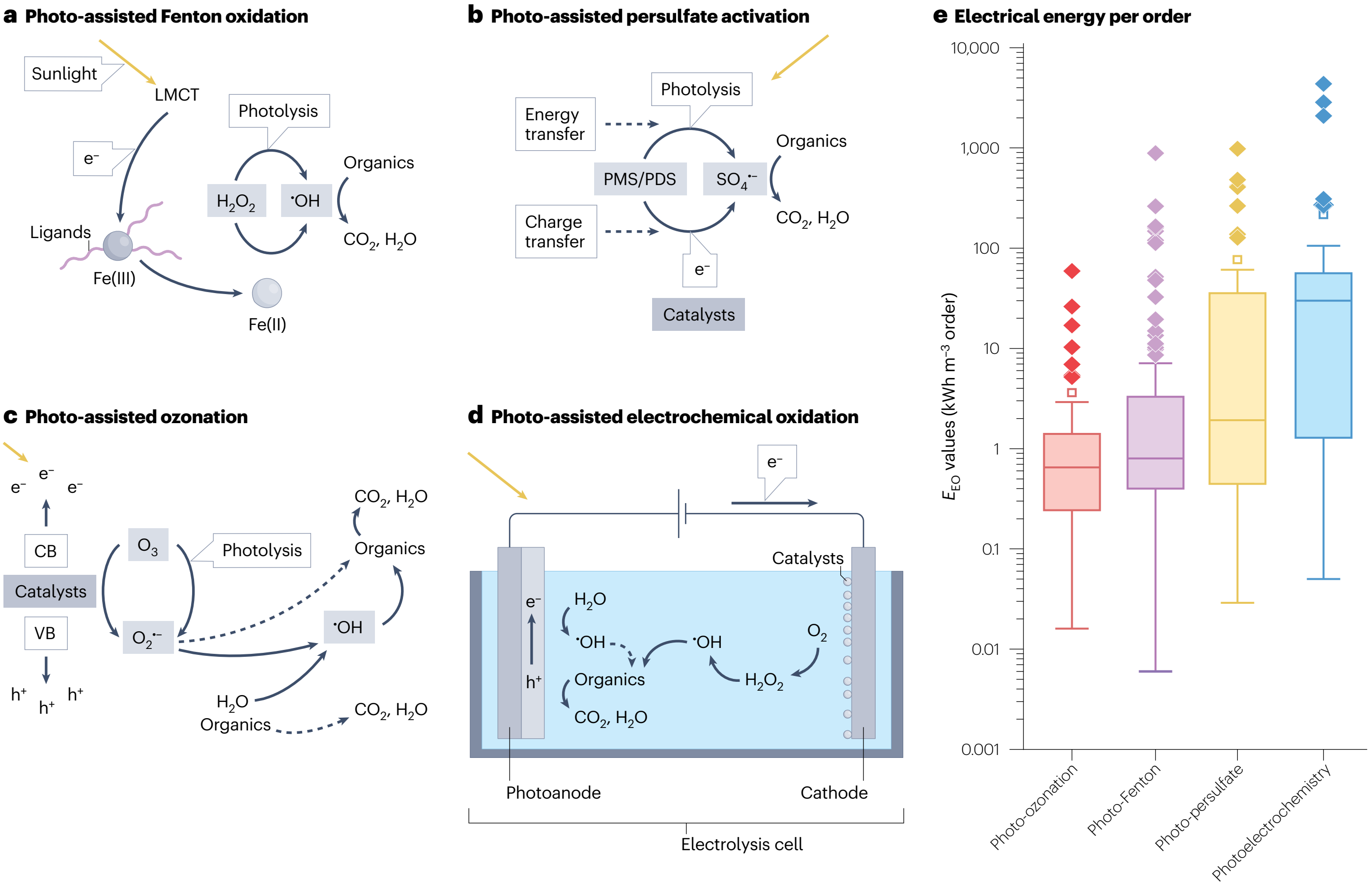

Fig. 2 | Photo-assisted technologies for water purification. Mechanisms of photo-assisted technologies for water purification. **a**, In photo-assisted Fenton oxidation, light can directly photolyse H_2O_2, or excite catalysts to generate electrons that will decompose H_2O_2 to generate the hydroxyl radical, $^{\bullet}OH$. **b**, In photo-assisted persulfate activation, persulfate is activated by light directly or a photogenerated charge carrier to produce $SO_4^{\bullet-}$ and $^{\bullet}OH$. **c**, In photo-assisted ozonation, ozone can react with ultraviolet (UV) light or photoexcited electrons to produce $^{\bullet}OH$ and $O_2^{\bullet-}$ radicals that react with pollutants in water and eliminate them. Full arrows represent the main reaction route, whereas the dashed arrows indicate secondary reaction routes. **d**, In photo-assisted electrochemical oxidation, light can excite either the photoanode or photovoltaic system to produce charge carriers to form reactive oxygen species. **e**, The electrical energy (E_{EO}) needed to degrade the concentration of a pollutant by one order of magnitude in 1 m^3 of water varies for different photo-assisted advanced oxidation processes. The E_{EO} values are based on data from ref. 63 and a defined experimental set-up with controlled conditions, including water quality, target contaminants and other relevant process parameters. When kinetic data are available, compounds that are susceptible to direct oxidation (for example, by ozone or UV photolysis) are excluded from consideration. For ozone-based and UV-based processes, the threshold values for rate constants are set at $k_{O3} < 10\ M^{-1}s^{-1}$ and $k_{UV} < 10^{-5}\ m^2\ J^{-1}$. The box plots show quartiles with the centre line indicating the median and the whiskers extending to 1.5× the interquartile range. CB, catalyst conduction band; LMCT, ligand-to-metal charge transfer; PDS, peroxodisulfate; PMS, peroxymonosulfate; VB, catalyst valence band. Panel **e** adapted with permission from ref. 63, Elsevier.

These improvements reduce the demand for oxidant chemicals and lower the operational costs of the homogeneous photo-Fenton reaction, highlighting its potential for large-scale applications similar to conventional homogeneous Fenton oxidation[59,60]. The technical feasibility of the homogeneous photo-Fenton process has been demonstrated in a 100-m^2 raceway pond reactor with a treatment capacity of 1.92 $m^3\ m^{-2}\ d^{-1}$ (ref. 61). This technology might be used to enhance the biodegradability of wastewater and to remove emerging contaminants, such as microplastics and persistent organic pollutants, in secondary effluents in wastewater treatment plants[62].

Despite the high variability in water quality, process capacity and target substances, the median value of electrical energy per order (E_{EO}, defined as the electrical energy (kWh) required to degrade a contaminant by one order of magnitude in 1 m^3 of water) of the photo-Fenton reaction ($E_{EO} = 2.6$ kWh m^{-3} order^{-1})[63] is at a medium level among AOP technologies (Fig. 2e). The use of compound parabolic collectors and raceway pond reactors can help to further reduce energy consumption of the photo-Fenton process, through the optimization of the light-harvesting capabilities of the reaction[64]. Typically, when the concentration of pollutants is in the range of milligrams per litre or above, tubular photoreactors with compound parabolic collectors are widely used because they can maximize the usage of irradiation energy (Fig. 3a). To remove contaminants at lower concentrations, raceway pond reactors have emerged as an alternative owing to their low production cost compared with other reactors, high volume to surface, and flexibility to optimize the liquid depth according to the radiation strength[65] (Fig. 3b).

Photo-assisted persulfate activation

In comparison with hydroxyl radicals ($^{\bullet}$OH) generated in H_2O_2-based (or O_3-based) oxidation processes, sulfate radicals ($SO_4^{\bullet-}$) offer marked advantages[66,67] (Fig. 2b). These advantages include a longer half-life (30–40 µs versus 20 ns for $^{\bullet}$OH) and a higher redox potential (2.5–3.1 V_{NHE} compared with 1.9–2.7 V_{NHE} for $^{\bullet}$OH)[68]. Moreover, the ease of transport and storage of solid persulfate salts (for example, peroxodisulfate and peroxymonosulfate), coupled with their high efficiency in generating radicals ($^{\bullet}$OH, $SO_4^{\bullet-}$ and $O_2^{\bullet-}$) and non-radical species ($^1O_2$ and high-valent metal-oxo), has made photo-assisted persulfate oxidation technique one of the most relevant AOPs for water decontamination[68].

Since UV light began being used for peroxodisulfate activation[69], the development of photo-assisted persulfate oxidation has evolved from light-based homogeneous activation processes to photoresponsive catalyst-driven heterogeneous catalysis[70]. The catalysts commonly used in a photo-assisted persulfate oxidation include metal-based oxides and their composites (such as TiO_2, bismuth oxides, Fe-based and Ti-based metal–organic frameworks, and transition metal dichalcogenides), and non-metal materials (such as graphitic carbon nitride (g-C_3N_4), carbon quantum dots and perylene diimide) and their composites[71]. In addition to enhancing radical generation, the use of photocatalysts in persulfate activation can also promote the formation of non-radical species[68]. These species enable non-radical oxidation of contaminants, which is emerging as a decontamination strategy owing to its strong resistance to complex water matrices and its high persulfate utilization efficiency (up to 90%) with a low stoichiometric ratio[72].

Energy transfer and electron transfer are two accepted mechanisms for photo-assisted persulfate oxidation. External light radiation-mediated energy transfer can directly induce the homolysis of peroxide bonds within peroxymonosulfate and peroxodisulfate, producing $SO_4^{\bullet-}$ and/or $^{\bullet}$OH in photo-assisted homogeneous persulfate activation[68]. Additionally, peroxymonosulfate and peroxodisulfate molecules can act as electron acceptors, capturing electrons generated on the light-irradiated surface of solid photocatalysts[19]. The photogenerated electrons can activate peroxodisulfate and peroxymonosulfate via electron transfer processes[68,71]. Photoresponsive catalysts, including TiO_2, Fe-based and Ti-based metal–organic frameworks, and transition metal dichalcogenides, usually have multiple surface structures and possess different catalytic activities in the persulfate activation, which can lead to the formation of ROS and thus the degradation of pollutants[71,73]. The use of photoresponsive materials is advantageous because it extends the light absorption range from UV to visible and near-infrared regions[73]. However, the rational design of photocatalysts with near-infrared light-reinforced persulfate activation is still a technological challenge.

The water purification performance of photo-assisted persulfate oxidation relies on the types of ROS and their resistance towards the water matrix (such as pH and inorganic ions)[69,74,75]. Given the broader range of second-order reaction rate constants of $SO_4^{\bullet-}$ with organic pollutants (10^5–10^{11} M^{-1} s^{-1} compared with 10^8 – 10^{10} M^{-1} s^{-1} for $^{\bullet}$OH) and its preferred oxidation pathways[68], the $SO_4^{\bullet-}$ radical is considered a more selective oxidant than $^{\bullet}$OH (ref. 76). This selectivity has led to the design of water matrix-specific decontamination processes[77]. For example, UV-mediated persulfate hybrid systems have been used in pilot-scale and industrial-scale tertiary wastewater treatment to remove various micropollutants, bacteria and their associated antibiotic resistant genes[77]. However, the practical implementation of photo-assisted persulfate oxidation techniques in water-related utilities is still in its early stages[74]. For instance, the pilot-scale application of photo-assisted persulfate oxidation is mainly focused on UVA-based homogeneous oxidation processes with a treated wastewater scale of about 50 m^3 d^{-1} (ref. 77). Although this pilot-scale application might be suitable for point-of-use water purification systems, it remains largely unknown whether this technology has the capacity to purify real effluents from large sewage treatment plants (>500,000 m^3 per day). Therefore, the technical viability of large-scale wastewater purification with these technologies should be evaluated, as well as their compatibility and potential conflicts with current purification technologies[75].

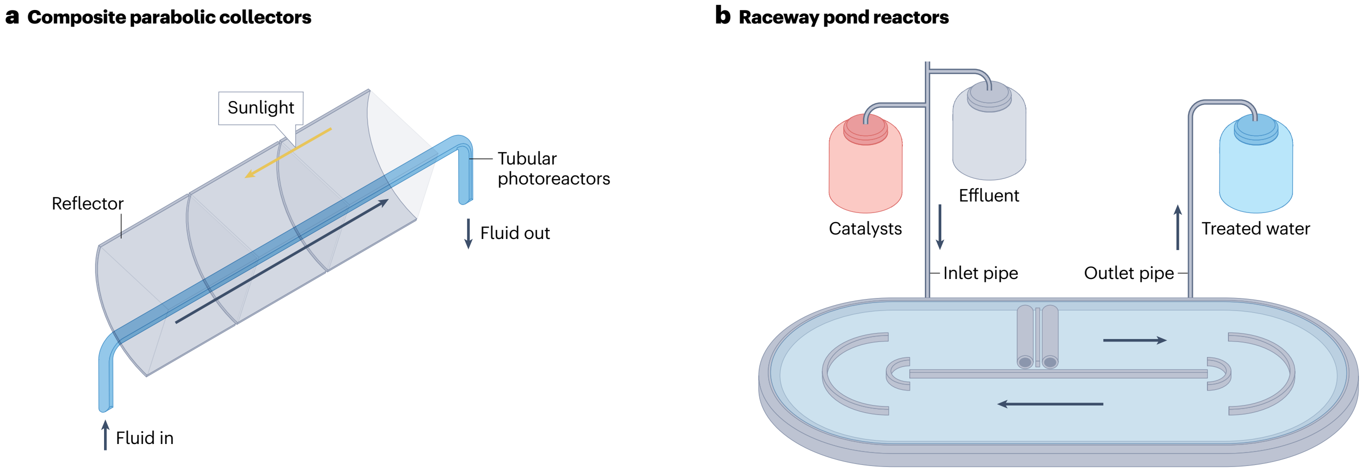

Fig. 3 | Operation of composite parabolic collectors and raceway pond reactors. Parabolic collectors and raceway pond reactors can improve light harvesting and help reduce the energy consumption of the photo-Fenton process. **a**, Composite parabolic collectors can concentrate and reflect most of the incident radiation to the absorber, and tubular photoreactors maximize the usage of irradiation energy. **b**, Raceway pond reactors have a high surface-area-to-volume ratio and the flexibility to optimize the liquid depth. Pretreated effluent and catalysts (for example, H_2O_2 and iron-based catalysts) enter the reactor through a vertical inlet pipe, and treated water is collected through a vertical outlet pipe.

Among other indicators, the energy consumption volume (E_{EO} value associated with the production of oxidants and catalysts and the degradation of contaminants) is an environmental and economical assessment parameter[63]. Available E_{EO} values for typical photo-assisted persulfate oxidation processes range from 3.8×10^{-4} to 4.8×10^{2} kWh m^{-3} order^{-1} (ref. 75). Differences in the E_{EO} values arise from many factors, such as the types of contaminant, water matrix conditions, catalyst synthesis procedures and the quality objective of water purification[63]. Given the wide range of E_{EO} values, the introduction of photocatalysts might not necessarily contribute to a lower E_{EO} value or to environmentally friendly water purification in some cases[75]. Compared with the photo-assisted homogeneous persulfate oxidation process, accurately calculating the E_{EO} values for photocatalyst-mediated heterogeneous processes is more complex[68]. This challenge arises primarily from the lack of data and uncertainties surrounding energy consumption associated with the recyclability and reusability of catalysts in real wastewater purification scenarios, and makes it difficult to conduct a comprehensive sustainability evaluation. Normalized protocols detailing the preparation of photocatalysts and their recyclability and reusability are encouraged to accurately calculate the energy consumption, and thus assist the development of photo-assisted persulfate oxidation technology with a low carbon footprint.

Photo-assisted ozonation

Ozone, as a powerful oxidizing reagent, has been used in wastewater purification owing to its strong redox potential (2.01 V_{NHE})[78]. However, the application of ozone alone faces the disadvantages of high production cost (US\$2.00 kg^{-1} of ozone for a concentration of ozone around 10–12 wt%)[79], slow volumetric mass transfer coefficient (0.5–1.5 min^{-1} depending on operating conditions)[80] and low mineralization efficiency (20–50%)[81,82] due to ozone's relatively poor solubility and stability in water, as well as its selective reactivity with organic compounds at acidic pH[83]. Integrating light with ozone, whether through homogeneous UV–O_3 processes or heterogeneous light–O_3–semiconductor systems, is advantageous[84]. The ozone consumption, per milligram of total organic carbon (TOC) removal, of a light–O_3–semiconductor system has been reported to be about 13% of that of a simple ozonation system[84]. In a heterogeneous system (Fig. 2c), light excites the semiconductor to generate electrons that preferably react with ozone rather than with O_2, owing to the high electrophilicity of ozone, thus generating more ROS, including $^{\bullet}OH$, $O_2^{\bullet-}$ and $^1O_2$, to enhance the degradation of pollutants[85]. The interaction between ozone and electrons also aids the separation of electron–hole pairs. The abundant active sites on the surface of photocatalysts, such as g-C_3N_4 and TiO_2, promote the interaction between ROS and pollutants, overcoming mass transfer in the ozonation reaction[86–88]. Furthermore, when O_3 is directly exposed to UV light, it dissociates to generate atomic oxygen, which can further react with water to produce $^{\bullet}OH$ (ref. 84).

Photocatalytic ozonation exhibits synergistically enhanced oxidation efficiencies (pseudo-zeroth-order rate of 4.79×10^{-2} mM min^{-1}) compared with the photocatalysis (5.00×10^{-4} mM min^{-1}) and ozonation (0 mM min^{-1}) systems operating separately[86]. The synergistic effect of photocatalytic ozonation is evident in the increasing degradation and/or mineralization efficiencies or oxidation rate constants of organic compounds[83]. The apparent rate constant of photocatalytic ozonation is 9.5 and 1.6 times higher than that of photocatalysis and ozonation, respectively, for mineralizing aromatic compounds[89]. This efficiency is attributed to the generation of more reactive but non-selective $^{\bullet}OH$ that reacts with almost all organic molecules at rates of 10^6–10^9 M^{-1} s^{-1} during the photocatalytic ozonation process[90].

Despite the synergistic effects of photocatalytic ozonation on pollutant decomposition in water, its economic viability must also be considered to assess sustainability. Photocatalytic ozonation, which requires additional electrical energy for ozone generation, at first glance seems to be more expensive than simple photocatalysis, which only consumes electricity for light irradiation sources. When comparing the costs of these oxidation techniques for water treatment, the specific energy consumption for each system should consider the decomposed pollutants[83]. Taking a TiO_2/O_3/UVA system as an example, the energy consumption primarily arises from the electrical energy necessary to generate O_3 and radiation, which is the main operation cost for those different processes[91]. The energy requirement for photocatalytic ozonation is 7.3–22.0 kWh m^{-3} order^{-1}, which is lower than the energy consumption of photocatalysis (38.9–47.1 kWh m^{-3} order^{-1}) and O_3 alone (26.2 kWh m^{-3} order^{-1})[91]. Accordingly, the operating cost of different systems can be calculated based on local electricity prices. Similar results have been reported in the literature[83,91–93], demonstrating the cost-effectiveness of photocatalytic ozonation.

Photo-assisted electrochemical oxidation

Although electrochemical advanced oxidation technology shows promise for industrial applications, the high electricity requirements increase operational costs[94]. Integrating solar energy into electrochemical advanced oxidation processes is regarded as an effective strategy to enhance efficiency and reduce energy demands[95] (Fig. 2d).

There are two general routes to achieve photo-assisted electrochemical oxidation processes. The first type consists of coupling external energy input (UV light or photovoltaic (PV) cells) with an electrolyser (UV-EC or PV-EC, Fig. 4a). An electrolyser includes a cathode, anode and electrolyte, in which the anode and cathode are responsible for removing pollutants through direct redox reactions or indirect production of active free-radical species[4]. The efficiency and lifespan of an electrolyser are primarily determined by the electrode substrate, electrocatalysts in the cathode and anode, and the fabrication processes[96]. Additionally, the pretreatment of influent water and the addition of strong oxidants to accelerate the generation of active free-radical species can substantially enhance the production of high-quality effluent water[2]. In a PV-EC system, an electrolyser containing electrocatalytic anodes, such as dimensionally stable anodes and boron-doped diamond electrodes[97], is powered by commercialized silicon-based PV cells. In a UV-EC system, the UV light can activate the electrolyte to produce free-radical species, thus promoting the degradation of pollutants[98]. The PV-EC system has been proven to be practical for small-scale rural water supply, yet restricted by the high costs (around US\$26,000) associated with equipment and maintenance[99]. For economic reasons, the application of this system could be more suitable in regions with more sunlight throughout the year and concentrated influent streams[99].

The second type of photo-assisted electrochemical oxidation process involves using semiconductor materials to prepare photoelectrodes for photoelectrochemical advanced oxidation (PECAO, Fig. 4b). In PECAO, the use of photoelectrodes simplifies the equipment set-up and enables more convenient connections with other multifunctional tandem components compared with a PV-EC system[100]. Moreover, a higher charge separation efficiency and easier recovery of the catalyst could be achieved compared with a photocatalytic system[100]. In the PECAO system, the solar energy used by the

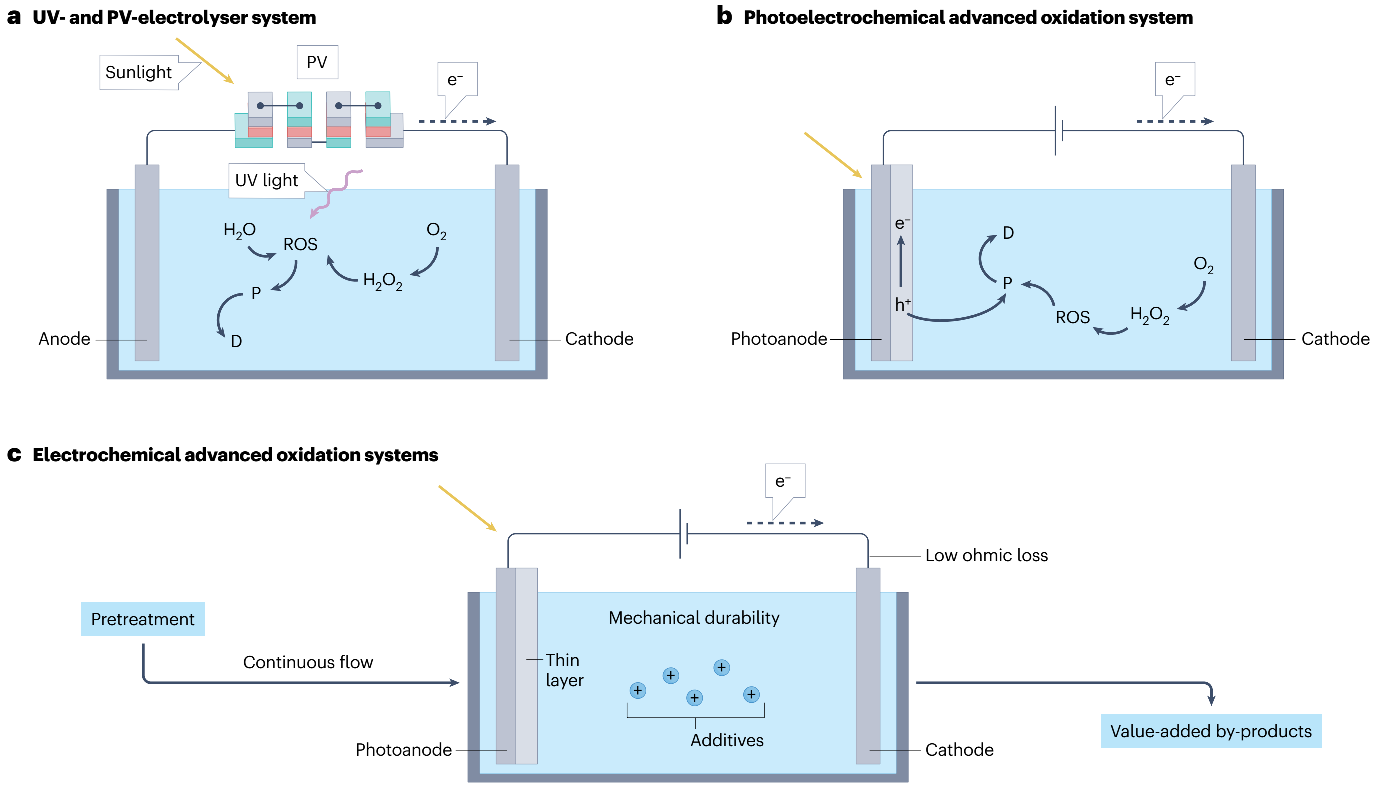

Fig. 4 | Photo-assisted electrochemical oxidation processes. **a**, Ultraviolet (UV)-electrolyser and photovoltaic (PV)-electrolyser system. **b**, Photoelectrochemical advanced oxidation (PECAO) system. **c**, Key properties of electrochemical advanced oxidation systems for practical wastewater treatment applications. The pretreatment reduces the interference of the influent water, whereas the continuous-flow mode enhances throughput capacity and operational stability. Under sunlight, the photoanode absorbs light energy to generate holes and electrons. A thin layer on the photoanode improves light utilization efficiency. The cathode catalyses oxygen reduction to produce reactive oxygen species (ROS), with electrolyte additives accelerating their generation. The mechanical durability of the electrodes determines their lifespan, directly influencing the overall device longevity. Low ohmic loss in the system minimizes unnecessary electrical consumption and improves operational stability. By coupling the photoanode and cathode, organic pollutants are efficiently removed. Furthermore, tuning catalytic properties and operating parameters can yield targeted value-added by-products, enhancing the economic viability of the process. D, degradation products; P, pollutants.

photoelectrode lowers the voltage required to drive the reactions, whereas the applied bias accelerates the charge separation process under an electric field[101]. The PECAO system includes photoelectrocatalysis, photoelectrochemical oxidation, photo-electrocoagulation and photoelectrochemical Fenton processes[102]. The photoelectrodes in the PECAO system undergo similar processes for solar light utilization. Upon absorbing solar light, the photoelectrodes generate electrons and holes in the conduction and valence bands, respectively[103]. The electrons are transferred to the counterelectrode, while the holes drive various reactions[103]. In photoelectrocatalysis, the holes aid the formation of ROS upon reaching the surface of the photoelectrocatalysts[104]. In photoelectrochemical oxidation, the holes directly oxidize pollutants[105]. In photo-electrocoagulation, the holes accelerate the electrochemical dissolution of the anode, resulting in the formation of coagulant agents[102]. In photoelectrochemical Fenton processes, the holes enhance the Fenton reaction[106]. Considering that different ROS (for example, $O_2^{\cdot-}$, H_2O_2, $^{\cdot}OH$, and $^1O_2$) have distinct standard potential values, reaction tendencies and complex interconversion pathways, photo-assisted electrochemical oxidation demonstrates potential by offering a convenient method to control ROS generation with specific compositions for targeted wastewater treatment[107].

Photoelectrodes in PECAO are generally composed of inorganic semiconductors, such as TiO_2 and $BiVO_4$, which have limited solid–liquid interface for both bulk and dense nanostructure photoelectrodes, resulting in low efficiencies[108]. Porous materials, such as metal–organic frameworks and covalent organic frameworks, which possess highly ordered structures, large porosities and diversified pore surfaces, are expected to lead to efficient wastewater treatment due to their fast mass transfer pathways and abundant exposed active sites[109]. As most ROS are generated at the anodic side by photogenerated holes, the cathode can accept photogenerated electrons to catalyse oxygen's reduction to generate H_2O_2 in an O_2-saturated solution using carbonaceous materials[110,111]. Although carbonaceous materials are cheap and readily available compared with metal materials, they are short lived and unstable in electrolytes, which motivates the development of inexpensive materials with high stability[110,111]. Alternatively, an electron–ion acceptor cathode can enhance the separation of electrons and holes, producing strong oxidant free radicals at the photoanode[112]. Based on mechanistic studies of charge transfer, separation kinetics and redox reactions on photoelectrodes, further research is recommended to explore the structure–activity relationship between ROS generation and their interactions with pollutants. This knowledge would help to advance the development of PECAO for practical applications in wastewater treatment.

Although substantial efforts have been made to improve the properties of the PECAO system under simplified simulated conditions in the laboratory, challenges remain for its practical application. Real-world wastewater treatment imposes higher demands on the design of the PECAO system and electrodes because of complex interferences, variable water quality and large-scale water volumes[113] (Fig. 4c). To reduce the interferences, membrane filtration[52] has been a common pretreatment process used to remove suspended solid and colloidal particles in wastewater. Moreover, to improve the throughput capacity of a PECAO system, rationally designing continuous-flow reactors and larger photoelectrodes of higher specific surface area can enhance the mass transfer and treatment efficiency[114]. To further increase the light utilization efficiency, reducing the thickness of semiconductors and electrolytes between the photoelectrodes and light source could be a cost-effective strategy[114]. Additionally, designing photoanodes that respond to near-infrared light could be an effective approach to increase sunlight utilization[115,116].

The lifetime of a PECAO system is another important aspect that is heavily affected by the properties of wastewater and the abovementioned improvement strategies[117]. However, current research on the PECAO system is mainly focused on its feasibility, and its practical application is still very limited. The mechanical stability of catalyst immobilization on photoelectrodes primarily determines the lifetime, especially in continuous-flow systems[117]. Advanced preparation methods of photoelectrodes, such as sputtering and atomic layer deposition, have been developed to improve the mechanical stability of catalysts. The sputtering method focuses on depositing thin films on the surface of the silicon and/or wafer glass, and the atomic layer deposition method can create planar or nanostructured electrodes[118,119].

Finally, the cost of electrical energy consumption limits the present output-to-input ratio of the PECAO system and other photo-assisted electrochemical oxidation technologies[113]. Simultaneously reducing the unnecessary electrical cost and increasing the added revenue would promote the practical application of PECAO[113]. Electrical cost can be reduced by lowering the ohmic loss of every component in devices and developing photoelectrodes for using solar energy[113]. The added revenue could be increased by coupling the photo-assisted electrochemical oxidation processes with value-added production processes, such as CO_2 reduction or H_2 evolution, when the concentration of pollutants is low and the produced H_2 can be used as an electron donor for anaerobic fermentation[120]. Although photo-assisted electrochemical oxidation technologies are currently challenged by cost and lifetime, they have shown potential for sustainable water treatment.

Integrated multiple photo-assisted oxidation processes

Coupling multiple AOP technologies might help achieve more efficient water-treatment outcomes and reduce overall energy consumption, compared with individual advanced oxidation technologies[100,121]. By combining different AOPs, a wider variety of ROS and radicals such as hydroxyl, sulfate and ozone-derived radicals can be generated[100]. This variety increases the likelihood of targeting and degrading a broader range of contaminants[100]. The introduction of light can activate catalysts and/or sensitizers within the system, leading to the generation of additional reactive species. These reactive species can accelerate the degradation of pollutants and improve the overall energy efficiency of the remediation process[122,123]. For example, the photoelectro-Fenton process combines the advantages of photo-Fenton and electro-Fenton processes[122], using light to enhance the production of hydroxyl radicals while the electrochemical component regenerates the iron catalyst and hydrogen peroxide, ensuring continuous pollutant degradation.

Additionally, light helps to regenerate Fe^{2+} from Fe^{3+}, maintaining the catalytic cycle and aiding continuous production of hydroxyl radicals. The stability of catalysts over longer periods can be further improved by integrating light with multiple AOPs, reducing frequent replacement or regeneration of catalysts[121]. A coupled solar photoelectro-Fenton and solar photocatalysis system exhibited higher efficiency and stability than electrochemical oxidation and photoelectro-Fenton processes towards salicylic acid degradation[121]. The energy consumption of the coupled system at 50 mA cm^{-2} was determined to be 0.249 kWh g^{-1} TOC at 360 min, which is less expensive than solar photoelectro-Fenton (0.286 kWh g^{-1} TOC) and anodic oxidation–H_2O_2–solar photocatalysis (0.751 kWh g^{-1} TOC), confirming the viability of the solar photoelectro-Fenton and solar photocatalysis system for the remediation of polluted wastewater[121].

Photo-assisted multi-technologies could improve treatment efficiency, but this has challenges, such as the complexity of reaction mechanisms and the risk of formation of by-products[19]. The interactions between different oxidative species and pollutants can lead to unexpected reaction pathways, potentially generating harmful by-products[82]. Photo-assisted multi-system structures can be rationally optimized to be more efficient[124] through strategic considerations across multiple factors, including the selection of AOP combinations, catalyst development, reaction conditions and reactor design[125]. Different photo-assisted AOPs generate specific reactive species (for example, $^{\bullet}OH$, $O_2^{\bullet-}$ and $SO_4^{\bullet-}$), enabling broader pollutant degradation[100]. By coupling AOPs that produce complementary radicals, treatment processes can target diverse contaminants more effectively while minimizing by-products and reducing the need for post-treatment[100].

Catalyst development has a role in enhancing the generation of reactive species and overall degradation efficiency. Designing dual-function photocatalysts that activate multiple oxidants, such as H_2O_2 and persulfate under light irradiation, can optimize systems such as photo-Fenton–persulfate[126]. Incorporating noble or transition metals with semiconductor catalysts improves light absorption, charge carrier separation, and activation of oxidants such as H_2O_2 and ozone[85], enhancing both Fenton and ozonation processes efficiencies in multi-AOPs systems. Reaction conditions also influence the system performance. Parameters such as pH, light intensity, temperature, and the concentrations of oxidants and contaminants must be carefully controlled[75]. For instance, excessive oxidant concentrations could result in radical scavenging, whereas insufficient levels reduce oxidation efficiency[127]. Acidic conditions favour Fenton reactions, whereas persulfate systems are more effective under neutral to slightly alkaline conditions[128,129]. Designing systems that operate efficiently across a pH range enhances their adaptability for diverse wastewater compositions.

Efficient reactor design is critical for maximizing interactions between light, catalysts and pollutants[125]. Reactor configurations that enhance light penetration, such as cylindrical reactors with central light sources or flat-plate reactors, promote even illumination and minimize shadowing effects[130]. Optimized flow configurations

Table 1 | Advantages and disadvantages of photo-assisted advanced oxidation process technologies

Photo-assisted advanced oxidation processes	Advantages	Disadvantages	Environmental scenarios
Photo-Fenton	Formation of strong non-selective $^{\bullet}OH$ Efficient for a wide range of contaminants Simple implementation	High operational costs[194] (€0.44 to €2.18 m^{-3}) Additional oxidants (H_2O_2) required Difficulties in transporting chemicals such as H_2O_2	Drinking water treatment system; effluent from municipal wastewater treatment plants; raw oily wastewater
Photo-persulfate	Longer lifetime of $SO_4^{\bullet-}$ (30–40 μs) than $^{\bullet}OH$ (20 ns) High oxidation potential[68] (2.5–3.1 V_{NHE}) Rapid reaction rate (10^5–10^{11} $M^{-1}s^{-1}$) Wide work pH range (2.0–8.0)	Increases the salt content and presence of sulfate ions as end products Additional oxidants (persulfate, peroxymonosulfate) required Health and safety concerns	Pharmaceutical wastewater; effluent from municipal wastewater treatment plants
Photo-ozonation	High yield of $^{\bullet}OH$ radicals (above 13%)[195] Efficient for a wide range of contaminants No pH restrictions No oxidants required	Risks associated with ozone generation Requires high electrical energy to generate reactive species (7–161.8 kWh m^{-3} $order^{-1}$)[91,196] Generation of toxic by-products	Drinking water treatment system; effluent from municipal wastewater treatment plants; pharmaceutical wastewater
Photoelectrochemical oxidation	High controllability No oxidants required Multiple reactive species production Easy to recycle	High cost of electrode materials (such as conductive diamond electrodes[197], platinum, ruthenium, iridium) Electrode fouling Requires high electrical energy to generate reactive species (39.3–331.8 kWh m^{-3} $order^{-1}$)[198] Generation of secondary pollutants	Petroleum refinery wastewater; effluent from municipal wastewater treatment plants

ensure consistent pollutant–catalyst contact and effective mixing[131]. For large-scale applications, continuous-flow reactors equipped with UV lamps or solar collectors can improve throughput while reducing operational costs[130]. The degradation efficiency can also be improved using advanced control and monitoring systems, integrating real-time sensors for light intensity and pollutant concentration[132].

For large-scale applications, photo-assisted AOP technologies must consider practical environmental scenarios, as different photo-assisted AOPs offer distinct advantages and limitations (Table 1). The varying conditions of wastewater necessitate the selection of the most appropriate treatment approach (Supplementary Table 1).

Air purification

Air purification technologies include both recovery techniques (such as absorption, condensation and membrane separation) and destructive methods (such as thermal incineration and thermal catalytic oxidation)[133–135]. Destructive methods completely degrade organic pollutants (especially VOCs such as toluene and benzene) into small molecules such as CO_2 and water[136]. However, destructive methods generally require the application of external energy and/or catalysts to decompose pollutants into final products[137,138]. A typical process like thermal catalytic oxidation benefits from the introduction of renewable energy sources, such as solar energy, as an auxiliary energy source[135,139]. Solar energy can be directly converted into electrical, thermal and chemical energy via photo-assisted thermal (or photothermal) catalysis[140], which enables a more comprehensive exploitation of energy across the solar spectrum, encompassing extended wavelength ranges such as visible and infrared light. Therefore, energy-intensive thermal catalysis methods can benefit from light-induced heating effects or concentrated solar irradiation to attain elevated temperatures, which reduces the energy consumption of the system[141–143].

Photothermal catalytic processes can be generally classified into two categories[144,145]: photo-assisted thermal catalysis driven by external electric heating and auxiliary light, and photo-driven (photo)thermal catalysis obtaining energy from the solar spectrum (Fig. 5a). Photo-assisted thermal catalysis uses photochemical processes to enhance thermal reactions by introducing additional light into traditional thermal catalytic systems[146]. Photogenerated charge carriers and their derived oxidizing species boost the primary thermal oxidation process[140]. During photo-assisted thermal catalytic oxidation, light promotes the activation of reactants, improving the overall efficiency[140]. Additionally, the charge separation in the photocatalytic system can be accelerated by the presence of an external heat source[143]. The selection of a photo-assisted thermal catalysis process should consider the volume of pollutant gases (Supplementary Fig. 1).

Photo-induced (photo)thermal catalysis involves light as a heat source without relying on external heat[147]. Taking transition metal oxides as examples, the oxidation mechanism of VOCs follows the Mars–Van Krevelen mechanism[143]. Under light irradiation, the photothermal catalyst layer absorbs photons and converts solar energy into thermal energy through non-radiative relaxation, leading to a rapid increase in the layer temperature[138,148–150]. Then, the lattice oxygen in catalysts reacts with VOC molecules driven by the light-induced heat and is subsequently replenished by adsorbed oxygen species[151,152]. Additionally, transition metal oxide semiconductors can be excited by light to generate charge carriers, producing strong oxidative species (photogenerated holes, $^{\bullet}OH$ and $O_2^{\bullet-}$) that enhance VOC oxidation performance[153]. The high temperature of catalysts (generally above 200 °C) also aids the separation and mobility of charge carriers[143]. Moreover, light enhances the activation of lattice oxygen in transition metal oxides, thereby accelerating the reaction rate[143]. This approach uses the entire solar spectrum (200–2,500 nm) without the need for external electric heat sources, integrating the benefits of both photochemical and thermochemical pathways[145].

Photo-assisted thermal catalysis for air purification has advanced owing to its harnessing of sunlight and its superior catalytic efficiency compared with conventional thermal catalytic processes[154–156]. With the

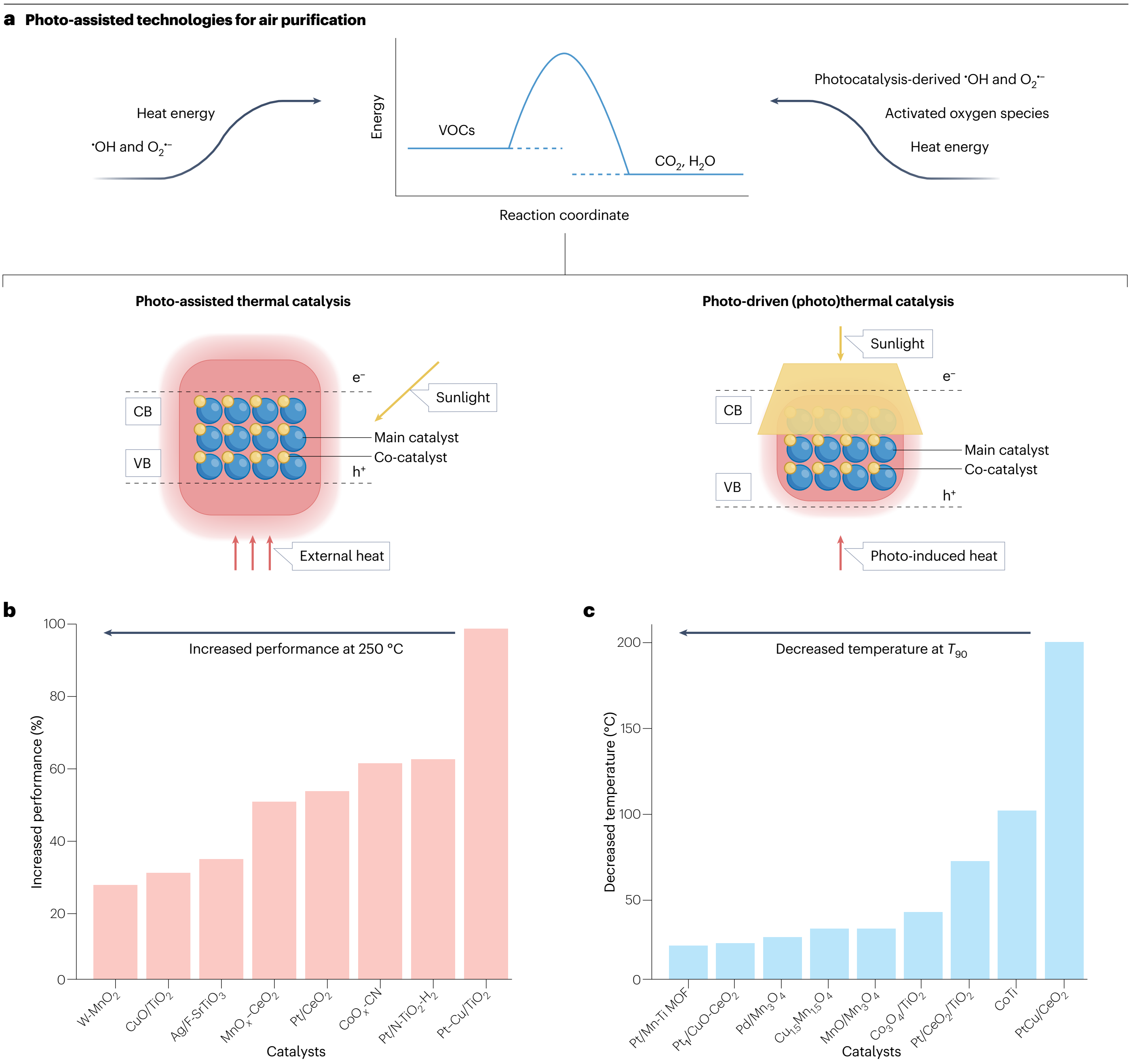

Fig. 5 | Photo-assisted technologies for air purification. Photo-assisted thermal catalysis for air treatment. **a**, Mechanisms of photo-assisted technologies for air purification. **b**, Improved performance of photothermal catalysis, compared with traditional thermal catalysis, supplied by electric heating at the reaction temperature of 250 °C for different catalysts. **c**, Decreased temperature to reach 90% of pollutant conversion (T_{90}) for different catalysts by photothermal catalysis driven with light irradiation and traditional thermal catalysis powered with electric heating. Data in Supplementary Table 2. CB, catalyst conduction band; VB, catalyst valence band; VOC, volatile organic compound.

assistance of light irradiation, the thermal catalytic reaction system performance — VOC conversion efficiency — can increase by at least 30%[146]. This increase is attributed to the enhanced activation of the reactants by photoexcited holes and the generated oxidative radicals[146]. Tailoring the microscopic structure of catalysts can help to enhance light-harvesting efficiency and catalytic activity[157–159]. The design criteria of photothermal catalysts typically aims to achieve comprehensive absorption across the solar spectrum, high photothermal conversion efficiency (>99%) and good reactivity and stability (longer than 100 h) towards targeted reactions[143].

Commonly used photothermal catalysts include supported precious metal catalysts (such as Au, Ag and Pt)[156,160,161], transition metal oxides (such as MnO_x and CoO_x)[147,162], plasmonic metals[138] and zeolites[163,164], many of which absorb light, making them suitable for photothermal catalytic VOC oxidation (Fig. 5b,c and Supplementary Table 2). Factors such as cost, reaction activity and operational stability are critical for the development and application of these catalysts[156]. For example, precious metal catalysts are efficient and thus appealing in industrial applications, but their high cost limits their widespread use[153]. Enhancing the activity of non-precious metal catalysts while reducing reliance on precious metals is crucial for the economic viability of photothermal catalytic air purification. Addressing stability and resistance to carbon deposition and poisoning by chlorine and sulfur is also essential for practical applications[165–167]. In industrial settings, the economic repercussions of catalyst poisoning and instability, which can lead to production halts, are often substantial[165]. Therefore, improving the resilience of catalysts to such issues is a key area of ongoing research and development.

Photo-assisted thermal catalysis for air purification remains largely confined to laboratory-scale experimentation and has not achieved large-scale applications[168]. However, compared with conventional thermal catalysis, laboratory-scale photothermal catalytic processes using artificial sunlight (xenon lamp) show some cost advantage. In some cases, the costs of photothermal reactions can be reduced by 40% compared with thermal catalysis, even though the use of simulated light sources requires additional energy input[169]. Moreover, the use of renewable solar energy could reduce the carbon emissions and simultaneously produce fuels such as methanol during the reaction process[170–172]. For large-scale applications, optimizing energy supply mechanisms and reactor configurations is important to achieve high temperatures for VOC degradation. One approach uses an electric heating furnace with a light window on its sidewall for light ingress[173]. Another approach uses a cylindrical stainless-steel model mimicking the design of a photocatalytic reactor, with light introduced from above through quartz glass[174]. Owing to the intermittent nature of solar irradiance, electron storage mechanisms within materials need to be investigated to enable reactions to continue in the absence of light.

The practical applications of photothermal catalytic oxidation of VOCs also focus on harnessing outdoor natural sunlight[175]. An all-quartz reactor was used outdoors for gas pollutant degradation under natural sunlight. Complete VOC conversion was achieved using a condenser lens under midday sunlight, although sensitivity to cloud cover was observed[176]. The development of photothermal catalytic systems under natural sunlight decreases the need for thermal sources (electrical energy supply) and thus reduces the overall cost[175].

Furthermore, in practical applications, various VOCs might be present in complex environments, such as high temperature (>250 °C) and high humidity (10–90%) conditions[177,178]. The combination of photothermal catalysis with multiple technologies demonstrates an effective way to further improve the efficiency of VOC elimination[179,180]. Combining photo-assisted catalytic technology with established adsorption, catalytic oxidation or plasma technologies might improve overall removal efficiencies while mitigating secondary pollution[175].

For real-world application of photo-assisted technologies for air purification, their sustainability should be assessed considering environmental, economic and social dimensions[181]. Traditional thermal catalysis relies on electric heating systems to raise the temperature of the entire system (200–1,200 °C)[182], leading to energy waste and low efficiency of heat utilization[181]. By contrast, photothermal catalytic VOC oxidation achieves precise local heating of active sites of catalysts with high heat utilization efficiency at lower reaction temperatures (room temperature to 400 °C)[168]. This method shows a similar or superior pollutant mineralization and is expected to reduce carbon deposition by-products compared with the conventional thermal catalytic oxidation process[183].

Like most chemical engineering systems, photo-assisted thermal catalytic oxidation of VOCs involves initial device costs (reactor construction and installation, catalyst preparation and startup expenses), operating costs (running and maintaining) and life-cycle costs[184–186]. The main cost can be attributed to the construction of the catalytic reaction system[185]. For photo-assisted air purification, a critical challenge is selecting catalysts with optimal spectral absorption characteristics and catalytic active components that have good photothermal activity, high stability and low cost[181]. When sunlight is the sole energy source, optimizing its utilization for powering reactions is required. Dependence on solar irradiance reduces electricity consumption, and over time the cost savings from harnessing light energy can offset the initial investment in the device[185].

Despite the various advantages of photo-assisted thermal technologies, their development faces some challenges. Photo-assisted thermal catalytic reactions involve both photochemical and thermochemical processes, complicating the differentiation between the roles and quantities of photoelectrons and hot electrons[181]. Conventional thermocouple-based temperature measurement methods provide insights only into the overall temperature of the catalytic bed, failing to capture the nuanced local temperature variations of nanoparticles[183]. Additionally, VOC oxidation reactions typically involve exothermic processes, and localized temperature spikes can induce structural alterations in the catalyst, diminishing removal efficiency, promoting undesired reduction reactions, and generating by-products[186]. Catalyst deactivation due to carbon deposition – a common issue in VOC oxidation reactions – also affects photothermal catalytic processes[167,187]. Assessments of VOC catalytic reactions often overlook the introduction of contaminants such as sulfur or chlorine, which are prevalent in actual operational environments and typically involve single-component reactants[165,166,188]. Consequently, the potential impact of sulfur, chlorine and composite pollutants (such as the mixture of benzene, toluene and chlorobenzene) on photothermal catalyst performance remains uncertain. Furthermore, given the predominantly unidirectional illumination of the catalyst bed, research on designing photothermal catalytic reactors and optimizing the catalyst stacking configuration to enhance light energy absorption is still lacking. Photothermal catalytic air purification remains predominantly at the laboratory scale. Enhancing our understanding of these aspects is vital for the successful implementation of photothermal catalytic technologies in real-world applications.

Summary and future perspectives

Photo-assisted technologies can be used to eliminate organic pollutants in water and air. By harnessing the power of solar energy, pollutant removal efficiency can be enhanced along with reduced energy consumption. Despite progress, there are still challenges to the large-scale application of these photo-assisted technologies for environmental remediation, such as limited efficiency of light utilization.

During wastewater treatment, the impurities in water can absorb or reflect light, which reduces the interaction between light and catalytic materials or oxidants such as H_2O_2 and O_3, thus diminishing the efficiency of photo-assisted AOPs. To address this challenge, designing reactors that minimize the need for deep light penetration, such as flat reactors, can enhance the effectiveness of photo-assisted technologies. Additionally, it is important to design advanced catalytic materials with high light absorption efficiency to use low-energy photons, such as visible or infrared light. Enhanced light absorption can be achieved through several strategies: selecting narrow-bandgap catalysts, introducing dopants or defects to create mid-gap states that narrow the bandgap of semiconductors, coating catalysts with substances that show localized surface plasmon resonance effects (such as plasmonic materials or carbon-based materials), using dye-sensitizers or quantum dots, integrating up-conversion materials to convert infrared light into UV or visible light, and creating nanostructured materials (such as nanorods, nanowires, photonic crystal structures and surface texturing). Improving light absorption will benefit the generation of ROS and increase the degradation efficiency. For air purification in office buildings, factories and homes, developing catalysts capable of harnessing indoor light could offer a pathway towards the practical implementation of photo-assisted technology for air purification systems[189].

The economic analysis of photo-assisted technologies has often been overlooked. Much of the existing research has been focused on operational expenses and energy consumption, such as the light sources, which are generally lower for photo-assisted technologies compared with traditional methods[121]. However, traditional methods benefit from established infrastructure and are easier to scale up[190], whereas the initial capital costs for implementing light-assisted technologies – including investments in photoreactors, light sources, catalysts and associated infrastructure – are seldom considered. High-quality light sources, effective and stable catalysts, and well-designed photoreactors are essential for achieving high environmental remediation efficiency[191]. Combining photo-assisted technologies with other wastewater treatment systems could reduce system costs. For instance, the total energy consumption associated with a solar photoelectro-Fenton process for the removal of organic pollutants in anaerobic digestion is US$1.4 per hour at current densities of 10 mA cm^{-2}, which is approximately one-tenth of the energy cost for a conventional activated sludge process[192] (US$10.64 per hour). Similarly, combining photo-Fenton or ozonation with a membrane system could reduce the operating costs of the oxidation process due to the decrease of the total treatment volume[193]. Therefore, integrating these technologies with existing systems shows potential for cost reduction and improved efficiency, potentially making them a viable option for large-scale environmental remediation.

Many of these technologies rely on catalysts made from rare or expensive materials such as noble metals. The extraction, processing and disposal of these materials can have a substantial environmental impact. Catalysts should be both economical and stable in the long term, and able to withstand prolonged exposure to light and contaminants without degrading. To enhance the sustainability of these processes, the development of new reaction systems is also essential. For instance, dual-functional photo(electro)catalytic processes that enable wastewater treatment while simultaneously recovering energy, such as by producing H_2 and H_2O_2, could be a strategy for the next-generation of photo-assisted water-treatment technologies[120]. A comprehensive life-cycle assessment – evaluating the entire process, from raw material extraction to end-of-life disposal – is crucial to verify the sustainability of these technologies. Such assessments are still lacking in the photo-assisted technologies field.

References

1. Shannon, M. A. et al. Science and technology for water purification in the coming decades. *Nature* **452**, 301–310 (2008).
2. Lin, J. et al. Environmental impacts and remediation of dye-containing wastewater. *Nat. Rev. Earth Environ.* **4**, 785–803 (2023).
3. Wei, S. et al. Self-carbon-thermal-reduction strategy for boosting the Fenton-like activity of single Fe-N_4 sites by carbon-defect engineering. *Nat. Commun.* **14**, 7549 (2023).
4. Hodges, B. C., Cates, E. L. & Kim, J.-H. Challenges and prospects of advanced oxidation water treatment processes using catalytic nanomaterials. *Nat. Nanotechnol.* **13**, 642–650 (2018).
5. He, F., Jeon, W. & Choi, W. Photocatalytic air purification mimicking the self-cleaning process of the atmosphere. *Nat. Commun.* **12**, 2528 (2021).
6. Weon, S., He, F. & Choi, W. Status and challenges in photocatalytic nanotechnology for cleaning air polluted with volatile organic compounds: visible light utilization and catalyst deactivation. *Environ. Sci. Nano* **6**, 3185–3214 (2019).
7. Khin, M. M., Nair, A. S., Babu, V. J., Murugan, R. & Ramakrishna, S. A review on nanomaterials for environmental remediation. *Energy Environ. Sci.* **5**, 8075–8109 (2012).
8. Zheng, L. et al. Mixed scaling patterns and mechanisms of high-pressure nanofiltration in hypersaline wastewater desalination. *Water Res.* **250**, 121023 (2024).
9. Yang, X., Sun, H., Li, G., An, T. & Choi, W. Fouling of TiO_2 induced by natural organic matters during photocatalytic water treatment: mechanisms and regeneration strategy. *Appl. Catal. B* **294**, 120252 (2021).
10. Le, N. T. H. et al. Freezing-enhanced non-radical oxidation of organic pollutants by peroxymonosulfate. *Chem. Eng. J.* **388**, 124226 (2020).
11. Weng, B., Lu, K.-Q., Tang, Z., Chen, H. M. & Xu, Y.-J. Stabilizing ultrasmall Au clusters for enhanced photoredox catalysis. *Nat. Commun.* **9**, 1543 (2018).
12. Su, Y. et al. Unveiling the function of oxygen vacancy on facet-dependent CeO_2 for the catalytic destruction of monochloromethane: guidance for industrial catalyst design. *Environ. Sci. Technol.* **58**, 8086–8095 (2024).
13. Su, Y. et al. Surface-phosphorylated ceria for chlorine-tolerance catalysis. *Environ. Sci. Technol.* **58**, 1369–1377 (2024).
14. Yuan, X. et al. Anti-poisoning mechanisms of Sb on vanadia-based catalysts for NOx and chlorobenzene multi-pollutant control. *Environ. Sci. Technol.* **57**, 10211–10220 (2023).
15. Su, Z. et al. Probing the actual role and activity of oxygen vacancies in toluene catalytic oxidation: evidence from in situ XPS/NEXAFS and DFT + *U* calculation. *ACS Catal.* **13**, 3444–3455 (2023).
16. Wang, B., Song, Z. & Sun, L. A review: comparison of multi-air-pollutant removal by advanced oxidation processes — industrial implementation for catalytic oxidation processes. *Chem. Eng. J.* **409**, 128136 (2021).
17. Adeleye, A. S. et al. Engineered nanomaterials for water treatment and remediation: costs, benefits, and applicability. *Chem. Eng. J.* **286**, 640–662 (2016).
18. Brillas, E. Solar photoelectro-Fenton: a very effective and cost-efficient electrochemical advanced oxidation process for the removal of organic pollutants from synthetic and real wastewaters. *Chemosphere* **327**, 138532 (2023).
19. Wang, D., Junker, A. L., Sillanpää, M., Jiang, Y. & Wei, Z. Photo-based advanced oxidation processes for zero pollution: where are we now? *Engineering* **23**, 19–23 (2023).
20. Dey, A. K., Mishra, S. R. & Ahmaruzzaman, M. Solar light-based advanced oxidation processes for degradation of methylene blue dye using novel Zn-modified CeO_2@biochar. *Environ. Sci. Pollut. Res.* **30**, 53887–53903 (2023).
21. Su, L., Wang, P., Ma, X., Wang, J. & Zhan, S. Regulating local electron density of iron single sites by introducing nitrogen vacancies for efficient photo-Fenton process. *Angew. Chem. Int. Ed.* **60**, 21261–21266 (2021).
22. Yang, Q. et al. Recent advances in photo-activated sulfate radical-advanced oxidation process (SR-AOP) for refractory organic pollutants removal in water. *Chem. Eng. J.* **378**, 122149 (2019).
23. Yang, J., Zhu, M. & Dionysiou, D. D. What is the role of light in persulfate-based advanced oxidation for water treatment? *Water Res.* **189**, 116627 (2021).
24. Weng, B., Qi, M.-Y., Han, C., Tang, Z.-R. & Xu, Y.-J. Photocorrosion inhibition of semiconductor-based photocatalysts: basic principle, current development, and future perspective. *ACS Catal.* **9**, 4642–4687 (2019).
25. Zhou, Q., Chen, Q., Tong, Y. & Wang, J. Light-induced ambient degradation of few-layer black phosphorus: mechanism and protection. *Angew. Chem. Int. Ed.* **55**, 11437–11441 (2016).
26. Bi, Z. et al. The generation and transformation mechanisms of reactive oxygen species in the environment and their implications for pollution control processes: a review. *Environ. Res.* **260**, 119592 (2024).
27. Chen, M. et al. Synthesis of carbon quantum dots decorating Bi_2MoO_6 microspherical heterostructure and its efficient photocatalytic degradation of antibiotic norfloxacin. *Chin. Chem. Lett.* **35**, 109336 (2024).
28. Oh, V. B.-Y., Ng, S.-F. & Ong, W.-J. Is photocatalytic hydrogen production sustainable? Assessing the potential environmental enhancement of photocatalytic technology against steam methane reforming and electrocatalysis. *J. Clean. Prod.* **379**, 134673 (2022).
29. Wu, F., Zhou, Z. & Hicks, A. L. Life cycle impact of titanium dioxide nanoparticle synthesis through physical, chemical, and biological routes. *Environ. Sci. Technol.* **53**, 4078–4087 (2019).
30. Zhang, X. et al. Nanoconfinement-triggered oligomerization pathway for efficient removal of phenolic pollutants via a Fenton-like reaction. *Nat. Commun.* **15**, 917 (2024).

31. Ghanbarzadeh Lak, M., Sabour, M. R., Ghafari, E. & Amiri, A. Energy consumption and relative efficiency improvement of photo-Fenton — optimization by RSM for landfill leachate treatment, a case study. *Waste Manage* **79**, 58–70 (2018).
32. Barndõk, H., Blanco, L., Hermosilla, D. & Blanco, Á. Heterogeneous photo-Fenton processes using zero valent iron microspheres for the treatment of wastewaters contaminated with 1,4-dioxane. *Chem. Eng. J.* **284**, 112–121 (2016).
33. Santos, L. V. de S., Meireles, A. M. & Lange, L. C. Degradation of antibiotics norfloxacin by Fenton, UV and UV/H_2O_2. *J. Environ. Manage.* **154**, 8–12 (2015).
34. Kang, W. et al. Photocatalytic ozonation of organic pollutants in wastewater using a flowing through reactor. *J. Hazard. Mater.* **405**, 124277 (2021).
35. Khaleel, G. F., Ismail, I. & Abbar, A. H. Application of solar photo-electro-Fenton technology to petroleum refinery wastewater degradation: optimization of operational parameters. *Heliyon* **9**, e15062 (2023).
36. Anipsitakis, G. P. & Dionysiou, D. D. Radical generation by the interaction of transition metals with common oxidants. *Environ. Sci. Technol.* **38**, 3705–3712 (2004).
37. De Laat, J. & Gallard, H. Catalytic decomposition of hydrogen peroxide by Fe(III) in homogeneous aqueous solution: mechanism and kinetic modeling. *Environ. Sci. Technol.* **33**, 2726–2732 (1999).
38. Feng, W. & Nansheng, D. Photochemistry of hydrolytic iron(III) species and photoinduced degradation of organic compounds. A minireview. *Chemosphere* **41**, 1137–1147 (2000).
39. Sun, M. et al. New insights into photo-Fenton chemistry: the overlooked role of excited iron^{III} species. *Environ. Sci. Technol.* **58**, 10817–10827 (2024).
40. Yang, X.-j., Xu, X.-m., Xu, J. & Han, Y.-f. Iron oxychloride (FeOCl): an efficient Fenton-like catalyst for producing hydroxyl radicals in degradation of organic contaminants. *J. Am. Chem. Soc.* **135**, 16058–16061 (2013).
41. Li, M. et al. Iron-organic frameworks as effective Fenton-like catalysts for peroxymonosulfate decomposition in advanced oxidation processes. *npj Clean Water* **6**, 37 (2023).
42. Wang, Y. et al. Comparison of Fenton, UV-Fenton and nano-Fe_3O_4 catalyzed UV-Fenton in degradation of phloroglucinol under neutral and alkaline conditions: role of complexation of Fe^{3+} with hydroxyl group in phloroglucinol. *Chem. Eng. J.* **313**, 938–945 (2017).
43. Zheng, J., Li, Y. & Zhang, S. Engineered nanoconfinement activates Fenton catalyst at neutral pH: mechanism and kinetics study. *Appl. Catal. B* **343**, 123555 (2024).
44. Clarizia, L., Russo, D., Di Somma, I., Marotta, R. & Andreozzi, R. Homogeneous photo-Fenton processes at near neutral pH: a review. *Appl. Catal. B* **209**, 358–371 (2017).
45. Zhu, Y. et al. Strategies for enhancing the heterogeneous Fenton catalytic reactivity: a review. *Appl. Catal. B* **255**, 117739 (2019).
46. Brillas, E. Fenton, photo-Fenton, electro-Fenton, and their combined treatments for the removal of insecticides from waters and soils. A review. *Sep. Purif. Technol.* **284**, 120290 (2022).
47. Heidari, Z., Pelalak, R. & Zhou, M. A critical review on the recent progress in application of electro-Fenton process for decontamination of wastewater at near-neutral pH. *Chem. Eng. J.* **474**, 145741 (2023).
48. Ahile, U. J., Wuana, R. A., Itodo, A. U., Sha'Ato, R. & Dantas, R. F. A review on the use of chelating agents as an alternative to promote photo-Fenton at neutral pH: current trends, knowledge gap and future studies. *Sci. Total Environ.* **710**, 134872 (2020).
49. Vallés, I. et al. On the relevant role of iron complexation for the performance of photo-Fenton process at mild pH: role of ring substitution in phenolic ligand and interaction with halides. *Appl. Catal. B* **331**, 122708 (2023).
50. Li, W.-Q. et al. Boosting photo-Fenton process enabled by ligand-to-cluster charge transfer excitations in iron-based metal organic framework. *Appl. Catal. B* **302**, 120882 (2022).
51. Rodríguez, M., Bussi, J. & Andrea De León, M. Application of pillared raw clay-base catalysts and natural solar radiation for water decontamination by the photo-Fenton process. *Sep. Purif. Technol.* **259**, 118167 (2021).
52. Wu, Q. et al. Visible-light-driven iron-based heterogeneous photo-Fenton catalysts for wastewater decontamination: a review of recent advances. *Chemosphere* **313**, 137509 (2023).
53. Deng, G. et al. Ferryl ion in the photo-Fenton process at acidic pH: occurrence, fate, and implications. *Environ. Sci. Technol.* **57**, 18586–18596 (2023).
54. Gao, X. et al. New insight into the mechanism of symmetry-breaking charge separation induced high-valent iron(IV) for highly efficient photodegradation of organic pollutants. *Appl. Catal. B* **321**, 122066 (2023).
55. Jiang, J. et al. Spin state-dependent in-situ photo-Fenton-like transformation from oxygen molecule towards singlet oxygen for selective water decontamination. *Water Res.* **244**, 120502 (2023).
56. Lian, Z. et al. Photo-self-Fenton reaction mediated by atomically dispersed Ag–Co photocatalysts toward efficient degradation of organic pollutants. *Angew. Chem. Int. Ed.* **63**, e202318927 (2024).
57. Ciggin, A. S., Sarica, E. S., Doğruel, S. & Orhon, D. Impact of ultrasonic pretreatment on Fenton-based oxidation of olive mill wastewater — towards a sustainable treatment scheme. *J. Clean. Prod.* **313**, 127948 (2021).
58. Ahmed, Y., Zhong, J., Yuan, Z. & Guo, J. Roles of reactive oxygen species in antibiotic resistant bacteria inactivation and micropollutant degradation in Fenton and photo-Fenton processes. *J. Hazard. Mater.* **430**, 128408 (2022).
59. Li, Y. & Cheng, H. Autocatalytic effect of in situ formed (hydro)quinone intermediates in Fenton and photo-Fenton degradation of non-phenolic aromatic pollutants and chemical kinetic modeling. *Chem. Eng. J.* **449**, 137812 (2022).
60. Zhou, Y., Yu, M., Zhang, Q., Sun, X. & Niu, J. Regulating electron distribution of $Fe/Ni\text{-}N_4P_2$ single sites for efficient photo-Fenton process. *J. Hazard. Mater.* **440**, 129724 (2022).
61. Gualda-Alonso, E. et al. Continuous solar photo-Fenton for wastewater reclamation in operational environment at demonstration scale. *J. Hazard. Mater.* **459**, 132101 (2023).
62. Silva, T. F. C. V., Fonseca, A., Saraiva, I., Boaventura, R. A. R. & Vilar, V. J. P. Scale-up and cost analysis of a photo-Fenton system for sanitary landfill leachate treatment. *Chem. Eng. J.* **283**, 76–88 (2016).
63. Miklos, D. B. et al. Evaluation of advanced oxidation processes for water and wastewater treatment — a critical review. *Water Res.* **139**, 118–131 (2018).
64. Gualda-Alonso, E. et al. Large-scale raceway pond reactor for CEC removal from municipal WWTP effluents by solar photo-Fenton. *Appl. Catal. B* **319**, 121908 (2022).
65. Gualda-Alonso, E., Soriano-Molina, P., García Sánchez, J. L., Casas López, J. L. & Sánchez Pérez, J. A. Mechanistic modeling of solar photo-Fenton with Fe^{3+}-NTA for microcontaminant removal. *Appl. Catal. B* **318**, 121795 (2022).
66. Duan, X., Sun, H. & Wang, S. Metal-free carbocatalysis in advanced oxidation reactions. *Acc. Chem. Res.* **51**, 678–687 (2018).
67. Han, B. et al. Microenvironment engineering of single-atom catalysts for persulfate-based advanced oxidation processes. *Chem. Eng. J.* **447**, 137551 (2022).
68. Lee, J., von Gunten, U. & Kim, J.-H. Persulfate-based advanced oxidation: critical assessment of opportunities and roadblocks. *Environ. Sci. Technol.* **54**, 3064–3081 (2020).
69. Zhang, S., Zheng, H. & Tratnyek, P. G. Advanced redox processes for sustainable water treatment. *Nat. Water* **1**, 666–681 (2023).
70. Guo, R. et al. Catalytic degradation of lomefloxacin by photo-assisted persulfate activation on natural hematite: performance and mechanism. *Chin. Chem. Lett.* **33**, 3809–3817 (2022).
71. He, S., Chen, Y., Li, X., Zeng, L. & Zhu, M. Heterogeneous photocatalytic activation of persulfate for the removal of organic contaminants in water: a critical review. *ACS EST. Eng* **2**, 527–546 (2022).
72. Zhang, Y.-J. et al. Simultaneous nanocatalytic surface activation of pollutants and oxidants for highly efficient water decontamination. *Nat. Commun.* **13**, 3005 (2022).
73. Yin, R. et al. Near-infrared light to heat conversion in peroxydisulfate activation with MoS_2: a new photo-activation process for water treatment. *Water Res.* **190**, 116720 (2021).
74. Weng, Z. et al. Site engineering of covalent organic frameworks for regulating peroxymonosulfate activation to generate singlet oxygen with 100% selectivity. *Angew. Chem. Int. Ed.* **62**, e202310934 (2023).
75. Yan, Y. et al. Merits and limitations of radical vs. nonradical pathways in persulfate-based advanced oxidation processes. *Environ. Sci. Technol.* **57**, 12153–12179 (2023).
76. Gan, P. et al. The degradation of municipal solid waste incineration leachate by UV/persulfate and UV/H_2O_2 processes: the different selectivity of $SO_4^{\cdot-}$ and •OH. *Chemosphere* **311**, 137009 (2023).
77. Guerra-Rodríguez, S. et al. Pilot-scale sulfate radical-based advanced oxidation for wastewater reuse: simultaneous disinfection, removal of contaminants of emerging concern, and antibiotic resistance genes. *Chem. Eng. J.* **477**, 146916 (2023).
78. Wang, Y., Duan, X., Xie, Y., Sun, H. & Wang, S. Nanocarbon-based catalytic ozonation for aqueous oxidation: engineering defects for active sites and tunable reaction pathways. *ACS Catal.* **10**, 13383–13414 (2020).
79. Mundy, B. et al. A review of ozone systems costs for municipal applications. Report by the municipal committee — IOA Pan American group. *Ozone Sci. Eng.* **40**, 266–274 (2018).
80. Zhou, H. & Smith, D. W. Ozone mass transfer in water and wastewater treatment: experimental observations using a 2D laser particle dynamics analyzer. *Water Res.* **34**, 909–921 (2000).
81. Lu, J. et al. Efficient mineralization of aqueous antibiotics by simultaneous catalytic ozonation and photocatalysis using $MgMnO_3$ as a bifunctional catalyst. *Chem. Eng. J.* **358**, 48–57 (2019).
82. Bessegato, G. G., Cardoso, J. C., da Silva, B. F. & Zanoni, M. V. B. Combination of photoelectrocatalysis and ozonation: a novel and powerful approach applied in Acid Yellow 1 mineralization. *Appl. Catal. B* **180**, 161–168 (2016).
83. Mehrjouei, M., Müller, S. & Möller, D. A review on photocatalytic ozonation used for the treatment of water and wastewater. *Chem. Eng. J.* **263**, 209–219 (2015).
84. Beltrán, F. J., Aguinaco, A., García-Araya, J. F. & Oropesa, A. Ozone and photocatalytic processes to remove the antibiotic sulfamethoxazole from water. *Water Res.* **42**, 3799–3808 (2008).
85. Yu, D., Li, L., Wu, M. & Crittenden, J. C. Enhanced photocatalytic ozonation of organic pollutants using an iron-based metal-organic framework. *Appl. Catal. B* **251**, 66–75 (2019).
86. Xiao, J., Xie, Y., Rabeah, J., Brückner, A. & Cao, H. Visible-light photocatalytic ozonation using graphitic C_3N_4 catalysts: a hydroxyl radical manufacturer for wastewater treatment. *Acc. Chem. Res.* **53**, 1024–1033 (2020).
87. Xiao, J. et al. Is C_3N_4 chemically stable toward reactive oxygen species in sunlight-driven water treatment? *Environ. Sci. Technol.* **51**, 13380–13387 (2017).
88. Lincho, J., Zaleska-Medynska, A., Martins, R. C. & Gomes, J. Nanostructured photocatalysts for the abatement of contaminants by photocatalysis and photocatalytic ozonation: an overview. *Sci. Total Environ.* **837**, 155776 (2022).
89. Ye, M., Chen, Z., Liu, X., Ben, Y. & Shen, J. Ozone enhanced activity of aqueous titanium dioxide suspensions for photodegradation of 4-chloronitrobenzene. *J. Hazard. Mater.* **167**, 1021–1027 (2009).
90. Andreozzi, R., Caprio, V., Insola, A. & Marotta, R. Advanced oxidation processes (AOP) for water purification and recovery. *Catal. Today* **53**, 51–59 (1999).
91. Mecha, A. C., Onyango, M. S., Ochieng, A. & Momba, M. N. B. Ultraviolet and solar photocatalytic ozonation of municipal wastewater: catalyst reuse, energy requirements and toxicity assessment. *Chemosphere* **186**, 669–676 (2017).

92. Mehrjouei, M., Müller, S. & Möller, D. Energy consumption of three different advanced oxidation methods for water treatment: a cost-effectiveness study. *J. Clean. Prod.* **65**, 178–183 (2014).
93. Mecha, A. C., Onyango, M. S., Ochieng, A., Fourie, C. J. S. & Momba, M. N. B. Synergistic effect of UV–vis and solar photocatalytic ozonation on the degradation of phenol in municipal wastewater: a comparative study. *J. Catal.* **341**, 116–125 (2016).
94. Moreira, F. C., Boaventura, R. A. R., Brillas, E. & Vilar, V. J. P. Electrochemical advanced oxidation processes: a review on their application to synthetic and real wastewaters. *Appl. Catal. B* **202**, 217–261 (2017).
95. Pandey, A. K. et al. Utilization of solar energy for wastewater treatment: challenges and progressive research trends. *J. Environ. Manage.* **297**, 113300 (2021).
96. Pham, C. V., Escalera-López, D., Mayrhofer, K., Cherevko, S. & Thiele, S. Essentials of high performance water electrolyzers — from catalyst layer materials to electrode engineering. *Adv. Energy Mater.* **11**, 2101998 (2021).
97. Valero, D., García-García, V., Expósito, E., Aldaz, A. & Montiel, V. Electrochemical treatment of wastewater from almond industry using DSA-type anodes: direct connection to a PV generator. *Sep. Purif. Technol.* **123**, 15–22 (2014).
98. Huang, Y. et al. The efficient abatement of contaminants of emerging concern by LED-UV$_{275nm}$/electrochemical chlorine for wastewater reuse: kinetics, degradation pathways, and cytotoxicity. *Chem. Eng. J.* **480**, 148032 (2024).
99. Otter, P. et al. Economic evaluation of water supply systems operated with solar-driven electro-chlorination in rural regions in Nepal, Egypt and Tanzania. *Water Res.* **187**, 116384 (2020).
100. Koiki, B. A. et al. Sulfate radical in (photo)electrochemical advanced oxidation processes for water treatment: a versatile approach. *J. Phys. Chem. Lett.* **14**, 8880–8889 (2023).
101. Son, A. et al. Persulfate enhanced photoelectrochemical oxidation of organic pollutants using self-doped TiO$_2$ nanotube arrays: effect of operating parameters and water matrix. *Water Res.* **191**, 116803 (2021).
102. García-Espinoza, J. D., Robles, I., Durán-Moreno, A. & Godínez, L. A. Photo-assisted electrochemical advanced oxidation processes for the disinfection of aqueous solutions: a review. *Chemosphere* **274**, 129957 (2021).
103. Vanags, M. et al. Sol-gel auto-combustion synthesis of Ca$_2$Fe$_2$O$_5$ brownmillerite nanopowders and thin films for advanced oxidation photoelectrochemical water treatment in visible light. *J. Environ. Chem. Eng.* **7**, 103224 (2019).
104. Yao, T., An, X., Han, H., Chen, J. Q. & Li, C. Photoelectrocatalytic materials for solar water splitting. *Adv. Energy Mater.* **8**, 1800210 (2018).
105. Lu, S. & Zhang, G. Recent advances on inactivation of waterborne pathogenic microorganisms by (photo) electrochemical oxidation processes: design and application strategies. *J. Hazard. Mater.* **431**, 128619 (2022).
106. Fekadu, S. et al. Treatment of healthcare wastewater using the peroxi-photoelectrocoagulation process: predictive models for COD, color removal and electrical energy consumption. *J. Water Process Eng.* **41**, 102068 (2021).
107. Rengifo-Herrera, J. A. & Pulgarin, C. Why five decades of massive research on heterogeneous photocatalysis, especially on TiO$_2$, has not yet driven to water disinfection and detoxification applications? Critical review of drawbacks and challenges. *Chem. Eng. J.* **477**, 146875 (2023).
108. Zeng, J. et al. Nanomaterials enabled photoelectrocatalysis for removing pollutants in the environment and food. *Trends Analyt. Chem.* **166**, 117187 (2023).
109. Song, Y., Zhang, J.-Y., Yang, J., Bo, T. & Ma, J.-F. Highly efficient photoelectrocatalytic oxidation of arsenic(III) with a polyoxometalate-thiacalix[4]arene-based metal–organic complex-modified bismuth vanadate photoanode. *Green Chem.* **26**, 3874–3883 (2024).
110. Jiao, Y., Ma, L., Tian, Y. & Zhou, M. A flow-through electro-Fenton process using modified activated carbon fiber cathode for orange II removal. *Chemosphere* **252**, 126483 (2020).
111. Zhou, W. et al. Rates of H$_2$O$_2$ electrogeneration by reduction of anodic O$_2$ at RVC foam cathodes in batch and flow-through cells. *Electrochim. Acta* **277**, 185–196 (2018).
112. Dang, Q. et al. Bias-free driven ion assisted photoelectrochemical system for sustainable wastewater treatment. *Nat. Commun.* **14**, 8413 (2023).
113. Divyapriya, G. et al. Treatment of real wastewater by photoelectrochemical methods: an overview. *Chemosphere* **276**, 130188 (2021).
114. Tedesco, G. C. & Moraes, P. B. Innovative design of a continuous flow photoelectrochemical reactor: hydraulic design, CFD simulation and prototyping. *J. Environ. Chem. Eng.* **9**, 105917 (2021).
115. Tao, Y. et al. Near-infrared-driven photoelectrocatalytic oxidation of urea on La-Ni-based perovskites. *Chem. Eng. J.* **446**, 137240 (2022).
116. Vivar, M., Skryabin, I., Everett, V. & Blakers, A. A concept for a hybrid solar water purification and photovoltaic system. *Sol. Energy Mater. Sol. Cell* **94**, 1772–1782 (2010).
117. Sboui, M. et al. Fabrication of electrically conductive TiO$_2$/PANI/PVDF composite membranes for simultaneous photoelectrocatalysis and microfiltration of azo dye from wastewater. *Appl. Catal. A* **644**, 118837 (2022).
118. Garg, R. et al. Sputtering thin films: materials, applications, challenges and future directions. *Adv. Colloid Interface Sci.* **330**, 103203 (2024).
119. Noked, M. et al. Electrochemical thin layers in nanostructures for energy storage. *Acc. Chem. Res.* **49**, 2336–2346 (2016).
120. Jeon, T. H., Koo, M. S., Kim, H. & Choi, W. Dual-functional photocatalytic and photoelectrocatalytic systems for energy- and resource-recovering water treatment. *ACS Catal.* **8**, 11542–11563 (2018).
121. Garza-Campos, B. et al. Salicylic acid degradation by advanced oxidation processes. Coupling of solar photoelectro-Fenton and solar heterogeneous photocatalysis. *J. Hazard. Mater.* **319**, 34–42 (2016).
122. Wang, Y. et al. Efficient photo-electro-Fenton catalysis of perfluorooctanoic acid with MOFs based 2D CoFe nanosheets: oxygen vacancy-mediated adsorption and mineralization ability. *Chem. Eng. J.* **483**, 149385 (2024).
123. Marinho, B. A. et al. Photocatalytic, electrocatalytic and photoelectrocatalytic degradation of pharmaceuticals in aqueous media: analytical methods, mechanisms, simulations, catalysts and reactors. *J. Clean. Prod.* **343**, 131061 (2022).
124. Zheng, J., Zhang, P., Li, X., Ge, L. & Niu, J. Insight into typical photo-assisted AOPs for the degradation of antibiotic micropollutants: mechanisms and research gaps. *Chemosphere* **343**, 140211 (2023).
125. Braham, R. J. & Harris, A. T. Review of major design and scale-up considerations for solar photocatalytic reactors. *Ind. Eng. Chem. Res.* **48**, 8890–8905 (2009).
126. Salazar, L. M., Grisales, C. M. & Garcia, D. P. How does intensification influence the operational and environmental performance of photo-Fenton processes at acidic and circumneutral pH. *Environ. Sci. Pollut. Res.* **26**, 4367–4380 (2019).
127. Meng, T., Sun, W., Su, X. & Sun, P. The optimal dose of oxidants in UV-based advanced oxidation processes with respect to primary radical concentrations. *Water Res.* **206**, 117738 (2021).
128. Xu, S.-L. et al. Expanding the pH range of Fenton-like reactions for pollutant degradation: the impact of acidic microenvironments. *Water Res.* **270**, 122851 (2025).
129. Wang, Y. et al. Enhanced orange II removal using Fe/Mn/Mg$_2$-LDH activated peroxymonosulfate: synergistic radical oxidation and adsorption. *Catalysts* **14**, 380 (2024).
130. Binjhade, R., Mondal, R. & Mondal, S. Continuous photocatalytic reactor: critical review on the design and performance. *J. Environ. Chem. Eng.* **10**, 107746 (2022).
131. Grčić, I. & Li Puma, G. Six-flux absorption-scattering models for photocatalysis under wide-spectrum irradiation sources in annular and flat reactors using catalysts with different optical properties. *Appl. Catal. B* **211**, 222–234 (2017).
132. Wu, Z. et al. In situ infared optical fiber sensor monitoring reactants and products changes during photocatalytic reaction. *Anal. Chem.* **97**, 1229–1235 (2025).
133. Li, S., Lin, Y., Liu, G. & Shi, C. Research status of volatile organic compound (VOC) removal technology and prospect of new strategies: a review. *Environ. Sci. Process. Impacts* **25**, 727–740 (2023).
134. He, C. et al. Recent advances in the catalytic oxidation of volatile organic compounds: a review based on pollutant sorts and sources. *Chem. Rev.* **119**, 4471–4568 (2019).
135. Zhang, K. et al. Research progress of a composite metal oxide catalyst for VOC degradation. *Environ. Sci. Technol.* **56**, 9220–9236 (2022).
136. Yang, Y. et al. Recent advancement and future challenges of photothermal catalysis for VOCs elimination: from catalyst design to applications. *Green Energy Env.* **8**, 654–672 (2023).
137. Jiang, C. et al. Modifying defect states in CeO$_2$ by Fe doping: a strategy for low-temperature catalytic oxidation of toluene with sunlight. *J. Hazard. Mater.* **390**, 122182 (2020).
138. Sun, P. et al. Efficiently photothermal conversion in a MnOx-based monolithic photothermocatalyst for gaseous formaldehyde elimination. *Chin. Chem. Lett.* **33**, 2564–2568 (2022).
139. Shan, C. et al. Recent advances of VOCs catalytic oxidation over spinel oxides: catalyst design and reaction mechanism. *Environ. Sci. Technol.* **57**, 9495–9514 (2023).
140. Li, J.-J. et al. Efficient infrared light promoted degradation of volatile organic compounds over photo-thermal responsive Pt–rGO–TiO$_2$ composites. *Appl. Catal. B* **233**, 260–271 (2018).
141. Hong, J. et al. Photothermal chemistry based on solar energy: from synergistic effects to practical applications. *Adv. Sci.* **9**, 2103926 (2022).
142. Ren, Y. et al. Concentrated solar CO$_2$ reduction in H$_2$O vapour with >1% energy conversion efficiency. *Nat. Commun.* **15**, 4675 (2024).
143. Li, J., Lv, X., Weng, B., Roeffaers, M. B. J. & Jia, H. Engineering light propagation for synergetic photo- and thermocatalysis toward volatile organic compounds elimination. *Chem. Eng. J.* **461**, 142022 (2023).
144. Kennedy, J. C. & Datye, A. K. Photothermal heterogeneous oxidation of ethanol over Pt/TiO$_2$. *J. Catal.* **179**, 375–389 (1998).
145. Zhang, M. et al. In situ construction of manganese oxide photothermocatalysts for the deep removal of toluene by highly utilizing sunlight energy. *Environ. Sci. Technol.* **57**, 4286–4297 (2023).
146. Ma, J., Wang, J. & Dang, Y. Photo-assisted oxidation of gaseous benzene on tungsten-doped MnO$_2$ at lower temperature. *Chem. Eng. J.* **388**, 124387 (2020).
147. Yu, X., Zhao, C., Yang, L., Zhang, J. & Chen, C. Photothermal catalytic oxidation of toluene over the Pt–Mn$_2$O$_3$/CN nanocomposite catalyst. *EES Catal.* **2**, 811–822 (2024).
148. Wu, P., Jin, X., Qiu, Y. & Ye, D. Recent progress of thermocatalytic and photo/thermocatalytic oxidation for VOCs purification over manganese-based oxide catalysts. *Environ. Sci. Technol.* **55**, 4268–4286 (2021).
149. Mateo, D., Cerrillo, J. L., Durini, S. & Gascon, J. Fundamentals and applications of photo-thermal catalysis. *Chem. Soc. Rev.* **50**, 2173–2210 (2021).
150. Agbovhimen Elimian, E., Zhang, M., Sun, Y., He, J. & Jia, H. Harnessing solar energy towards synergistic photothermal catalytic oxidation of volatile organic compounds. *Sol. RRL* **7**, 2300238 (2023).
151. Shan, C. et al. Acid etching-induced in situ growth of λ-MnO$_2$ over CoMn spinel for low-temperature volatile organic compound oxidation. *Environ. Sci. Technol.* **56**, 10381–10390 (2022).
152. Ma, Y. et al. Understanding the different roles of adsorbed oxygen and lattice oxygen species in the distinct catalytic performance of metal oxides for *o*-xylene oxidation. *ACS Catal.* **14**, 16624–16638 (2024).
153. Wang, H. et al. Boosting photothermocatalytic oxidation of toluene over Pt/N-TiO$_2$: the gear effect of light and heat. *Environ. Sci. Technol.* **58**, 7662–7671 (2024).

154. Wang, X. et al. Electro-assisted photothermal synergy for removal of volatile organic compounds over Au single atoms anchored TiO_2 nanotubes. *Appl. Catal. B* **358**, 124338 (2024).
155. Ren, L., Yang, X., Sun, X. & Yuan, Y. Synchronizing efficient purification of VOCs in durable solar water evaporation over a highly stable Cu/$W_{18}O_{49}$@graphene material. *Nano Lett.* **24**, 715–723 (2024).
156. Cui, X. et al. Photothermal nanomaterials: a powerful light-to-heat converter. *Chem. Rev.* **123**, 6891–6952 (2023).
157. Li, Y. et al. Efficient photothermal catalytic oxidation enabled by three-dimensional nanochannel substrates. *Environ. Sci. Technol.* **58**, 5153–5161 (2024).
158. Leung, S.-F. et al. Efficient photon capturing with ordered three-dimensional nanowell arrays. *Nano Lett.* **12**, 3682–3689 (2012).
159. Wang, F. et al. Manganese oxides with rod-, wire-, tube-, and flower-like morphologies: highly effective catalysts for the removal of toluene. *Environ. Sci. Technol.* **46**, 4034–4041 (2012).
160. Jiang, D., Wang, W., Sun, S., Zhang, L. & Zheng, Y. Equilibrating the plasmonic and catalytic roles of metallic nanostructures in photocatalytic oxidation over Au-modified CeO_2. *ACS Catal.* **5**, 613–621 (2015).
161. Žerjav, G. et al. Photo, thermal and photothermal activity of TiO_2 supported Pt catalysts for plasmon-driven environmental applications. *J. Environ. Chem. Eng.* **11**, 110209 (2023).
162. Zhao, J. et al. Interface engineering of Mn_3O_4/Co_3O_4 S-scheme heterojunctions to enhance the photothermal catalytic degradation of toluene. *J. Hazard. Mater.* **452**, 131249 (2023).
163. Wang, Z.-Y. et al. MXene/CdS photothermal–photocatalytic hydrogels for efficient solar water evaporation and synergistic degradation of VOC. *J. Mater. Chem. A* **12**, 10991–11003 (2024).
164. Elimian, E. A. et al. Construction of Pt-mTiO_2/USY multifunctional catalyst enriched with oxygen vacancies for the enhanced light-driven photothermocatalytic degradation of toluene. *Appl. Catal. B* **307**, 121203 (2022).
165. Bi, F. et al. Chlorine-coordinated Pd single atom enhanced the chlorine resistance for volatile organic compound degradation: mechanism study. *Environ. Sci. Technol.* **56**, 17321–17330 (2022).
166. Wang, Z. et al. Simulated solar light driven photothermal catalytic purification of toluene over iron oxide supported single atom Pt catalyst. *Appl. Catal. B* **298**, 120612 (2021).
167. Kong, J., Xiang, Z., Li, G. & An, T. Introduce oxygen vacancies into CeO_2 catalyst for enhanced coke resistance during photothermocatalytic oxidation of typical VOCs. *Appl. Catal. B* **269**, 118755 (2020).
168. Wei, L., Yu, C., Yang, K., Fan, Q. & Ji, H. Recent advances in VOCs and CO removal via photothermal synergistic catalysis. *Chin. J. Catal.* **42**, 1078–1095 (2021).
169. Ding, X., Liu, W., Zhao, J., Wang, L. & Zou, Z. Photothermal CO_2 catalysis toward the synthesis of solar fuel: from material and reactor engineering to techno-economic analysis. *Adv. Mater.* **37**, e2312093 (2025).
170. Yu, X. et al. Advances in photothermal catalysis for air pollutants. *Chem. Eng. J.* **486**, 150192 (2024).
171. Tackett, B. M., Gomez, E. & Chen, J. G. Net reduction of CO_2 via its thermocatalytic and electrocatalytic transformation reactions in standard and hybrid processes. *Nat. Catal.* **2**, 381–386 (2019).
172. Wang, S. et al. Grave-to-cradle upcycling of Ni from electroplating wastewater to photothermal CO_2 catalysis. *Nat. Commun.* **13**, 5305 (2022).
173. Zeng, M. et al. Synergetic effect between photocatalysis on TiO_2 and thermocatalysis on CeO_2 for gas-phase oxidation of benzene on TiO_2/CeO_2 nanocomposites. *ACS Catal.* **5**, 3278–3286 (2015).
174. Song, C. et al. Volatile-organic-compound-intercepting solar distillation enabled by a photothermal/photocatalytic nanofibrous membrane with dual-scale pores. *Environ. Sci. Technol.* **54**, 9025–9033 (2020).
175. Song, C., Wang, Z., Yin, Z., Xiao, D. & Ma, D. Principles and applications of photothermal catalysis. *Chem. Catal.* **2**, 52–83 (2022).
176. Li, J. et al. Convergent ambient sunlight-powered multifunctional catalysis for toluene abatement over in situ exsolution of Mn_3O_4 on perovskite parent. *Chem. Eng. J.* **412**, 128560 (2021).
177. Wang, H. et al. A review of whole-process control of industrial volatile organic compounds in China. *J. Environ. Sci.* **123**, 127–139 (2023).
178. Wang, R. et al. Emission characteristics and reactivity of volatile organic compounds from typical high-energy-consuming industries in North China. *Sci. Total Environ.* **809**, 151134 (2022).
179. Guaitella, O., Thevenet, F., Puzenat, E., Guillard, C. & Rousseau, A. C_2H_2 oxidation by plasma/TiO_2 combination: influence of the porosity, and photocatalytic mechanisms under plasma exposure. *Appl. Catal. B* **80**, 296–305 (2008).
180. Taranto, J., Frochot, D. & Pichat, P. Combining cold plasma and TiO_2 photocatalysis to purify gaseous effluents: a preliminary study using methanol-contaminated air. *Ind. Eng. Chem. Res.* **46**, 7611–7614 (2007).
181. Ma, R., Sun, J., Li, D. H. & Wei, J. J. Review of synergistic photo-thermo-catalysis: mechanisms, materials and applications. *Int. J. Hydrog. Energy* **45**, 30288–30324 (2020).
182. Wang, S., Ang, H. M. & Tade, M. O. Volatile organic compounds in indoor environment and photocatalytic oxidation: state of the art. *Environ. Int.* **33**, 694–705 (2007).
183. Nair, V., Muñoz-Batista, M. J., Fernández-García, M., Luque, R. & Colmenares, J. C. Thermo-photocatalysis: environmental and energy applications. *ChemSusChem* **12**, 2098–2116 (2019).
184. Zhang, Y. et al. Photocatalytic oxidation for volatile organic compounds elimination: from fundamental research to practical applications. *Environ. Sci. Technol.* **56**, 16582–16601 (2022).
185. Tomatis, M. et al. Removal of VOCs from waste gases using various thermal oxidizers: a comparative study based on life cycle assessment and cost analysis in China. *J. Clean. Prod.* **233**, 808–818 (2019).
186. Baskaran, D., Dhamodharan, D., Behera, U. S. & Byun, H.-S. A comprehensive review and perspective research in technology integration for the treatment of gaseous volatile organic compounds. *Environ. Res.* **251**, 118472 (2024).
187. Kong, J. et al. The synergic degradation mechanism and photothermocatalytic mineralization of typical VOCs over PtCu/CeO_2 ordered porous catalysts under simulated solar irradiation. *J. Catal.* **370**, 88–96 (2019).
188. Zeng, Y., Zhong, J., Feng, F., Ye, D. & Hu, Y. Synergistic photothermal catalytic oxidation of methanol and toluene mixture over Co-MOFs-derived catalyst: interfacial and promotion effects. *Chem. Eng. J.* **485**, 149720 (2024).
189. Sun, H. et al. Room-light-induced indoor air purification using an efficient Pt/N-TiO_2 photocatalyst. *Appl. Catal. B* **108–109**, 127–133 (2011).
190. Lu, H. et al. Pilot-scale and large-scale Fenton-like applications with nano-metal catalysts: from catalytic modules to scale-up applications. *Water Res.* **266**, 122425 (2024).
191. Boyjoo, Y., Sun, H., Liu, J., Pareek, V. K. & Wang, S. A review on photocatalysis for air treatment: from catalyst development to reactor design. *Chem. Eng. J.* **310**, 537–559 (2017).
192. Vidal, J., Carvajal, A., Huiliñir, C. & Salazar, R. Slaughterhouse wastewater treatment by a combined anaerobic digestion/solar photoelectro-Fenton process performed in semicontinuous operation. *Chem. Eng. J.* **378**, 122097 (2019).
193. Miralles-Cuevas, S. et al. Is the combination of nanofiltration membranes and AOPs for removing microcontaminants cost effective in real municipal wastewater effluents? *Environ. Sci. Water Res.* **2**, 511–520 (2016).
194. Rueda-Márquez, J. J., Levchuk, I., Manzano, M. & Sillanpää, M. Toxicity reduction of industrial and municipal wastewater by advanced oxidation processes (photo-Fenton, UVC/H_2O_2, electro-Fenton and galvanic Fenton): a review. *Catalysts* **10**, 612 (2020).
195. Nöthe, T., Fahlenkamp, H. & Sonntag, C. V. Ozonation of wastewater: rate of ozone consumption and hydroxyl radical yield. *Environ. Sci. Technol.* **43**, 5990–5995 (2009).
196. Mehralipour, J., Akbari, H., Adibzadeh, A. & Akbari, H. Tocilizumab degradation via photo-catalytic ozonation process from aqueous. *Sci. Rep.* **13**, 22402 (2023).
197. Radjenovic, J. & Sedlak, D. L. Challenges and opportunities for electrochemical processes as next-generation technologies for the treatment of contaminated water. *Environ. Sci. Technol.* **49**, 11292–11302 (2015).
198. Lanzarini-Lopes, M., Garcia-Segura, S., Hristovski, K. & Westerhoff, P. Electrical energy per order and current efficiency for electrochemical oxidation of *p*-chlorobenzoic acid with boron-doped diamond anode. *Chemosphere* **188**, 304–311 (2017).

Acknowledgements

The authors thank the National Key Research & Development Program of China (2021YFA1202700, 2022YFB3504203), the Youth Innovation Promotion Association of CAS support to J.X. (2022308) and J.Y. (2023320), the National Natural Science Foundation of China (22376193) and the Australian Research Council (FL230100178). J.H. and M.R. acknowledge financial support from the Research Foundation-Flanders (FWO, grant no. G0983.19N, G0F2322N, VS06523N) and Interne Fondsen KU Leuven through project C3/20/067 and CELSA/21/016. J.H. acknowledges the Flemish government through long-term structural funding Methusalem (CASAS2, Meth/15/04) and the Moonshot cSBO project P2C (HBC.2019.0108). The authors used ChatGPT with GPT-4 from OpenAI for language editing of earlier drafts of this manuscript.

Author contributions

All authors contributed substantially to discussion of the content, wrote the article and reviewed and/or edited the manuscript before submission.

Competing interests

The authors declare no competing interests.

Additional information

Supplementary information The online version contains supplementary material available at https://doi.org/10.1038/s44359-025-00037-1.

Peer review information *Nature Reviews Clean Technology* thanks M. Ateia, who co-reviewed with A. Butzlaff; L. Yang; and the other, anonymous, reviewer(s) for their contribution to the peer review of this work.