

Views & Comments

Photo-Based Advanced Oxidation Processes for Zero Pollution: Where Are We Now?



Dawei Wang^a, Allyson L. Junker^b, Mika Sillanpää^b, Yilan Jiang^a, Zongsu Wei^b

^a Key Laboratory of Integrated Regulation and Resource Development on Shallow Lake of Ministry of Education, College of Environment, Hohai University, Nanjing 210098, China
^b Centre for Water Technology (WATEC) & Department of Biological and Chemical Engineering, Aarhus University, Aarhus 8000, Denmark

1. Introduction

There is a pressing need to transition into a sustainable society, committed to achieving zero pollution. Water, humanity's most precious resource, can galvanize the environmental, social, and economic transformations called for in the European Union (EU) Green Deal. Improved water use and protection are essential components for addressing the global climate and biodiversity crises. To achieve the goal of zero pollution, investment is required and specific policies need to be implemented to address certain contaminants of emerging concern (CECs), such as endocrine-disrupting chemicals, pharmaceuticals, and microplastics; this is particularly pertinent given that conventional wastewater treatment is ineffective in dealing with these pollutants [1–4]. As such, innovative solutions that facilitate the transition into processes with zero pollution discharges are highly desirable.

Among the various solutions, photo-based advanced oxidation processes (photo-AOPs), which are able to break down trace CECs, have attracted considerable research attention, as reflected by the plethora of studies in the last decade (Fig. 1). Despite the advantages of AOPs and promising technological advances in the field, large scale applications remain limited. Moreover, even at a fundamental level, the understanding of oxidation reaction pathways, specific roles of different radical species, and surface catalytic reactivities is still nascent. Therefore, further research is required to determine the role of photo-AOPs in the elimination of CECs from water. Given these considerations, it is necessary to identify both the current status of AOP research as well as research gaps and future applications. Herein, we identify and discuss the feasibility of wider photo-AOP applications as state-of-the-art solutions to provide safe, clean, and affordable water in the context of a zero-pollution strategy.

2. Current utility of photo-AOPs

Various AOPs used in wastewater treatment have been integrated with artificial or natural light sources and have been of research interest for decades (Fig. 2). AOPs previously utilized include the use of photo-hydrogen peroxide (H_2O_2), -Fenton, -chlorine, -persulfate ($\text{S}_2\text{O}_8^{2-}$), -ozone (O_3), and -catalysis systems.

The **photo- H_2O_2** AOP, typically referred to as ultraviolet (UV)- H_2O_2 , is a conventional AOP that relies on H_2O_2 photolysis

to generate strong and non-selective oxidants, namely hydroxyl radicals ($\cdot\text{OH}$). UV- H_2O_2 has been widely studied since the late 1970s, given its ability to degrade trace organic chemicals [5]. However, due to its low absorption coefficient and scavenging effect for $\cdot\text{OH}$, additional H_2O_2 is inevitably required during the process, thus decreasing the process efficiency [6]. The $\cdot\text{OH}$ quenching and light-shielding effects of the water matrix also necessitate excess dosing. As such, even with excess H_2O_2 , the UV- H_2O_2 process generates an $\cdot\text{OH}$ concentration with a range of only 10^{-13} – 10^{-12} mol·L⁻¹ in pure water [7]. Typically, only 5%–10% of the H_2O_2 is consumed for water treatment purposes [8], with the remaining H_2O_2 needs to be removed prior to effluent discharge. With the goal of zero pollution discharges, there is a risk that even greater quantities of excess H_2O_2 will be needed to completely mineralize CECs.

The **photo-Fenton** AOP expands on the typical Fenton process and addresses some of its inherent challenges, such as its highly acidic environment, large reagent consumption, and ferric sludge production [9]. The addition of photons to Fenton AOPs accelerates the production of $\cdot\text{OH}$ through the photolysis of Fe(III) hydroxo-complexes, which simultaneously regenerates Fe(II), thereby

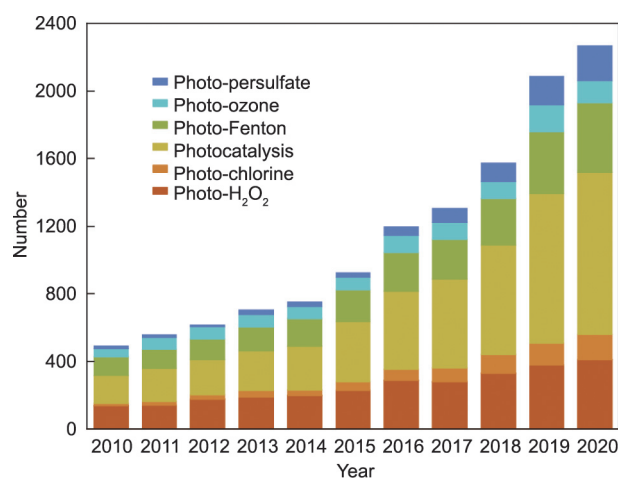


Fig. 1. Publication trends in photo-based AOP research (data collected from Web of Science®).

reducing reagent consumption. To address ferric sludge production, heterogeneous photo-Fenton AOPs using zero-valent iron, iron oxides, and composite materials have been developed [10]. However, metal leaching beyond the optimal pH range (typically < 4) leads to decreased catalytic performance and an increased H_2O_2 dose requirement. Hence, photo-Fenton AOPs are not currently cost-effective in treating large-volume effluents in the context of zero pollution [11].

The **photo-chlorine** AOP has been explored as an emerging AOP since the excessive consumption of chlorine in swimming pools under sunlight was observed in the 1980s [12]. Photo-chlorine, which typically takes the form of UV-chlorine, produces $\cdot OH$ and $Cl\cdot$ as the primary radicals through the photolysis of $HOCl$ and OCl^- [13]. The concentration of $\cdot OH$ is one or two orders of magnitude higher than that of $Cl\cdot$ because of the reactions between $Cl\cdot$ and H_2O or OH^- . Secondary radicals, including $Cl_2^{\cdot-}$ and $ClO\cdot$, can also be produced during this process. Compared to $\cdot OH$, reactive chlorine species (RCSs) are more selective and thus less sensitive to the scavenging effects of the water matrix [13]. It is also noteworthy that the irradiated light wavelength can alter the radical species [14]. Photons with wavelengths > 300 nm can produce ground-state oxygen atoms, which are also expected to degrade organic compounds via the decomposition of OCl^- [15].

$HOCl$ and OCl^- can only be activated by UV light because their absorption lies in the UV range. However, the activation wavelength can extend into the visible range by incorporating heterogeneous catalysts [16]. As an emerging AOP, UV-chlorine is typically comparable to UV- H_2O_2 in terms of target pollutant removal, energy consumption, and by-product formation. However, contrasting research findings are common, likely as a result of different target pollutant properties and water matrices [17,18].

The **photo-persulfate** AOP is a hybrid persulfate-based AOP; here, activated persulfate ($S_2O_8^{2-}$) produces sulfate radicals ($SO_4^{\cdot-}$), which are strong single-electron oxidants. Certain commonalities can be seen with Fenton reactions, as transition metals in combination with photosensitized dyes, ligands, and catalysts are used to activate persulfate [19]. Thus, persulfate-based AOPs are occasionally referred to as Fenton-like AOPs [20]. $SO_4^{\cdot-}$ has a higher redox potential, longer half-life, and wider pH range compared to the major reactive oxygen species (ROS) in Fenton processes (i.e., $\cdot OH$). In addition, $SO_4^{\cdot-}$ is more selective, minimizing

the loss of oxidation power due to the scavenging effects of the water matrix [21].

Photo-persulfate AOPs perform better than their non-irradiated counterparts and have seen two decades of research [22]. Moreover, the research interest in photo-persulfate AOPs has recently intensified. Various oxidants and oxidation mechanisms give persulfate-based AOPs a unique advantage, as they can degrade persistent CECs that are inert to $\cdot OH$ (e.g., per- and polyfluoroalkyl substances (PFAS)) [23–26]. However, homogeneous systems produce metallic sludge (e.g., Fe), while heterogeneous systems could be inactivated by the sulfate layer that gradually forms on the catalyst surface [27].

The **photo- O_3** AOP is an expanded form of O_3 -based AOPs. Given that dissolved O_3 has an absorption peak at 260 nm and can be photolyzed into H_2O_2 , the UV- O_3 AOP has been developed to decompose O_3 into $\cdot OH$, allowing further degradation of target pollutants. Similar to other AOPs, homo- or heterogeneous catalysts based on transition metals can be added to the system, to accelerate the overall oxidation reaction.

The O_3 injection rate and pH significantly affect the performance of the photo- O_3 AOP by determining the O_3 solubility and subsequent $\cdot OH$ generation [28]. Although photo- O_3 AOPs were originally developed for wastewater treatment in the 1970s [29], their full-scale application remains limited, owing to high capital and operational costs. A few recent studies have attempted to improve O_3 utilization efficiency by decreasing the injected O_3 gas bubble diameters [30]; this is an expensive operation, particularly in the context of targeting complete CEC mineralization.

Photocatalytic AOPs use illuminated heterogeneous catalysts and produce charge carriers, which in turn react with the water to generate ROS (e.g., $\cdot OH$). In some cases, the charge carriers (i.e., both electrons and holes) participate directly in redox reactions with pollutants. Photocatalysis has been of environmental interest since 1985, when the photocatalytic degradation of chloroform was first investigated [31]. Given that engineered photocatalysts may degrade CECs, a strong focus has been placed on designing novel catalysts to allow higher pollutant degradation efficiency through the improvement of charge carrier separation and manipulation of energy band gaps [32–34].

Despite reports of promising performance, photocatalytic AOPs have been criticized for their low adoption rates and applicability

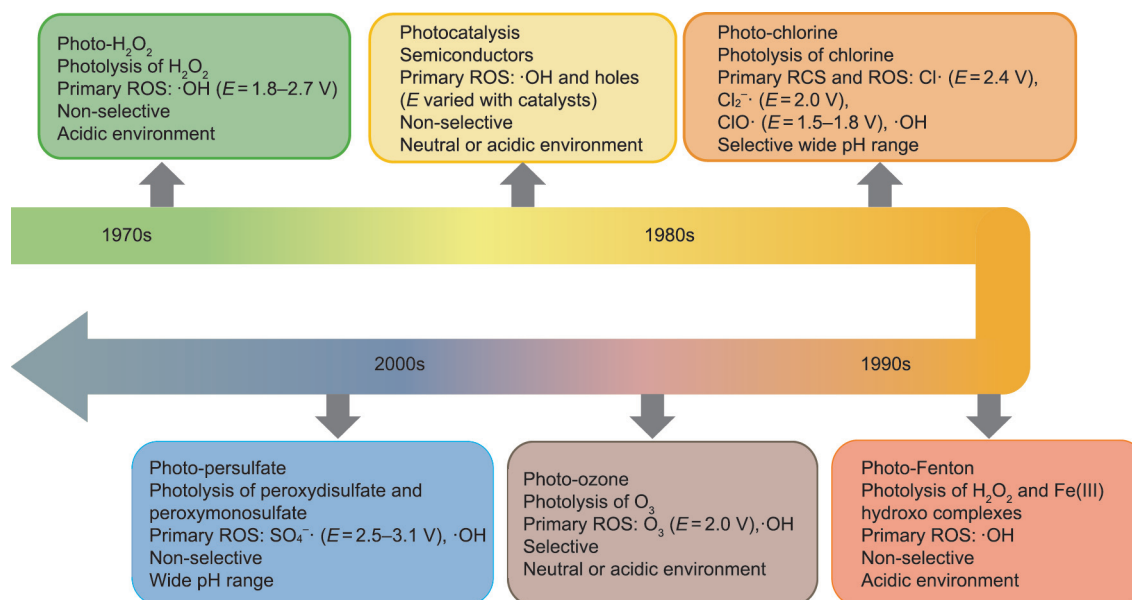


Fig. 2. History of photo-AOP research. ROS: reactive oxygen species; RCS: reactive chlorine species; E: the redox potential.

at scale. Furthermore, the efficient recovery of photocatalytic materials and their light-shielding effects present challenges to the overall cost and scalability of the technology [35]. Fortunately, recent pilot-scale studies have endorsed the unique advantages of this technology and support its potential transition into some niche applications; nonetheless, its utility in municipal wastewater treatment applications to zero pollution discharges remains impractical [34,36].

3. Strategies towards zero pollution

The fundamental objective of zero-pollution photo-AOPs is to sustainably and continuously produce clean water that is free of secondary contamination at a low cost. Theoretical and technological innovation development to meet this objective is an extremely challenging task; indeed, not only are CECs found in trace amounts, but they are also persistent and stable in the aquatic environment. Nevertheless, the challenge of advancing next-generation photo-AOPs that will enable the complete degradation of water pollutants should be undertaken.

In this regard, photo-AOPs have shown great potential and success in degrading endocrine disrupting chemicals (EDCs) [37], PFAS [35], and even microplastics [38], which are considered among the most challenging pollutants to deal with when targeting zero pollution. Photo-AOPs produce various oxidation species with different redox potentials that decompose CECs at high reaction rates, for example, second-order reaction rates with a range of 10^7 – 10^{10} mol·L⁻¹·s⁻¹ [7]. In addition, advances in material science have generated new potential heterogeneous photo-AOPs which are more effective than conventional AOPs. Despite these recent advances, several knowledge gaps remain and the photo-AOP technology still require further development to achieve the ultimate zero-pollution goal. A recent study serves as a reminder that many reaction mechanisms, including by-product formation, reaction pathways, and interference from water matrix components, remain unexplored. For instance, SO₄^{•-} was shown to react with water matrix components to produce harmful aromatic organosulfates [39].

Additional water matrix interferences, including oxidative radical scavenging and the absorbance of photons, affect the performance of photo-AOPs and reduce light utilization efficiency. However, some photolysis products of the water matrix components act as oxidizing agents, offsetting the scavenger effect [40]. Photo-AOPs also alter some water matrix components (e.g., dissolved organic matter) to produce disinfection by-products [41]. The various impacts of the water matrix on the performance, mechanisms, and by-product formation (including potentially toxic intermediate compounds) of photo-AOPs necessitate a comprehensive assessment, given the objective of achieving zero pollution.

The fundamental limitation of photo-AOPs is the short light penetration path within the water matrix. As a result of this limitation, photo-AOPs tend to typically serve as enhancements for existing technologies, for example, in achieving high-quality effluent for water reclamation. However, tertiary water treatment usually requires the integration of various technologies. Indeed, processes have been proposed that integrate two or more photo-AOPs to reduce the overall energy consumption and the risk of by-product formation [42]. However, the mechanisms involved with these integrated systems remain largely unknown. Although significant advances have been made in determining pathways, especially those involving ·OH and O₃ [43], unanticipated reactions may occur during AOP operation. For example, *N*-nitrosodimethylamine and aldehydes were formed when O₃ was injected at the Edward C. Little Water Treatment Facility (El

Segundo, CA, USA) to prevent microfiltration fouling; this illustrates the need for preliminary research to ensure rational designs of integrated systems [28]. Regarding heterogeneous systems, complexity is added by the light-shielding effect and catalyst mass transfer limitations, ultimately warranting comprehensive modeling and reactor design efforts. Moreover, catalyst production cost, durability, and ease of recovery are key issues [44] that need to be resolved to meet the zero-pollution objective.

Selecting a suitable light source is a major cost consideration for all photo-AOPs. The widespread notion that photo-AOPs are cost-effective has been criticized, primarily due to the high energy input required by artificial light sources. Nonetheless, technological advances in artificial light sources, as seen in light-emitting diodes (LED), may provide new opportunities [45]. UV-LEDs offer a different light distribution compared to conventional UV lamps, possibly resulting in more compact and efficient reactors. Other advantages of UV-LEDs when compared to conventional lamps include lower energy consumption, higher mechanical strength, lower cost, longer life span, less mercury use, and accurate tuning of the photon wavelength.

On the other hand, the intensity of solar light is weaker and highly dependent on weather conditions, time, and location. Therefore, a larger reaction space is required to achieve a treatment performance equivalent to that of an artificial light source system. Indeed, the larger footprint equates to a higher capital requirement, and thus, the overall treatment costs of solar light-based AOPs can be much higher than that of their UV-based counterparts [44].

The treatment costs of photo-AOPs follow their respective energy consumptions; more specifically, UV-chlorine has the lowest cost and consumption, followed by UV-persulfate, UV-O₃, UV-H₂O₂, UV-Fenton, and finally, with the highest cost and energy consumption, UV-photocatalysis [17]. However, the treatment costs vary significantly according to the treatment goal and influent quality. With a zero-pollution target, more energy is required for the complete mineralization of organic pollutants compared to the targeting of specific discharge limits. The impact of influent quality on AOPs is illustrated in a case where increased energy consumption (i.e., 6.4–41.1 kW·h·m⁻³) in the UV/TiO₂ process resulted from an increase in influent alkalinity (i.e., CaCO₃ content increase from 0 to 120 mg·L⁻¹) [46]. Nonetheless, when considering the entire life cycle of zero pollution water treatment, an urgent need to reduce the energy consumption of photo-AOPs is evident.

Overall, achieving zero pollution requires several theoretical and technical challenges to be addressed directly, for example, reducing (or eliminating) water matrix interference, toxic by-products, high energy consumption, and chemical use. Although photo-AOPs can theoretically undertake complete mineralization of any toxic chemical, innovations related to scaling up, costs, operations, and system integration are strongly recommended.

4. Conclusions

Photo-AOPs represent a promising technology to be used in achieving zero-pollution goals, owing to their ability to break down trace CECs. However, intrinsic properties of AOPs, particularly the photon penetration limitations, make photo-AOPs more suitable as a refinement technology, to be used in the final processing step. Although some photo-AOPs have been implemented at scale, most notably those in water reclamation facilities, promoting their wider application to achieve the zero-pollution objective will require several key issues to be carefully considered, for example, novel photocatalyst designs, efficient photoreactor development, and advances in artificial light sources. Furthermore, integrating different photo-AOPs for CEC removal could be a feasible strategy

for achieving the zero-pollution objective. Hybridization with photoelectrochemical technologies may render other AOPs more cost-effective [47,48]; however, to ensure rational designs and to avoid possible failure of integrated systems, a complete preliminary assessment should be conducted on performance and by-product formation. In addition, comparing the performance, treatment costs, and reaction pathways of different AOPs should be conducted at bench- and pilot-scales. Engineering design innovations are also required to address the challenges in scaling up this technology. Ultimately, in accordance with the green transition being undertaken in the water sector, energy-efficient and chemical-free photo-AOPs should be pursued.

Acknowledgment

The authors would like to thank the financial support from the Fundamental Research Funds for the Central Universities (B200204033 and B210201025), National Natural Science Foundation of China (52100178), Aarhus University Centre for Water Technology (AU-WATEC) Start-Up Fund from Grundfos Foundation, Aarhus University Research Foundation Starting Grant (AUFF-E-2019-7-28), and Novo Nordisk Foundation (NNF200C0064799).

References

- [1] Soares A. Wastewater treatment in 2050: challenges ahead and future vision in a European context. *Environ Sci Ecotechnol* 2020;2:100030.
- [2] Organisation for Economic Co-operation and Development (OECD). Financing water supply, sanitation and flood protection: challenges in EU member states and policy options, OECD studies on water. Paris: OECD Publishing; 2020.
- [3] Yao X, Hu X, Cui Y, Huang J, Zhang W, Wang X, et al. Effect of Mie resonance on photocatalytic hydrogen evolution over dye-sensitized hollow C-TiO₂ nanoshells under visible light irradiation. *Chin Chem Lett* 2021;32(2):750–4.
- [4] Che H, Gao X, Chen J, Hou J, Ao Y, Wang P. Iodide-induced fragmentation of polymerized hydrophilic carbon nitride for high performance quasi-homogeneous photocatalytic H₂O₂ production. *Angew Chem Int Ed Engl* 2021;60(48):25546–50.
- [5] Koubeck E, Annapolis MD, inventors; the United States of America as represented by the Secretary of the Navy, assignee. Oxidation of refractory organics in aqueous waste streams by hydrogen peroxide and ultraviolet light. United States patent US 4012321A. 1977 Mar 15.
- [6] Guo K, Wu ZH, Fang JY. UV-based advanced oxidation process for the treatment of pharmaceuticals and personal care products. In: Hernández-Maldonado AJ, Blaney L, editors. Contaminants of emerging concern in water and wastewater: advanced treatment processes. Cambridge: Elsevier Inc.; 2020. p. 367–408.
- [7] Guo K, Wu Z, Yan S, Yao B, Song W, Hua Z, et al. Comparison of the UV/chlorine and UV/H₂O₂ processes in the degradation of PPCPs in simulated drinking water and wastewater: kinetics, radical mechanism and energy requirements. *Water Res* 2018;147:184–94.
- [8] Rosenfeldt E, Boal AK, Springer J, Stanford B, Rivera S, Kashinkunti RD, et al. Comparison of UV-mediated advanced oxidation. *J Am Water Works Assoc* 2013;105(7):29–33.
- [9] Doong RA, Chang WH. Photoassisted iron compound catalytic degradation of organophosphorous pesticides with hydrogen peroxide. *Chemosphere* 1998;37(13):2563–72.
- [10] Thomas N, Dionysiou DD, Pillai SC. Heterogeneous Fenton catalysts: a review of recent advances. *J Hazard Mater* 2021;404(Pt B):124082.
- [11] Xu M, Wu CY, Zhou YX. Advancements in the Fenton process for wastewater treatment. In: Bustillo-Lecompte C, editor. Advanced oxidation processes—applications, trends, and prospects. London: IntechOpen; 2020. p. 1–17.
- [12] Jin J, El-Din MG, Bolton JR. Assessment of the UV/chlorine process as an advanced oxidation process. *Water Res* 2011;45(4):1890–6.
- [13] Guo K, Wu Z, Shang C, Yao B, Hou S, Yang X, et al. Radical chemistry and structural relationships of PPCP degradation by UV/chlorine treatment in simulated drinking water. *Environ Sci Technol* 2017;51(18):10431–9.
- [14] Yin R, Ling L, Shang C. Wavelength-dependent chlorine photolysis and subsequent radical production using UV-LEDs as light sources. *Water Res* 2018;142:452–8.
- [15] Sun P, Lee WN, Zhang R, Huang CH. Degradation of DEET and caffeine under UV/chlorine and simulated sunlight/chlorine conditions. *Environ Sci Technol* 2016;50(24):13265–73.
- [16] Cheng Z, Ling L, Wu Z, Fang J, Westerhoff P, Shang C. Novel visible light-driven photocatalytic chlorine activation process for carbamazepine degradation in drinking water. *Environ Sci Technol* 2020;54(18):11584–93.
- [17] Miklos DB, Remy C, Jekel M, Linden KG, Drewes JE, Hübner U. Evaluation of advanced oxidation processes for water and wastewater treatment—a critical review. *Water Res* 2018;139:118–31.
- [18] Zhang Z, Chuang YH, Szczuka A, Ishida KP, Roback S, Plumlee MH, et al. Pilot-scale evaluation of oxidant speciation, 1,4-dioxane degradation and disinfection byproduct formation during UV/hydrogen peroxide, UV/free chlorine and UV/chloramines advanced oxidation process treatment for potable reuse. *Water Res* 2019;164:114939.
- [19] Yang J, Zhu M, Dionysiou DD. What is the role of light in persulfate-based advanced oxidation for water treatment? *Water Res* 2021;189:116627.
- [20] Avetta P, Pensato A, Minella M, Malandrino M, Maurino V, Minero C, et al. Activation of persulfate by irradiated magnetite: implications for the degradation of phenol under heterogeneous photo-Fenton-like conditions. *Environ Sci Technol* 2015;49(2):1043–50.
- [21] Lee J, von Gunten U, Kim JH. Persulfate-based advanced oxidation: critical assessment of opportunities and roadblocks. *Environ* 2020;54(6):3064–81.
- [22] Manoj P, Varghese R, Manoj VM, Aravindakumar CT. Reaction of sulphate radical anion (SO₄^{•-}) with cyanuric acid: a potential reaction for its degradation? *Chem Lett* 2002;31(1):74–5.
- [23] Qian Y, Guo X, Zhang Y, Peng Y, Sun P, Huang CH, et al. Perfluorooctanoic acid degradation using UV-persulfate process: modeling of the degradation and chlorate formation. *Environ Sci Technol* 2016;50(2):772–81.
- [24] Wei Z, Xu T, Zhao D. Treatment of per- and polyfluoroalkyl substances in landfill leachate: status, chemistry and prospects. *Environ Sci Water Res Technol* 2019;5(11):1814–35.
- [25] Li F, Duan J, Tian S, Ji H, Zhu Y, Wei Z, et al. Short-chain per- and polyfluoroalkyl substances in aquatic systems: occurrence, impacts and treatment. *Chem Eng J* 2020;380:122506.
- [26] Yang Q, Ma Y, Chen F, Yao F, Sun J, Wang S, et al. Recent advances in photo-activated sulfate radical-advanced oxidation process (SR-AOP) for refractory organic pollutants removal in water. *Chem Eng J* 2019;378:122149.
- [27] Ma J, Wei Z, Spinney R, Dionysiou DD, Xiao R. Emerging investigator series: could superoxide radical be implemented in decontamination processes? *Environ Sci Wat Res Technol* 2021;7(11):1966–70.
- [28] Ikehata K, Li Y. Ozone-based processes. In: Ameta SC, Ameta R, editors. Advanced oxidation processes for waste water treatment. Cambridge: Academic Press; 2018. p. 115–34.
- [29] Peyton GR, Glaze WH. Destruction of pollutants in water with ozone in combination with ultraviolet radiation. 3. Photolysis of aqueous ozone. *Environ Sci Technol* 1988;22(7):761–7.
- [30] Matsumoto M, Wada Y, Matsumiya S, Onoe K. Enhanced generation of active oxygen species induced by O₃ fine bubble injection under H₂O₂ addition and UV irradiation. *Ozone Sci Eng* 2021;43(6):562–70.
- [31] Ollis DF. Contaminant degradation in water. *Environ Sci Technol* 1985;19(6):480–4.
- [32] Wang D, Pillai SC, Ho SH, Zeng J, Li Y, Dionysiou DD. Plasmonic-based nanomaterials for environmental remediation. *Appl Catal B* 2018;237:721–41.
- [33] Chong MN, Jin B, Chow CWK, Saint C. Recent developments in photocatalytic water treatment technology: a review. *Water Res* 2010;44(10):2997–3027.
- [34] Loeb SK, Alvarez PJJ, Brame JA, Cates EL, Choi W, Crittenden J, et al. The technology horizon for photocatalytic water treatment: sunrise or sunset? *Environ Sci Technol* 2019;53(6):2937–47.
- [35] Zhou Q, Ma S, Zhan S. Superior photocatalytic disinfection effect of Ag-3D ordered mesoporous CeO₂ under visible light. *Appl Catal B* 2018;224:27–37.
- [36] Qanbarzadeh M, Wang D, Ateia M, Sahu SP, Cates EL. Impacts of reactor configuration, degradation mechanisms, and water matrices on perfluorocarboxylic acid treatment efficiency by the UV/Bi₂O(OH)(PO₄)₂ photocatalytic process. *ACS ES&T Eng* 2021;1(2):239–48.
- [37] Wang D, Li Y, Li Puma G, Wang C, Wang P, Zhang W, et al. Ag/AgCl@helical chiral TiO₂ nanofibers as a visible-light driven plasmon photocatalyst. *Chem Commun* 2013;49(88):10367–9.
- [38] Ricardo IA, Alberto EA, Silva Júnior AH, Macuvele DLP, Padoin N, Soares C, et al. A critical review on microplastics, interaction with organic and inorganic pollutants, impacts and effectiveness of advanced oxidation processes applied for their removal from aqueous matrices. *Chem Eng J* 2021;424:130282.
- [39] Van Buren J, Cuthbertson AA, Ocasio D, Sedlak DL. Ubiquitous production of organosulfates during treatment of organic contaminants with sulfate radicals. *Environ Sci Technol Lett* 2021;8(7):574–80.
- [40] Yang Y, Pignatello JJ, Ma J, Mitch WA. Effect of matrix components on UV/H₂O₂ and UV/S₂O₈²⁻ advanced oxidation processes for trace organic degradation in reverse osmosis brines from municipal wastewater reuse facilities. *Water Res* 2016;89:192–200.
- [41] Xiang Y, Gonsior M, Schmitt-Kopplin P, Shang C. Influence of the UV/H₂O₂ advanced oxidation process on dissolved organic matter and the connection between elemental composition and disinfection byproduct formation. *Environ Sci Technol* 2020;54(23):14964–73.
- [42] Lee Y, Gerrity D, Lee M, Gamage S, Pisarenko A, Trenholm RA, et al. Organic contaminant abatement in reclaimed water by UV/H₂O₂ and a combined process consisting of O₃/H₂O₂ followed by UV/H₂O₂: prediction of abatement efficiency, energy consumption, and byproduct formation. *Environ Sci Technol* 2016;50(7):3809–19.
- [43] von Gunten U. Oxidation processes in water treatment: are we on track? *Environ Sci Technol* 2018;52(9):5062–75.
- [44] Wang D, Mueses MA, Márquez JAC, Machuca-Martínez F, Grčić I, Peralta Muniz Moreira R, et al. Engineering and modeling perspectives on photocatalytic reactors for water treatment. *Water Res* 2021;202:117421.

- [45] Vilhunen S, Sillanpää M. Recent developments in photochemical and chemical AOPs in water treatment: a mini-review. *Rev Environ Sci* 2010;9(4):323–30.
- [46] Autin O, Hart J, Jarvis P, MacAdam J, Parsons SA, Jefferson B. Comparison of UV/TiO₂ and UV/H₂O₂ processes in an annular photoreactor for removal of micropollutants: influence of water parameters on metaldehyde removal, quantum yields and energy consumption. *Appl Catal B* 2013;138–139:268–75.
- [47] Han J, Bian Y, Zheng X, Sun X, Zhang L. A photoelectrochemical cell for pollutant degradation and simultaneous H₂ generation. *Chin Chem Lett* 2017;28(12):2239–43.
- [48] Ding J, Bu L, Cui B, Zhao G, Gao Q, Wei L, et al. Assessment of solar-assisted electrooxidation of bisphenol AF and bisphenol A on boron-doped diamond electrodes. *Environ Sci Ecotechnol* 2020;3:100036.