Application of visible light active photocatalysis for water contaminants: A review

Yifan Sun | David W. O’Connell

Department of Civil and Environmental Engineering, Trinity College Dublin, Dublin 2, Ireland

Correspondence
David W. O’Connell, Department of Civil and Environmental Engineering, Trinity College Dublin, College Green, Museum Building, Dublin 2, Ireland.
Email: david.oconnell@tcd.ie

Abstract
Organic water pollutants are ubiquitous in the natural environment arising from domestic products as well as current and legacy industrial processes. Many of these organic water pollutants are recalcitrant and only partially degraded using conventional water and wastewater treatment processes. In recent decades, visible light active photocatalyst has gained attention as a non-conventional alternative for the removal of organic pollutants during water treatment, including industrial wastewater and drinking water treatment. This paper reviews the current state of research on the use of visible light active photocatalysts, their modified methods, efficacy, and pilot-scale applications for the degradation of organic pollutants in water supplies and waste streams. Initially, the general mechanism of the visible light active photocatalyst is evaluated, followed by an overview of the major synthesis techniques. Because few of these photocatalysts are commercialized, particular attention was given to summarizing the different types of visible light active photocatalysts developed to the pilot-scale stage for practical application and commercialization. The organic pollutant degradation ability of these visible light active photocatalysts was found to be considerable and in many cases comparable with existing and commercially available advanced oxidation processes. Finally, this review concludes with a summary of current achievements and challenges as well as possible directions for further research.

Practitioner Points
• Visible light active photocatalysis is a promising advanced oxidation process (AOP) for the reduction of organic water pollutants.
• Various mechanisms of photocatalysis using visible light active materials are identified and discussed.
• Many recent photocatalysts are synthesized from renewable materials that are more sustainable for applications in the 21st century.
• Only a small number of pilot-scale applications exist and these are outlined in this review.
INTRODUCTION

Water pollution has serious negative impacts on both aquatic environments and associated human activities. The effluent from industry, agriculture, hospital, and households may contain many organic pollutants, such as dyes, paints, pesticides, gasoline, and pathogen (Cunha et al., 2019; Priyanka et al., 2020; Tran et al., 2014; Vatanpour et al., 2019). Some of them are recalcitrant and can only partially be treated through the traditional wastewater treatment process; examples are shown in Table 1. Due to rapid population increase, global industrialization, and urbanization, clean water resources are under pressure due to large increases in demand over the past number of decades. Organic pollutants discharged from such activities and sources have exacerbated the problem and many traditional wastewater treatment methods have limitations and disadvantages in treating water laden with persistent organic pollutants (Pardeshi & Patil, 2008; Villaluz et al., 2019); hence, advanced oxidation processes (AOPs) have been developed to improve treatment performance.

AOPs rely on the in situ generation of high oxidant species such as hydroxyl radicals that completely mineralize organic pollutants. This has been recognized as a promising water treatment solution, especially for those refractory contaminants (e.g., phenolic compounds, adsorbable organic halides, bisphenol A [BPA], and antibiotics) (Cai et al., 2019; Garcia-Segura et al., 2018; Oh et al., 2016; Villaluz et al., 2019; Zhang et al., 2020). In the past several decades, many AOPs have been developed, such as peroxide, electrochemical, Fenton, sonolysis, microwave, and photocatalytic (Miklos et al., 2018; Zhang et al., 2020) (Table 2).

Among all AOPs, photocatalysis has received increasing attention, due to its lower cost, non-toxic materials, relatively high chemical stability of the catalyst, and efficiency under mild conditions using potential sunlight (Miklos et al., 2018; Xu et al., 2020; Yusuff et al., 2020). In addition, it also has a high potential for complete degradation, destruction, or mineralization of organic pollutants (dos Santos et al., 2019; Gmurek et al., 2019; Katal et al., 2019).

Photocatalysis may be divided into two categories, ultraviolet (UV) active photocatalysis and solar/visible light active photocatalysis, which has become a preferred choice (Shaniba et al., 2020; Sujatha et al., 2020). Although UV photocatalysis generally has better treatment performance, as the intensity of UV is stronger than solar/visible light's (Sujatha et al., 2020), but due to the economics of solar/visible light photocatalysis, it is preferred over UV light photocatalysis and has been considered an environmentally friendly technology for pollutant removal.

Recently, significant progress has been made on the visible light active photocatalysts. This review summarizes the latest developments in visible light active photocatalysis. It starts with the mechanism of photocatalysis, followed by synthesis and doping methods of several common photocatalysts, and the application of visible light active photocatalysis. Special attention has been devoted to pilot-scale tests and introduced separately. Finally, current research deficiencies and prospects for future research are considered. We believe that this review will not only promote the further developments of

---

**TABLE 1** Examples of recalcitrant pollutants

| Categories     | Pollutants       | Reference                      |
|----------------|------------------|--------------------------------|
| Textile        | Axo dyes         | (Raman & Kanmani, 2019)        |
|                | Alizarin yellow R| (Ahmed et al., 2020)           |
|                | (AYR)            |                                |
|                | Laccases         | (Giovanella et al., 2020)      |
| Pharmaceutical | Levofoxacin (LEV)| (Wang, Chen, et al., 2020)     |
|                | Sulfamethoxazole | (Domingues et al., 2020)       |
|                | Cotinine         | (Chavez et al., 2020)          |
|                | Benzodiazepines  | (Cunha et al., 2019)           |
|                | Naproxen (NPX)   | (Amini et al., 2019)           |
|                | Acetaminophen (ACE)| (Tobajas et al., 2017)     |
| Industrial     | Coffee processing wastewater | (Sujatha et al., 2020) |
|                | Trichloroethylene (TCE)| (Jung et al., 2020)    |
|                | Phenol           | (Scott et al., 2019)           |
|                | Chloro-phenol    | (Villaluz et al., 2019)        |
|                | Bisphenol A (BPA)| (Lim et al., 2019)             |
| Pesticides     | Malathion        | (Vela et al., 2018b)           |
|                | Acetamiprid      | (Garrido et al., 2020)         |

**KEYWORDS**

organic pollutants, pilot-scale applications, visible light active photocatalyst, water treatment
TABLE 2  AOP technology and associated advantages and disadvantages

| AOP technology          | Advantages                                         | Disadvantages                          | Reference                  |
|-------------------------|----------------------------------------------------|----------------------------------------|-----------------------------|
| Electrochemical oxidation | No chemical compounds created                       | Consumes electricity                   | (Krzeminska et al., 2015)   |
|                         | Versatility                                        |                                        | (Garcia-Segura et al., 2018)|
| Sonolysis               | Low interference from the water matrix              | Highly energy intensive                | (Pang et al., 2011)         |
|                         | Less heat transfer                                  | Low electrical efficiency              | (Pang et al., 2011)         |
| Microwave               | Enhance reaction rates reduce selectivity heating   | Low electrical efficiency              | (Miklos et al., 2018)       |
|                         |                                                    | Required cooling devices               |                             |
| Fenton                  | The high contaminants removal efficiency            | Chemical consumption                   | (Babuponnusami & Muthukumar, 2012)|
|                         |                                                    |                                        | (Krzeminska et al., 2015)   |
|                         |                                                    |                                        | (Bokare & Choi, 2014)       |
| Fenton-like oxidation process | Low cost                                        | Each non-ferrous catalyst has its merits and demerits | (Bokare & Choi, 2014)       |
|                         |                                                    | Limited application                    | (Garrido-Ramirez et al., 2010)|
| Ozonization             | High degradation and mineralization efficiency      | Not effective for recalcitrant organics| (Malik et al., 2020)        |

visible light active photocatalysis but also could therefore help to address the attention for the pilot-scale tests and even real-world application of visible light active photocatalysts in water treatment.

VISIBLE LIGHT ACTIVE PHOTOCATALYSTS

Visible light active photocatalysis is a type of AOP based on the generation of radicals after photoexcitation of a semiconductor material (Zuniga-Benitez & Penuela, 2020). In general, the visible light active photocatalyst consists of semiconductor materials, light-harvesting antennas, and active species (Dong et al., 2015; Waso et al., 2020; Xu et al., 2020). The mechanism and materials are critical information for photocatalysis research. In this section, the mechanism of photocatalytic function and materials have been reviewed.

Mechanism of photocatalytic function

In general, the mechanism of visible light active photocatalysis is using solar/visible energy to create radical and other active species and then degrade pollutants. The series of actions possibly happened at the visible light active photocatalysts due to light absorption for pollutant degradation, which has been intensively reported in much literature (Ali et al., 2019; Bibova et al., 2019; Chong et al., 2010; Dong et al., 2015; Fujishima et al., 2008; Pena et al., 2005) and it summarized as follows:

\[
\text{Photocatalyst} + h\nu \rightarrow \text{Photocatalyst} \left( h^+ + e^- \right) \quad (1)
\]

\[
h^+ + \text{H}_2\text{O} \rightarrow \cdot \text{OH} + \text{H}^+ \quad (2)
\]

\[
h^+ + \text{OH}^- \rightarrow \cdot \text{OH} \quad (3)
\]

\[
e^- + \text{O}_2 \rightarrow \cdot \text{O}_2^- \quad (4)
\]

\[
\text{O}_2^- + \text{H}^+ \rightarrow \cdot \text{OOH} \quad (5)
\]

\[
\cdot \text{OOH} + \cdot \text{O}_2^- \rightarrow \cdot \text{OH}^- + \text{O}_2 \quad (6)
\]

\[
\text{OOH}^- + h^+ \rightarrow \cdot \text{OOH} \quad (7)
\]

\[
2 \cdot \text{OOH} \rightarrow \text{O}_2 + \text{H}_2\text{O}_2 \quad (8)
\]

\[
\text{H}_2\text{O}_2 + \cdot \text{O}_2^- \rightarrow \cdot \text{OH} + \text{OH}^- + \text{O}_2 \quad (9)
\]

\[
\text{H}_2\text{O}_2 + h\nu \rightarrow 2 \cdot \text{OH} \quad (10)
\]

\[
\text{Pollutant} + \left( \cdot \text{OH}, h^+, \cdot \text{OOH}, \text{or O}_2^- \right) \rightarrow \text{degradation product} + \text{CO}_2 + \text{H}_2\text{O} \quad (11)
\]

\[
h^+ + e^- \rightarrow \text{heat} \quad (12)
\]

If visible light energy \((h\nu, \nu \text{ is light’s frequency, } h \text{ is called Planck’s constant and equal to } 6.62608 \times 10^{-34} \text{ Js})\) absorbed by the photocatalyst is stronger than its band...
gap energy ($E_g$), valence band (VB) electrons ($e^-$) will be excited to the conduction band (CB) and leave behind photogenerated holes ($h^+$) at the VB (Equation 1) (Dong et al., 2015; Jung et al., 2020). Then, the produced $e^-/h^+$ will migrate to the surface and participate in a range of redox reactions shown above (Fujishima et al., 2008; Perović et al., 2020). Dong et al. (2015) summarized the three main active species for photocatalytic: $h^+$, hydroxyl radical (-OH), and superoxide radical (-O$_2^-$), where -OH has been considered the primary oxidant with scavenging properties (Chong et al., 2010). -OH is generated by three routes: (1) H$_2$O oxidized by $h^+$ form H$^+$ and -OH (Equation 2); (2) O$_2$ in the aqueous solution is reduced by $e^-/C_0$ to form -OH (Equation 4), which reacts with H$^+$ and form -OOH (Equation 5). -OOH decomposes into O$_2$ and H$_2$O$_2$ (Equation 8), which is continually reduced by -O$_2^-$ to OH$^-$ (Equation 9) and forms -OH by $h^+$ (Equation 3); and (3) H$_2$O$_2$ decomposed by light forming -OH directly (Equation 10). Pollutants degraded by -OH, $h^+$, and -O$_2^-$ produce degradation products, CO$_2$ and H$_2$O. If the of h$^+$ with e$^-$ and h$^+$ are not quickly cleared after photoexcitation, it will lead to recombination. The recombination of h$^+$ with e$^-$ release heat/energy (Equation 11) has a negative impact on photocatalysis (Fujishima et al., 2008). The photocatalytic reaction mechanism is shown in Figure 1.

The mechanism of modified photocatalyst composites, except for the reactions above, usually includes the transfer of e$^-$ and h$^+$ between different photocatalysts, due to the different band potential (Geng et al., 2019; B. S. Li, Lai, et al., 2019). A good design of composite will lead to optimized parameters (like broadened energy band), efficient separation of photogenerated electron–hole pairs, and charge carrier recombination hindrance (Meena et al., 2020).

To capture solar energy effectively and achieve the above reactions, the semiconductor material for photocatalytic must have several critical properties. First, semiconductor materials should have a narrow band gap to absorb visible light effectively (Gopalakrishnan et al., 2020); the band gap determines the wavelength of light that materials can be absorbed (Casbeer et al., 2012). Secondly, the semiconductor materials should have a low recombination rate of $h^+-e^-$ pairs to ensure $h^+$ and $e^-$ migrate to the surface (Shaniba et al., 2020). Moreover, the semiconductor material should have good chemical and structural stability with the ability to operate under normal temperature and pressure (Chong et al., 2010). Other preferable properties include low cost, good stability, non-toxicity, desired environmental acceptance, and easy to be separated (Xu et al., 2020). The choice of semiconductor material is crucial for photocatalysis.

Overall, the design of a good photocatalyst involves two key factors: (1) suitable semiconductor materials, preferable characteristics including good chemical and structural stability, solar energy absorption properties, and separation efficiency of charge carriers; and (2) favorable surface areas structure design of the photocatalyst (Berger et al., 2020); generally, the higher surface areas will lead to improved solar absorption and higher reaction rate but may leave traces as residue in water (Sharmila et al., 2020). Two common methods to fabricate better photocatalysts are modifying known materials and developing new semiconductor materials.

FIGURE 1 Photocatalytic reaction mechanism
Photocatalysis materials

Photocatalysts can be divided into two categories which include heterogeneous and homogeneous catalysts. Heterogeneous photocatalyst is in a different phase from the reactants (e.g., TiO₂ for water treatment) (Ameta et al., 2018). On the contrary, a homogeneous photocatalyst is an assembly of soluble molecular catalysts in the same phase as the reactants, and all reactions are carried out in a single form (e.g., photo-Fenton [PF] reagent for water treatment) (Shwetharani & Balakrishna, 2014; Tahir et al., 2020). Furthermore, heterogeneous catalysts may be divided into metallic compounds including carbon-based compounds and metal-carbon composites.

The metallic compound is very popular as a photocatalyst material. Generally, titanium dioxide (TiO₂) and zinc oxide (ZnO) are the most common materials for photocatalysis, which have been widely used in the past few decades, due to their chemical stability, non-toxic nature, abundance, and cost-effectiveness (Priyanka et al., 2020; Shaniba et al., 2020; Xu et al., 2020; Yazdanbakhsh et al., 2019). Moreover, they can be easily prepared by simple and scalable approaches (Serra, Zhang, et al., 2019; Wang et al., 2019). However, TiO₂ can only absorb UV light, which is only approximately 3%-5% of the entire light emitted across the solar spectrum (wavelengths shorter than 400 nm) because of its large band gap energy (3–3.2 eV) and fast charge recombination of h+ and e– before reaching the surface. In addition, TiO₂ powder is hard to separate from the reaction system. These defects lead to poor photocatalytic efficiency (Jung et al., 2020; Kavil et al., 2020; Shaniba et al., 2020; Weon et al., 2019; Xu et al., 2020). ZnO also has similar drawbacks; it has a wide band gap energy (3.3 eV), high photocorrosion activity, high electron mobility (200–300 cm²/V/s), low quantum efficiency, high h+ and e– recombination rate, long electron lifetime (>10 s) (Ani et al., 2018; Hu et al., 2019; Serra, Gomez, & Philippe, 2019), and potential ecotoxicological effects (Serra et al., 2020). In addition, in this particular case, ZnO can cause ecotoxicological effects, especially relevant for some microorganisms, such as microalgae (Djearamane et al., 2018; Shahid et al., 2020).

Through hydrogenation of TiO₂, it is possible to generate a black TiO₂ solution. Black TiO₂ has recently been developed, first reported in 2011 (X. Chen et al., 2011), and has triggered much research interest in recent years. It displays excellent red-shifted light absorption properties, mainly owing to hydrogenation dramatically changing the structural, chemical, electronic, and optical properties of TiO₂ nanoparticles (NPs), so it has a stronger visible light utilization ability (J. U. Choi et al., 2019; Y. Liu et al., 2017). However, according to the latest review, summarized by Rajaraman et al. (2020), the synthesis of black TiO₂ is quite challenging and, in some cases, compared with pristine TiO₂, the black TiO₂ actually showed reduced photoactivity.

Another common solution is doping, coating, and decorating elements into TiO₂ and ZnO (Scott et al., 2019; Shaniba et al., 2020; Villaluz et al., 2019). These elements can act as a sink for h+ and e– and reduce their recombination rates (Shaniba et al., 2020). Also, research has proved dopants can improve photocatalysis efficiency by reducing the requirement of absorbed energy, shifting absorbed light to visible wavelength, and enhancing photocatalysis activity (Ani et al., 2018; Yusuff et al., 2020). Some examples include nitrogen (Shaniba et al., 2020), pumice (Yusuff et al., 2020), Ag (Shahid et al., 2020), Ni (Serra, Zhang, et al., 2019), and Prussian blue (Rachna et al., 2020). Also, combining TiO₂ or ZnO with other semiconductors to form heterojunction photocatalysts has been wildly studied, like black TiO₂/g-C₃N₄ (L. Shen et al., 2017) and ZnO/Bi₂WO₆ (Duan et al., 2020). Other metal compound photocatalyst materials also have been studied in the last several years, such as Bi₂O₃ (Zhang et al., 2020), MnO (Wang, Chen, et al., 2020), Ag₃VO₄ (Priyanka et al., 2020), and BiOBr (Jung et al., 2020).

In recent years, metal-free carbon-based materials have provoked much research interest. Some carbon-based materials such as graphene, graphitic carbon nitride (g-C₃N₄), and graphene oxide (GO) are nonmetal semiconductors and have been studied as cocatalysts due to their eco-friendly composition, lightweight structure, high surface area, tunable band gap stability, and cost effectual process of preparation (Priyanka et al., 2020; Wang, Li, et al., 2020; Zheng et al., 2019). For instance, g-C₃N₄ has 1.8–2.7 eV band gaps that allow the harvesting of visible light up to 460–698 nm (Zheng et al., 2016). Such metal-free carbon-based materials can combine to enhance photocatalytic ability, examples including g-C₃N₄/GO aerogel (Tong et al., 2015) and g-C₃N₄/agar (Tan et al., 2019). The carbon-based material also can combine with metallic compounds, such as sulfur-doped graphene oxide (sGO)/Ag₃VO₄ (Priyanka et al., 2020) and Ag₃PO₄/polyaniline@g-C₃N₄ (Balasubramanian et al., 2020). Some cutting-edge carbon-based materials also have been invested as photocatalysts, examples including carbon quantum dots (CQDs) (D. Choi et al., 2018; Rahbar et al., 2019), graphene quantum dots (GQDs) (Ge et al., 2016; Wei et al., 2016), and multi-walled carbon nanotubes (MWCNTs) (Cong et al., 2011; Yan et al., 2011). However, these materials only have been discovered in the last several decades, and the research on their green synthesis and mechanism is still at an early stage (Heng et al., 2021; Kaur et al., 2018).
There is less research on the homogenous catalyst, compared to heterogeneous catalysts. The homogenous catalyst usually combines light radiation with chemical oxidizing agents (Stan et al., 2012). PF is one of the most common homogenous catalysts, which usually consists of iron ion (Fe^{2+} or Fe^{3+}) and hydrogen peroxide (H_{2}O_{2}) (Moncayo-Lasso et al., 2009; Shwetharani & Balakrishna, 2014).

**METHODS OF SYNTHESIS**

The synthesis of NP semiconductor materials is a major challenge in photocatalysis research. Synthesis methods have a significant impact on photocatalysts' morphology, structure, and performance (Sahu & Biswas, 2011; Sun et al., 2019; Taherinia et al., 2019).

**Metal-associated visible light active photocatalysts synthesis**

**Sol-gel method**

The sol-gel method has a large scope of application in the preparation of inorganic ceramic and glass materials (Czok & Golonka, 2016; Jones, 2013; Wang et al., 2014). Due to its wide range of advantages, including high chemical purity, good uniformity, and controllable morphology (Taherinia et al., 2019; Wetchakun et al., 2012), it has become a common method for photocatalysts synthesis. It is important to mention that a change in molar ratios may lead to different hydrolysis speeds and further different structures and properties (Lu et al., 2013; Wang et al., 2014; You et al., 2012).

A typical example of the sol-gel method is the synthesis of TiO_{2}. In this method, TiO_{2} is synthesized by alkoxide precursors, like titanium butoxide (Ti(OBu)_{4}) and titanium isopropoxide (TTIP). Initially, the sol-gel method was a one-step process (Long & Yang, 2002), and now, it usually contains two steps. First, dissolve the precursor with/without doping materials into a solvent, usually alcoholic (i.e., ethanol) or acid (i.e., HNO_{3}). Due to hydrolysis, the sol is formed, and under polycondensation and action of density, the sol particles form a three-dimensional network, resulting in the production of gel. Sonication could be applied in this step to enhance the reaction. Second, the gel is calcined in a muffle furnace at 400–700°C and, after this, it is dried and powdered (Kavil et al., 2020; Khataee et al., 2017; Taherinia et al., 2019; Villaluz et al., 2019). A schematic of this method is shown in Figure 2. Wang et al. (2014) have summarized the reaction mechanism as follows:

\[
\text{Ti} \left( \text{OR} \right)_{n} + \text{H}_{2}\text{O} \rightarrow \text{Ti(OH)} \left( \text{RO} \right)_{n-1} + \text{ROH} \quad \text{(hydrolysis)} \]

\[
\text{Ti(OH)(OR)}_{n-1} + \text{H}_{2}\text{O} \rightarrow \text{Ti(OH)}_{2} \left( \text{OR} \right)_{n-1} + \text{ROH} \quad \text{(hydrolysis)} \]

\[
-\text{Ti} - \text{OH} + \text{HO} - \text{Ti} - \rightarrow -\text{Ti} - \text{O} - \text{Ti} - + \text{H}_{2}\text{O} \quad \text{(polycondensation)}
\]

\[
-\text{Ti} - \text{OR} + \text{HO} - \text{Ti} - \rightarrow -\text{Ti} - \text{O} - \text{Ti} - + \text{ROH} \quad \text{(polycondensation)}
\]

By adjusting the precursor and solvent, sol-gel can also be used to synthesize other photocatalysts, examples including ZnO (Rafie et al., 2019), Bi_{2}O_{3} (Zhang et al., 2020), Al_{80}Ce_{10}Zr_{10} (Perez-Osorio et al., 2020), and Ag/g-C_{3}N_{4}/V_{2}O_{5} (El-Sheshtawy et al., 2019).
Hydrothermal method

Hydrothermal technology is an important liquid-phase preparation technology, which has extensive application in materials science, chemistry, physics, biology, metallurgy, and earth science (Yang & Park, 2019). It has been applied to produce nano TiO2 with high purity, crystal symmetry, metastable compounds with unique properties, and narrow particle size distributions (Byrappa & Adschiri, 2007) and is also preferred for ZnO synthesis (Danwittayakul et al., 2020). Concurrently, it has been widely used in photocatalyst synthesis, especially with carbon dopants (i.e., GO and activated carbon) (Shinde et al., 2018; Subramani et al., 2007; Yin et al., 2021; Zhang et al., 2017).

The hydrothermal method is a one-step process. A typical example of its application is the synthesis of TiO2. By mixing a titanium precursor with water or NaOH/isopropanol/2-propanol(peptizer)–water solution, or alternatively TTIP with the acidic ethanol–water environment, with/without doping materials, add them into autoclaves for 16–72 h at 110–180°C. The precipitate is then calcined and dried to gain well-defined TiO2 or composite TiO2 photocatalyst (X. Chen & Mao, 2007; Shinde et al., 2018).

The hydrothermal method can synthesize not only TiO2 and ZnO but also many other photocatalysts, including MoS2/reduced graphene oxide (rGO) (Gopalakrishnan et al., 2020), Mn3O4 (Zhao et al., 2017), ZnWO4 (Gong et al., 2020), FeCo2O4 (Yadav et al., 2019), and ZnS (Sabaghi et al., 2018).

Solvothermal method

The solvothermal method is very similar to the hydrothermal method, except the solvent used here is nonaqueous, with higher temperatures and pressures (X. Chen & Mao, 2007; Y. Wang et al., 2014). A typical procedure for using the solvothermal method to prepare ZnO is as follows. First, zinc acetate dehydrate (Zn(Ac)2.2H2O) or ZnCl2 is dissolved in organic solvent (i.e., ethanol and polyethylene glycol), with/without doping materials. Then NaOH is added with ultrasonication mixing and transferred into an autoclave. After reaction and cooling, the ZnO is precipitated (Chouchene et al., 2016; Chu et al., 2014; Ruba et al., 2019). Apart from ZnO synthesis, the solvothermal method has a wide range of additional applications, including synthesizing TiO2 (Chavez et al., 2020), ZnFe2O4 (Ahmadpour et al., 2020), Ag2PO4/PANI@gC3N4 (Balasubramanian et al., 2020), MgFe2O4 (Y. Shen et al., 2013), and BiOI (Qiu et al., 2019).

Miscellaneous methods

The sol-gel method, hydrothermal method, and solvothermal method are popular in the current study. Along with these commonly used synthesis methods, researchers have developed some additional methods and techniques.

Co-precipitation can synthesize ZnO by adding solution (i.e., either adipic acid [C6H10O4], ethylene glycol, or NH4OH) into aqueous solution (i.e., zinc acetate Zn(CH3COO)2.2H2O and Zn(NO3)2.6H2O), which create zinc adipate precipitation. After drying, zinc adipate is obtained by using both mediums and is decomposed at 450–500°C to produce ZnO (Thorat et al., 2012; Vlazan et al., 2015). Other applications include CuMgFe-LDH (Zhang et al., 2020), magnetic graphene-TiO2 (Chavez et al., 2020), and Bi2Ti2O7 (Y. F. Li, Zhong, et al., 2018).

The anodic oxidation method can be effectively employed to fabricate nanotubes and also has been developed for photocatalysts penetration (Nevarez-Martinez et al., 2017; Tran et al., 2014). Examples include the V2O5–TiO2 nanotube array (Nevarez-Martinez et al., 2017) and MoS2/TiO2 nanotube arrays (Yan et al., 2020).

Solution combustion methods have also been developed by mixing precursors, fuel, and oxidizers under a high temperature to synthesize photocatalysts (Cubas et al., 2020; Meena et al., 2020). Some examples of materials developed include MFO/ZrO2 (Meena et al., 2020), Ag/CeO2 (Shang et al., 2020), and CuCrO4 (Cubas et al., 2020).

The template method entails the synthesis of monodisperse tubular or wire-like nanostructures within the pores of a membrane or nanoporous solid (Wang et al., 2014). For example, Nozaki et al. (2018) used commercial silica microspheres as template material, using cerium(III) nitrate hexahydrate as a precursor to synthesize CeO2.

The flame aerosol method is a single-step process and allows independent control of the material properties such as particle size, crystallinity, homogeneity, and degree of aggregation (Sahu & Biswas, 2011). In general, by burning precursors with fuel and oxygen, the photocatalyst will grow in the entrained air. Applications of this method include materials such as Cu-TiO2 (Sahu & Biswas, 2011), C-TiO2 (Lim et al., 2008), and Cr-TiO2 (Inturi et al., 2014).

The reverse microemulsion method is used to prepare inorganic NPs (Zhou et al., 2011). There are two basic types of microemulsions: direct microemulsions (oil in liquid) and reverse microemulsions (liquid in oil) (Kar et al., 2018; Sautina et al., 2019). The continuous oil phase, surfactant, co-surfactant, and precursor solution
are prepared required for the reverse microemulsion system. After mixing, hydrothermal treatment, filtration, and drying, photocatalysts are prepared (Ge et al., 2010; Zhou et al., 2011). Some examples of materials developed include TiO2/sulfonated polyaniline (Zhou et al., 2011), Bi2WO6 (Ge et al., 2010), and CdS-loaded K2Nb2O7 (Liang et al., 2013).

The sonochemical method has triggered much attention in advanced chemical synthesis as well as photocatalyst preparation. Ultrasonic generates alternating rarefaction and compression zones in this liquid, which leads to extremely high local energy densities (Wang et al., 2014). Briefly, precursors and capping agents reacted under ultrasonic and synthesized photocatalysts (Zinatloo-Ajabshir et al., 2020). Examples of reactive materials developed through this technique include rGO-V2O5 NPs (Mishra et al., 2020), silver tungstate (Zinatloo-Ajabshir et al., 2020), and graphene oxide@ZnO (Muthukrishnaraj et al., 2020).

The chemical vapor deposition (CVD) method uses the chemical reaction of gaseous species to deposit thin solid films (Wang, Zhu, et al., 2020) and has been applied in photocatalyst film preparation. Examples include MoO2 film (Matamura et al., 2020), MoO2/MoS2/TiO2 sandwich heterostructure (Wang, Zhu, et al., 2020), and Fe2O3/2D graphene/Cu film (Polat, 2020).

The physical vapor deposition (PVD) method shares a similar application with the CVD method. It deposits films or forms coatings that are transported through a vacuum or low-pressure gaseous/plasma environment (Wang et al., 2014), such as coating TiO2 (Shuang et al., 2016).

The electrodeposition method is a type of plating by depositing material on a substrate through electrochemical reduction (Hasan et al., 2019) and has been applied in photocatalyst preparation. Reactive materials developed using this method include Au/ZnO film (da Silva et al., 2013), TiO2 film (Hachisu et al., 2016), and TiO2 on a silicon wafer surface (Basheer et al., 2020).

Apart from these physical and chemical methods above, the biosynthesis process also has been developed. Ahmed et al. (2020) used A. Chinensis fruits extract with FeCl2·4H2O to prepare Fe NPs. Similarly, Ghazal et al. (2020) synthesize NiO NPs through the use of Cydonia oblonga extract.

**Carbon-based visible light active photocatalysts synthesis**

The calcination method has been used for graphitic carbon nitride (g-C3N4) composite preparation. G-C3N4 can be simply synthesized by directly calcining a precursor (i.e., melamine, urea, and thiourea) under an air atmosphere at around 550°C for several hours (L. Shen et al., 2017; Yu et al., 2016). Therefore, by calcining the mixture of melamine or urea and other materials, the g-C3N4 composite can be synthesized (L. Shen et al., 2017; Yu et al., 2016; Zhao et al., 2018). Examples include black TiO2/g-C3N4 (L. Shen et al., 2017), CeO2/g-C3N4 (Yu et al., 2016), and CeVO4/g-C3N4 (Ren et al., 2016).

Hummer’s method (Hummers & Offeman, 1958) is commonly used in GO synthesis (Barakat et al., 2019; Mishra et al., 2020; Priyanka et al., 2020). It is an oxidation method treating graphite with essentially a water-free mixture of concentrated sulfuric acid, sodium nitrate, and potassium permanganate to produce GO (Hummers & Offeman, 1958).

**Composite photocatalyst synthesis**

Specific methods have been developed to synthesize composite photocatalyst. Many researchers do not synthesize common photocatalysts like TiO2 and ZnO in the laboratory but instead purchase them with specific specifications of surface area and particle size (Davididou et al., 2018; Jung et al., 2020; Sujatha et al., 2020; Vela et al., 2018c; Zuniga-Benitez & Penuela, 2020). Methods introduced in previous sections may also apply to composite photocatalyst synthesis, but some unique methods are introduced below.

The wetness incipient impregnation method is used to synthesize composite photocatalysts by dissolving materials into the water followed by drying and calcining (Keshvadi et al., 2020; Yusuff et al., 2020). Examples include Ag- CeO2 (Keshvadi et al., 2020), ZnO/pumice (Yusuff et al., 2020), and loading material on TiO2/ZeY (Roongraung et al., 2020).

The photodeposition method utilizes photocatalytic activity to prepare metal-loaded photocatalysts. It uses photoexcited electrons to reduce metal cations to produce metal NPs on photocatalysts (Yamamoto et al., 2020). For example, Martins et al. (2019) mixed TiO2 (prepared by sol-gel method) with Ag and Pd precursors in solvents, respectively, and under UV-Vis light, Ag-TiO2 and Pd-TiO2 were synthesized. Other photocatalysts synthesized using a similar procedure include Fe2O3/TiO2 (Lee et al., 2017), Pt/TiO2 (Yamamoto et al., 2020), and TiO2–Pd (Gmurek et al., 2019).

The chemical bath deposition (CBD) method is used for film or array photocatalyst preparation. Briefly, metal slides/flakes are placed in a chemical bath and photocatalytic deposition is encouraged forming a photocatalyst film or array. Specifically, the slides/flakes can be ordinary supporting inorganic material, like glass slides, or semiconductor material that involved photocatalysis, like
TiO₂ nanoflakes (Chai et al., 2014; Kite et al., 2020; Zhou et al., 2019). Examples include WO₃/TiO₂ array (Zhou et al., 2019), Zn₀.₅Cd₀.₅S films (Chai et al., 2014), ZnS thin films (Y. Chen et al., 2012), and FeSe thin films (Sohrabi & Ghobadi, 2019).

**WATER CONTAMINANT TREATMENT**

**Textile and organic wastewater treatment**

Textile wastewater often contains highly toxic and chemically stable organic compounds, including dyes, surfactants, oils, acid, alkali, solvents, and some metal salts, which are graded as one of the foremost pollutants in all industrial sectors (Ahmed et al., 2020; Kavil et al., 2020; Yusuff et al., 2020). Globally, it has been estimated that 280,000 tons of textile dyes alone are produced every year (Perez-Osorio et al., 2020). Without appropriate treatment, before discharge, it has the potential to cause serious environmental contamination for receiving aquatic ecosystems.

**TiO₂ composites**

TiO₂ composites are a common form of photocatalyst, which have been widely investigated for textile and organic wastewater treatment. The commercial TiO₂-P25 already shows strong photocatalytic performance. Adamek et al. (2019) immobilized TiO₂-P25 on a glass fiber mat under sunlight and achieved decolorization of an anionic dye (Acid Orange 7; AO 7) within 20 min in comparison with commercial TiO₂-P25 alone. The main purpose of modified TiO₂ for visible light active photocatalysis is the enhancement of the visible light absorption capacity of the TiO₂ composite. Lim et al. (2019) combined nanocubic-like TiO₂ with N-doped graphene quantum dots (N-GQDs) and proved N-GQDs can provide light-harvesting ability, especially in visible light and near-infrared region, which completely removed BPA after 30 min. Similar results were also reported by Kavil et al. (2020) whereby a comparison of methylene blue (MB) removal was investigated from seawater against more conventional TiO₂, C/TiO₂, and Cu–C/TiO₂ catalysts. The Cu–C/TiO₂ had the best performance, which achieved maximum efficiency removing 100% MB in 45 min. Xu et al. (2020) prepared porous polymers/TiO₂/Cu (PPTC) through a two-step method and proved it performed better than TiO₂ and TiO₂/Cu. Feng et al. (2019) synthesized Z-scheme Mn-Cds/MoS₂/TiO₂ ternary photocatalyst, proving it had 3.16 times better performance than TiO₂ alone when treating methyl orange (MO) and 9-anthraceneacrylic acids (9-AC). It degraded N,N-dimethylformamide (DMF), MO, MB, and phenol of 73.7%, 97.8%, 100%, and 98.6%, respectively, under 3 h of xenon light exposure. Gmurek et al. (2019) modified TiO₂ catalysts with different metals (TiO₂-Pd, TiO₂-Au, TiO₂-Ag, and TiO₂-Pt) to treat five parabens (methylparaben [MP], ethylparaben [EP], propylparaben [PP], butylparaben [BuP], and benzylparaben [BeP]) and reported their performance under sunlight is better than under UVA. Among these TiO₂ composites, TiO₂-Pd had the best performance, which totally degraded paraben in 120 min. Other composites’ performance under sunlight and UV is shown in Table 3.

The photocatalysts support material also has an impact on photocatalysis. Barbosa et al. (2020) supported TiO₂ on aluminum mesh with H₂O₂ to degrade synthetic dyes Bordeaux Red (BR) and Tartrazine (TT) and achieve >99% degradation efficiency after 180 min. To remove 4-chlorophenol (4-CP), Bibova et al. (2019) coated SiO₂/TiO₂ composite on calcined Liapor, which showed calcined Liapor has the best removal rate among three lightweight substrates (natural cork, Liapor, and Sorbix), with the removal of around 95% in 360 min. Doped Fe/N/S on TiO₂ (Fe/N/S-TiO₂) showed a better removal ability for 4-CP, which achieved a 99.20% removal rate in 180 min (Villaluz et al., 2019). Similarly, S. Li, Hao, et al. (2018) employed a cellulose nanofiber/TiO₂ aerogel (CNFT) to remove MB and achieve total degradation in 10 h. To modify TiO₂, many studies have applied metal materials. Scott et al. (2019) coated ultrathin MgO overlayer on Ag/TiO₂ nanorods to treat phenol and reported the thickness of MgO coating has a significant impact on photocatalysis. Under optimum conditions, the degradation efficiency is up to 95% in 120 min. Ghanbari et al. (2019) prepared a new N-F-codoped TiO₂/SiO₂ nanocomposite (NFTS) via the sol-gel method to treat a mix of three azo dyes (Basic red 29, Basic blue 41, and Basic yellow 51). This achieved a 58.5% decrease in TOC under solar irradiation, in addition to reducing 100% of Cr(VI). Yuvaraj M. Hunge (2017) synthesized WO₃/TiO₂ thin films through spray pyrolysis and the sonochemical method, which degraded 66% benzoic acid (BA) after 320 min.

Carbon-based material also has been applied for TiO₂ photocatalysts. Das and Mahalingam (2019) immobilized TiO₂, rGO, and g-C₃N₄ in a polystyrene film under sunlight for the removal of Remazol Turquoise Blue (RTB), which achieved 60% decolorization and 51.43% degradation after 90 min. Also with g-C₃N₄, J. U. Choi et al. (2019) prepared Cu-loaded g-C₃N₄/1D hydrogenated black TiO₂ nanofiber (CuCNBTNF) for aqueous dye pollutant removal, which achieved 86.2% for Rhodamine B.
| Photocatalyst                  | Synthesis method                                      | Pollutants       | Illumination | Result                                      | Reference                        |
|-------------------------------|-------------------------------------------------------|------------------|--------------|---------------------------------------------|----------------------------------|
| TiO$_2$-P25 on the fiber mat  | Dryer method                                          | AO 7             | Sunlight     | Decolorization in 20 min                   | (Adamek et al., 2019)            |
| N-GQD$_x$/TiO$_2$             | Hydrothermal and physical mixing methods              | BPA              | Sunlight     | 30 min, 100%                               | (Lim et al., 2019)               |
| TiO$_2$, C/TiO$_2$, Cu-C/TiO$_2$ | Hydrolysis method                                      | MB               | Sunlight     | 60 min, 44%                                | (Kavil et al., 2020)             |
| PPTC                          | Hydrothermal and vacuum mixed methods                 | DMF, MO, MB, phenol | 500 W Xe lamp | 3 h, degradation rate: 73.7%, 97.8%, 100%, 98.6% | (Xu et al., 2020)                |
| Z-scheme Mn-CdS/MoS$_2$/TiO$_2$ ternary | Hydrothermal method (Feng et al., 2017)            | MO, 9-AC         | 300 W xenon arc lamp | 100 min, 98%; 35 min, 100% | (Feng et al., 2019)              |
| TiO$_2$-Pd                    | Photodeposition method                                | Parabens         | Sunlight     | 120 min, 100%                              | (Gmurek et al., 2019)            |
| TiO$_2$-aluminum meshes       | Sonochemical method (Barbosa et al., 2019; de Barros et al., 2014) | BR, TT           | Sunlight     | 180 min, 99%                               | (Barbosa et al., 2020)           |
| Fe/N/S-TiO$_2$                | Sol-gel method                                        | 4-CP             | Sunlight     | 180 min, 99.20%                            | (Villaluz et al., 2019)          |
| SiO$_2$/TiO$_2$/calcined Liapor | Utility model (Jirkovsky et al., 2013)                | 4-CP             | Photoreactor with 10 fluorescent black lamps | 360 min, 95%                      | (Bibow et al., 2019)             |
| CNFT                          | Hydrothermal methods                                  | MB               | Sunlight     | 10 h, 100%                                 | (Li, Hao, et al., 2018)          |
| MgO@Ag-TiO$_2$                | Photodeposition method and ALD system (Zhao et al., 2017) | Phenol           | 150 W Oriel® S1A system | 120 min, 95% | (Scott et al., 2019)               |
| NFTS                          | Sol-gel method                                        | Basic red 29, Basic blue 41, Basic yellow 51 | Sunlight with photoreactor | 12 h, TOC removal rate: 58.5% | (Ghanbari et al., 2019)          |
| WO$_3$/TiO$_2$ thin films     | Spray pyrolysis and sonochemical method                | BA               | Sunlight     | 320 min, 66%                               | (Hunge, 2017)                   |
| TiO$_2$/rGO/g-C$_3$N$_4$ nanocomposite | Staudenmaier’s (Moo et al., 2014) and calcination (Shen et al, 2017) methods | BTB              | Sunlight     | 90 min, 60% decolorized, 51.43% degraded   | (Das & Mahalingam, 2019)         |
| CuCNBTNF                      | Photodeposition, thermal polymerization, and hydrogenating methods | RhB              | 150 W xenon lamp | 5 h, 86.2%                                | (Choi et al., 2019)             |
| NiS/RGO/TiO$_2$               | Hydrothermal method                                   | TCP              | Sunlight     | 6 h, 95%                                    | (Alenizi et al., 2020)          |
(RhB) in 5 h. Alenizi et al. (2020) synthesized nickel sulfide-reduced graphene oxide-titanium dioxide (NiS/RGO/TiO₂) nanocomposite, which degraded 95% of trichlorophenol (TCP) in 6 h.

**ZnO composites**

ZnO composite photocatalysts are also applied for textile and organic wastewater treatment. The majority use metal materials to modify ZnO composites. For instance, Alseroury (2018) prepared ZnO/Mn₃O₄ to treat 4-bromophenol (4-BP) and 4-CP, which achieved a >95% removal rate for both pollutants in 240 min. Similarly, Duan et al. (2020) used a two-step hydrothermal method to synthesize ZnO/Bi₂WO₆ and proved that its photocurrent intensity is three times that of ZnO and Bi₂WO₆. Rafie et al. (2019) used Fe³⁺-doped ZnO to treat Reactive Black 5 (RB5) bisazo dye, and the degradation rate was observed to be up to 98.32% within 3 h. Hu et al. (2019) doped Ce on ZnO rods via the one-step pyrolysis method and found that 3% Ce exhibited the best RhB degradation rate, which degraded 97.66% within 2 h. Rachna et al. (2020) coupled Prussian blue (FeHCF) on ZnO through a solvothermal method to treat phenol, 3-aminophenol (3-AP), and 2,4-dinitrophenol (2,4-DNP) under sunlight and achieved the maximum 95%, 97%, and 93% degradation efficiency, respectively. Wei et al. (2019) prepared Fe₃O₄/ZnO/ZnS for MB removal, which removed 75.3% within 4 h. The Ag-coated ZnO nanoflowers show a similar result with about 98.32% MB degradation efficiency (Shahid et al., 2020). Recently, Bora et al. (2022) synthesized Ag₃PO₄/ZnO via a simple precipitation route and reported it can achieve a totally TOC removal for MB wastewater in 30 min and 32% disinfection of *Escherichia coli* in an hour.

Along with the photocatalytic material, the structure of the photocatalytic material has a significant impact on photocatalysis performance. Serra, Zhang, et al. (2019) synthesized ZnO-based biomimetic fern-like microleaves and found ZnO@ZnS micro/nanoferns had the best photo-remediation performance for persistent organic pollutants compared with ZnO, Ag-ZnO, and Ni-ZnO, which increased over sixfold for pollutant degradation rate capacity compared with pristine ZnO catalyst. The following research using the same bioinspired ZnO@ZnS photocatalyst achieved nearly 97% of MB after 60 min with mineralization of >98% of a mixture of MB, 4-nitrophenol (4-NP), and RhB after 210 min and the removal of nearly 65% of Cr(VI) after 180 min (Serra, Gomez, & Philippe, 2019). Recently, Bora et al. (2022) used a waste material-ground granulated blast furnace slag (GGBFS) as a low-cost geopolymer to hybridize with ZnO. They found that, due to the increased surface area, the discoloration efficiency of textile wastewater is twice better than normal ZnO (Table 4).

**Other composites**

Along with ZnO and TiO₂ composites, other metallic oxides have been extensively investigated for their organic pollutant degradative capacity. For instance, to treat colored azo dye effluents, dos Santos et al. (2019) used Nb₂O₅ to treat MO, which achieved complete decolorization with H₂O₂ in 40 min. Kalin-Fe₄O₉ had a similar performance, which removed 99.8% of RhB (Reddy et al., 2020). Abukhadra et al. (2018) synthesized bentonite/polyaniline composite (BE/PANI) as support for Ni₃O₄ (BE/PANI@Ni₃O₄), which reduced the band gap from 3.4 eV for pure Ni₃O₄ to only 1.61 eV, which totally removed safranin-O dye after 90 min. Similarly, for ponceau SS dye, Jung et al. (2020) modified sodium vermiculite and achieved an 84.1% degradation rate in 360 min.

Besides metallic oxides, metallate photocatalysts also have been widely developed. Zinatloo-Ajabshir et al. (2020) created nanostructured silver tungstate (Ag₂WO₄) by sonochemical pathway and reported that it can degrade 94.23% of Acid red 14 (AR14), 96.31% of eriochrome cyanine R (ECR), and 100% of RhB within 60 min. Similarly, an all-day-active photocatalyst was synthesized by employing Ag@AgI NPs decorated with Ag₃PO₄ cubes (C-Ag₃PO₄@Ag@AgI) designed by Cai et al. (2019), which completely degraded RhB and removed 80% of BPA in 80 min under sunlight. They also reported that this photocatalyst can maintain photocatalytic activity even on a cloudy day. Bora and Mewada (2017) synthesized Ag₃CO₃/SiC through a simple precipitation route and found that SiC improves Ag₃CO₃ photoactivity by inducing a charge transfer between SiC and Ag₃CO₃ mimicking the Z-scheme in photosynthesis, which removes 98% of MB in 4 h. X. Han et al. (2020) developed (Mg,Ni)(Fe,Al)₂O₄, which is a heterogeneous PF-like catalyst that can degrade over 90.0% of common organic dyes within 180 min. Yadav et al. (2019) used nanoflower-like FeCo₃O₄ to remove crystal violet (CV) and achieved a 94.19% removal rate in 160 min. Khan et al. (2019) electro-deposited nickel nitrate powder [Ni(NO₃)₂·6H₂O] inside the aluminum template to prepare one-dimensional Ni nanorods to remove methyl red (MR) and MO. It achieved complete degradation in 40 and 60 min, respectively. For MB, Dong et al. (2019) used ZnSn(OH)₆ nanocubes as the catalyst and, after 5 h of sunlight irradiation, achieved a 76.3% removal rate. Senthlinathan et al. (2019) deposited thin films of akaganeite (FeO(OH)) nanorices on muscovite mica surfaces (ANPM) and reported its MB degradation efficiencies...
### Table 4: ZnO composites for textile and organic wastewater treatment

| Photocatalyst                | Synthesis method                  | Pollutants                  | Illumination          | Result                  | Reference          |
|-----------------------------|-----------------------------------|-----------------------------|-----------------------|-------------------------|--------------------|
| ZnO/Mn$_3$O$_4$             | Chemical precipitation method     | 4-BP, 4-CP                  | Sunlight              | 240 min, >95%           | (Alseroury, 2018) |
| ZnO/Bi$_2$WO$_6$            | Hydrothermal method               | Phenol, p-chlorophenol, p-nitrophenol | 350 W xenon lamp     | 150 min, 99.3%, 100%, 100% | (Duan et al., 2020) |
| Fe$^{3+}$-doped ZnO         | Microwave-assisted sol-gel method | RB5                         | 72 W D65 lights       | 3 h, 98.32%             | (Rafie et al., 2019) |
| Ce/ZnO                      | Pyrolysis method                  | RhB                         | Sunlight stimulator   | 2 h, 97.66%             | (Hu et al., 2019)  |
| ZnO@FeHCF                   | Solvothermal method               | Phenol, 3-AP, 2,4-DNP       | Sunlight              | Degradation efficiency: 95%, 97%, 93% | (Rachna et al., 2020) |
| Fe$_3$O$_4$/ZnO/ZnS nanoparticles | Sol-gel method                 | MO, MB                      | Sunlight              | 4 h, 79.5%, 75.3%       | (Wei et al., 2019) |
| Ag-coated ZnO nanoflowers   | Template, hydrothermal, photoreduction methods | MB                         | Sunlight              | 3 h, removal rate: 98.32% | (Shahid et al., 2020) |
| ZnO/pumice                  | Incipient impregnation method     | Effluent from Nike Art Gallery | Sunlight              | 45.04 min, degradation efficiency: 90.17% | (Yusuff et al., 2020) |
| Ag$_2$CO$_3$/ZnO            | Precipitation                     | MB and *Escherichia coli*   | Sunlight              | 0.5 h, 100% TOC removal 1 h, 32% disinfection | (Bora et al., 2022) |
| ZnO@ZnS core@shell          | As-electrodeposited method        | MB, 4-nitrophenol, RhB, MB; a mixture of MB, 4-NP, and RhB; Cr (VI) | UV-filtered sunlight | 120 min, ~99%          | (Serra, Zhang, et al., 2019) |
|                            |                                   |                             | Sunlight              | 60 min, 97%; 210 min, >98%; 180 min, 65% | (Serra, Gomez, & Philippe, 2019) |
| GGBFS@ZnO                   | -                                 | Textile wastewater          | Sunlight              | Discoloration efficiency is twice better than normal ZnO | (Bora et al., 2022) |
Better removal efficiency is achieved by MnFe2O4/ZrO2 nanocomposite, which removes 95% MB in 90 min (Meena et al., 2020). Ahmed et al. (2020) used nanosized iron (FeNPs) solely to remove lizarin yellow R (AYR) dye, and in 42 h, 93.7% of AYR was degraded. Y. M. Hunge et al. (2019) prepared Cu2ZnSnS4 (CZTS) for phthalic acid (PA) removal and achieved a 56% removal rate in 240 min. Mota et al. (2020) prepared Zn(II)-porphyrin/poly(acrylic acid) (Zn(II)Pr@PAA) hybrid microparticles though and tested its performance by degrading MB, MO, and nitrobenzene (NB), which achieved above 96% chemical oxygen demand (COD) removal rate in 90 min. For azo dyes, Cubas et al. (2020) synthesized CuCr2O4 and removed 99.6% of it in 120 min.

Bismuth-based compounds have been recognized as promising visible light-responsive photocatalysts due to their unique layer structure and tremendous capacity for visible light absorption (Dutta et al., 2020; Q. Han, 2020; Z. J. Liu et al., 2019). Some investigations have been carried out recently to invest and enhance their performance. Z. J. Liu et al. (2019) constructed flower-like BiOCl/BiOCOOH p-n heterojunctions via an in situ anion-exchange strategy and totally removed MO dyes in 50 min. Similarly, 3D flower-like Ag/AgCl/BiOCOOH ternary heterojunction photocatalyst was used to remove RhB and CIP, which achieved 100% and 86.9% removal efficiency, respectively (S. J. Li, Xue, et al., 2019). They also prepared flower-like Ag2CO3/BiOCOOH to remove RhB and MB, which achieved 100% removal efficiency in 30 min and 100% in 60 min (S. J. Li, Mo, et al., 2018). Jung et al. (2020) removed trichloroethylene (TCE) from the solution using BiOBr enhanced by sulfite addition and achieved dechlorination efficiency ($R_{\text{dech}}$) by about 58%. Similarly, to treat perfluorooctanoic acid (PFOA), Sun et al. (2019) used a microwave solvothermal method to apply BiOCl with oxygen vacancies and its removal efficiency was 2.7 and 33.8 times higher than that of BiOCl fabricated by the conventional solvothermal and precipitation methods (Song et al., 2017). In addition, synthesis methods can also affect photocatalysts’ performance. Y. F. Li, Zhong, et al. (2018) compared Bi2Ti2O7 photocatalytic ability prepared by co-precipitation and solvothermal method and found that the Bi2Ti2O7 photocatalyst via co-precipitation method had better performance (240 min, 92.8% removal). Bismuth-based catalysts can also be modified with other compounds. T. Liu et al. (2014) compared a pure Bi2Mo3O12 sample with Bi2Mo3O12/MoO3, due to the excellent adsorption behavior of MoO3, Bi2Mo3O12/MoO3 showed an obviously enhanced photocatalytic activity, which removes 92% of MB.

Carbon-based materials also have a variety of applications in visible light active photocatalysis. Wang, Li, et al. (2020) synthesized sulfuric acid-treated graphitic carbon nitride (SA-g-C3N4) by thermal polymerization and chemical exfoliation methods embedded within a porous cellulose network (CN/CA film) (T. Li et al., 2013; Xu et al., 2013), which removed ~99% RhB in 150 min and reduced 95% of Cr(VI) in 100 min. Mishra et al. (2020) used RGO-V2O5 nanocomposite, which degraded 71% of MB in 20 min. A complete MB degradation was achieved by a hybrid of Zr-based metal-organic framework (UiO-66) with graphitic carbon nitride (g-C3N4) nanosheets (UiO-66/g-C3N4 sheets) photocatalysts within 240 min (Zhang et al., 2018). A similar result from V2O5/S-g-C3N4 was achieved by Chegeni et al. (2019) for MB and phenol treatment, which achieved a 99% and 89% removal rate within 60 min, respectively (Figure 3). Also, El-Sheshtawy et al. (2019) immobilized Ag on g-C3N4/V2O5.

![Figure 3](image-url)
surface to enhance its photocatalytic activity, which can totally reduce p-nitrophenol (NP) within 8 min under sunlight. They also reported that this photocatalyst only needs 60 min to totally reduce 4-NP and 4-AP in dark. Priyanka et al. (2020) synthesized sulfur-doped graphene oxide (sGO/Ag3VO4/Ag) through Hummers’s method (Hummers & Offeman, 1958) with a one-pot method that can degrade above 99% cationic dyes, 75%–80% anionic dyes, and 90% organic carbon in 1 h under sunlight. Sharma et al. (2019) used activated carbon-supported strontium/cerium bimetallic nanocomposite (Sr/Ce/AC BNC) to degrade RhB and reach 91% total degradation in 120 min. The wastewater mixture of MB and RhB was treated by MoS2/rGO/Cu2O grown on etched carbon paper, and 95% of MB and RhB are degraded in 45 min (Gopalakrishnan et al., 2020). The complete removal of MB was achieved by flexible graphene composites (FGCs) with Al2O3:Eu3+ and SrAl2O4:Bi3+ catalysts, respectively, after 180 and 270 min (Oliva et al., 2018).

Apart from the heterogeneous photocatalyst covered above, Sharmila et al. (2020) prepared mixed Spirulina platensis cultivated water (Sp cw) as a homogeneous photocatalyst motivated by its benign chemical composition and eco-friendly properties. This catalyst was shown to remove a mixture of 5 ppm of MB, 70 ppm of malachite green (MG), and 6 ppm of congo red (CR) within 3 h (Table 5).

**Pharmaceutical wastewater**

Pharmaceutical wastewater typically contains persistent organic pollutants that contain a high concentration of organic matter, microbial toxicity, and high salt content, which is difficult to biodegrade, and municipal water resource recovery facility cannot treat pharmaceutical wastewater effectively (Ahmad et al., 2017; Guo et al., 2017; Keshvadi et al., 2020). Pharmaceuticals and their metabolites, even at low concentrations, have potentially fatal effects on natural ecosystems and human health (He et al., 2020; Keshvadi et al., 2020). For example, the occurrence of antibiotics in an aquatic environment can develop antibiotic resistance (Ben et al., 2019; Walsh, 2013; Wang, Chen, et al., 2020). In addition, it has been shown that 58%–68% of consumed common mild analgesic medicine acetaminophen (ACE) is released into the environment, which may transform to N-acetyl-p benzoquinone-imine causing protein denaturation, lipid peroxidation, and DNA damage to organisms (Behravesh et al., 2020; Tobajas et al., 2017).

TiO2 composites are also common for pharmaceutical wastewater treatment. Shaniba et al. (2020) synthesized TiO2/nitrogen-doped holey graphene (TiO2/NHG) nanocomposite via hydrothermal and calcination methods to treat antibiotic cefixime and achieve complete mineralization in 25 mg/L concentration within 90 min. Using similar catalysts involving nitrogen-doped TiO2 (N-TiO2), Keshvadi et al. (2020) treated carbamazepine (CBZ), diclofenac (DCF), and trimethoprim (TMP) under sunlight. The high removal efficiency of up to 100% was observed. Similarly, Martins et al. (2019) used Pd-TiO2 and Ag-TiO2 to treat the mixture of sulfamethoxazole (SMX), CBZ, and lorazepam (LRZ). Pd-TiO2 showed the best performance with total compound degradation in 15 min, and both of them had better removal ability than pure TiO2. Sacco et al. (2019) prepared nitrogen-doped TiO2 coupled with ZnS blue phosphors (NTZsP_PS) and removed >95% of the antibiotic ceftriaxone (CEF). Alternatively, Amini et al. (2019) used magnetic TiO2/SiO2/Fe3O4 nanocomposite doped with nitrogen (NTSF) and achieved a 96.32% degradation rate of naproxen (NPX). TiO2 also can combine with carbon-based material to treat pharmaceutical wastewater. Cunha et al. (2019) synthesize TiO2/AC to treat benzodiazepine drugs via the impregnation method and reported that TiO2/AC10% (w/w) had the best removal efficiency of >97.5% within 60 min. Shinde et al. (2018) synthesized Pt-rGO-TiO2 to treat pharmaceutical pollutant β blocker Propranolol and showed a 20-fold increase in removal (COD removal rate: 94%) under simulated solar light compared with TiO2 alone under UV exposure. Notably, the contaminant degradative performance of TiO2 composites may not always be better than a simple conventional TiO2 catalyst. Palma et al. (2020) treated antibiotic chloramphenicol (CAP) and paracetamol (N-(4-hydroxyphenyl)acetamide) by TiO2 and PbS/TiO2. The results showed that TiO2 alone can remove 5% more CAP in 240 min than the PbS/TiO2 composite and can completely remove paracetamol in 235 min whereas PbS/TiO2 only removes 93% in 240 min. Moreover, Behravesh et al. (2020) compared the removal ability between zeolite-supported TiO2 (TiO2-Z) and ZnO (ZnO-Z) to degrade ACE and codeine and reported that ZnO-Z has better removal efficiency.

Other metallate photocatalysts also have been invested to remove organic contaminants. To remove the antibiotic tetracycline hydrochloride (TC), Z. J. Liu et al. (2019) synthesized flower-like BiOCl/BiOOCOH p-n heterojunctions, which achieved 80.4% removal efficiency in 60 min. AgI/Bi4O3I2Cl8 shows a similar degradation efficiency for TC, which degrades 85.35% in 1 h. It also can reduce 78.26% of Cr(VI) within 1 h (B. S. Li, Lai, et al., 2019). A better removal ability was achieved by (Mg,Ni)(Fe,Al)2O4 heterogeneous PF-like catalyst, which degraded 90% of TC within 180 min (X. Han et al., 2020), and S. J. Li, Mo, et al. (2018) used flower-like AgxCO3/...
| Photocatalyst                          | Synthesis method                                                                 | Pollutants                  | Illumination     | Result                                | Reference                                      |
|---------------------------------------|----------------------------------------------------------------------------------|----------------------------|-----------------|---------------------------------------|------------------------------------------------|
| Nb$_2$O$_5$                            | Calcined method                                                                  | MO                         | Sunlight        | 100% decolorized                      | (dos Santos et al., 2019)                     |
| Kaolin-Fe$_2$O$_3$                     | Sol-gel method                                                                   | RhB, CIP                   | Sunlight        | 60 min, RhB, 99.8%; COD, 88.3%       | (Reddy et al., 2020)                          |
| BE/PANI@Ni$_3$O$_3$                    | In situ polymerization and oxidation (Dey et al., 2015) methods                  | Safranin-O dye             | Sunlight        | 90 min, 100%                          | (Abukhadra et al., 2018)                      |
| Modified sodium vermiculite           | Cationic exchange with NaCl (Batista et al., 2019)                               | Ponceau SS dye             | Sunlight        | 360 min, 84.1%                       | (Jung et al., 2020)                           |
| Ag$_3$WO$_4$                           | Sonochemical                                                                     | RA14, ECR, RhB             | 125 W Osram lamp | 60 min, removal rate: 94.23%, 96.31%, 100% | (Zinatloo-Ajabshir et al., 2020)              |
| C-Ag$_3$PO$_4$@Ag@AgI                 | Ion-exchange method                                                              | RhB, BPA                   | Sunlight        | 80 min, 100%; 80%                     | (Cai et al., 2019)                            |
| Ag$_2$CO$_3$/SiC                       | Precipitation                                                                    | MB                         | Sunlight        | 4 h, 98%                              | (Bora & Mewada, 2017)                         |
| (Mg,Ni)(Fe,Al)$_2$O$_4$                | Hydrochloric acid leaching (Yan et al., 2015) and co-precipitation–calcination methods | Common organic dyes      | Xenon lamp (with an AM 1.5 G filter) | 180 min, 90.0%                        | (Han et al., 2020)                            |
| Nanoflower-like FeCo$_2$O$_4$          | Hydrothermal method (Yadav et al., 2018) with ultrasonic probe sonicator         | CV                         | Sunlight        | 160 min, 94.19%                       | (Yadav et al., 2019)                          |
| Ni (NO$_3$)$_2$·6H$_2$O                 | Electrodeposition method                                                         | MR, MO                     | Sunlight        | 40 min, 100%; 60 min, 100%           | (Khan et al., 2019)                           |
| ZnSn (OH)$_6$ nanocubes                | Liquid precipitation and hydrothermal methods                                     | MB                         | Sunlight        | 5 h, removal rate: 76.3%              | (Dong et al., 2019)                           |
| ANPM                                  | Hydrothermal method                                                              | MB                         | Sunlight        | 180 min, 89%                          | (Senthilnathan et al., 2019)                  |
| MnFe$_2$O$_4$/ZrO$_2$ nanocomposite    | Solution combustion method                                                       | MB, textile dye wastewater | Sunlight        | 90 min, degradation rate: 95%, 59%    | (Meena et al., 2020)                          |
| FeNPs                                 | Biosynthesis method                                                             | AYR                        | Sunlight        | 42 h, removal rate: 93.7%             | (Ahmed et al., 2020)                          |
| CZTS                                  | Sonochemical method                                                             | PA                         | Sunlight        | 240 min, 56%                          | (Hunge et al., 2019)                          |
| Zn (II)Pr@PAA                          | Reverse emulsion method                                                         | MB, MO, NB                 | Sunlight        | 90 min, COD removal rate: 96%         | (Mota et al., 2020)                           |

(Continues)
| Photocatalyst                        | Synthesis method                                  | Pollutants     | Illumination                                      | Result                  | Reference                        |
|------------------------------------|---------------------------------------------------|----------------|--------------------------------------------------|-------------------------|----------------------------------|
| CuCr$_2$O$_4$                      | Self-combustion method                            | Azo dyes       | 125 W high-pressure mercury lamp                  | 120 min, 99.6%          | (Cubas et al., 2020)             |
| Flower-like BiOCl/ BiOCOOH p-n heterojunctions | Solvothermal and in situ anion-exchange methods  | MO             | 300 W Xe lamp                                    | 50 min, 100%            | (Liu et al., 2019)               |
| 3D flower-like Ag/AgCl/ BiOCOOH ternary heterojunction photocatalyst | Solvothermal, in situ precipitation methods, light reduction methods | RhB; CIP       | 300 W Xe lamp                                    | 30 min, 100%; 86.9%     | (Li, Xue, et al., 2019)          |
| Flower-like Ag$_2$CO$_3$/ BiOCOOH | Solvothermal method                               | RhB; MB        | 300 W xenon lamp                                 | 30 min, 100%; 60 min, 100% | (Li, Mo, et al., 2018)          |
| BiOBr/sulfite                      | Hydrothermal method                               | TCE            | 100 W Xr arc lamp/reflector                       | 120 min, R$_{dech}$ 58%; 300 min, R$_{dech}$ 57% | (Jung et al., 2020)             |
| BiOCl                              | Microwave solvothermal method (Cui et al., 2018)  | PFOA           | 300 W xenon lamp                                 | 8.5 h, 68.8%            | (Sun et al., 2019)              |
| Bi$_3$Ti$_2$O$_7$                  | Co-precipitation method                            | RhB            | 300 W xenon lamp                                 | 240 min, 92.8%; 240 min, 74% | (Li et al., 2018)               |
| Bi$_2$Mo$_3$O$_{12}$/MoO$_3$        | Precursor suspension                              | MB             | 300 W Xe light with a 420 nm cutoff filter        | 90 min, 92%             | [176]                            |
| SA-g-C$_3$N$_4$/CN/CA film         | Thermal polymerization and chemical exfoliation methods | RhB; Cr (VI)  | Sunlight                                          | Removal rate: 150 min, 99%; 100 min, 95% | (Wang, Zhu, et al., 2020)       |
| RGO-V$_2$O$_5$                     | Hummer’s and sol-gel method                       | MB             | 40 W tube light                                   | 20 min, removal rate: 71% | (Mishra et al., 2020)           |
| UiO-66/g-C$_3$N$_4$                | Calcination and thermal method                    | MB             | 350 W xenon lamp                                 | 240 min, 100%           | (Zhang et al., 2018)            |
| V$_2$O$_5$/S-g-C$_3$N$_4$          | Thermally method                                  | MB; phenol     | Sunlight                                          | 60 min, 99%; 89%        | (Chegeni et al., 2019)          |
| Ternary Ag/g-C$_3$N$_4$/V$_2$O$_5$ | Photodeposition method                            | 4-NP, 4-AP     | Sunlight                                          | 8 min, 100%             | (El-Sheshtawy et al., 2019)     |
| SGO-Ag$_3$VO$_4$/Ag                | Hummer’s method, the one-pot method               | Cationic dyes, anionic dyes, organic carbon | Sunlight                                          | 1 h, degradation rate: 99%, 75%–80%, 90% | (Priyanka et al., 2020)         |
| Sr/Ce/AC BNC                       | Microwave reduction method                        | RhB            | Sunlight                                          | 120 min, 91%            | (Sharma et al., 2019)           |
BiOCOOH to remove TC, which achieved 93.4% degradation efficiency in 120 min. To degrade LOM (lomefloxacin), Zhang et al. (2020) fabricate Bi$_2$O$_3$/CuNiFe layered double hydroxide (LDH) composite photocatalyst through the co-precipitation method, which removes 84.6% of LOM (10 mg/L) in 40 min. For antibiotic levofloxacin (LEV) treatment, Wang, Chen, et al. (2020) prepared MnO@MnOx microspheres via the solvothermal method, which achieves 98.1% degradation and 81.4% mineralization in 30 min. To remove antibiotic ofloxacin (OFX), Geng et al. (2019) prepared Co$_3$(PO$_4$)$_2$/Ag$_3$PO$_4$ composites, which achieved 88.8% degradation efficiency in 5 min. Tie et al. (2019) employed N-doped ZnS photocatalyst and achieved a 99% removal rate for metronidazole (MTR). To apply the principle of “waste may govern waste,” Domingues et al. (2020) used red mud considered waste from the metal production industry to treat the organic waste compounds of CBZ, LRZ, and SMX and achieved 58%, 62%, and 51% removal efficiency, respectively (Table 6).

**Disinfection**

Worldwide, it is estimated that 844 million people still do not have access to basic drinking water services, and 159 million people in rural areas use untreated drinking water, which potentially may expose them to health risks from contaminated water sources (World Health Organization & Unicef, 2017; Yan et al., 2020). For example, 4 billion cases of diarrhea each year are caused by inadequate hygiene and sanitation drinking water (Danwittayakul et al., 2020; World Health Organization & Unicef, 2015). Compared with traditional drinking water disinfection methods, like adsorption, coagulation, chemical, and physical disinfection, solar disinfection (SODIS) is much cheaper and easier to access in most areas, and it can be environmentally favorable to inactivate microorganisms in natural surface waters and drinking water (Garcia-Gil et al., 2020; Malato et al., 2009; Rodriguez-Chueca et al., 2019; Zeng et al., 2020). In recent years, photocatalytic disinfection has sparked much attention and established a trend to replace traditional solar disinfection (Djellabi et al., 2020; Vivar et al., 2020; Yan et al., 2020). Just like the mechanism of photocatalytic degradation of pollutants, photocatalysts can produce hydroxyl radical (·OH), h$^+$, and superoxide radical (·O$_2^-$), which also can deactivate pathogens’ destroying cell membrane structure to achieve disinfection (Ge et al., 2016; Zeng et al., 2020).

TiO$_2$ composite catalysts are very common for water disinfection applications. Yan et al. (2020) used an anodic oxidation method to fabricate MoS$_2$/TiO$_2$ nanotube arrays and investigated its inactivation ability by treating
| Photocatalyst | Synthesis method | Pollutants | Illumination | Result | Reference |
|--------------|-----------------|------------|--------------|--------|-----------|
| TiO$_2$/NHG  | Hydrothermal and calcination | Cefixime | Sunlight | 90 min, removal rate: 100% | (Shaniba et al., 2020) |
| N-TiO$_2$    | Sol-gel method (Sacco et al., 2012) | CBZ; DCF; TMP | Sunlight | 247 min, 32%; 270 min, 100%; 300 min, 5% | (Keshvadi et al., 2020) |
| Pd-TiO$_2$   | Sol-gel and photodeposition (Gomes et al., 2017) methods | SMX, CBZ, LRZ | Sunlight | 15 min, 100%; 60 min, 100% | (Martins et al., 2019) |
| Ag-TiO$_2$   | Sol-gel method (Sacco et al., 2012) | CEF | Sunlight | 150 min, >95% | (Sacco et al., 2019) |
| NTZp-PS      | Sol-gel method (Sacco et al., 2012) | NPX | Sunlight | 217.06 min, 96.32% | (Amini et al., 2019) |
| TiO$_2$/AC   | Impregnation method | Benzodiazepine drugs | OSRAM 300 W Ultra-Vitaluz lamp | 60 min, 97.5% | (Cunha et al., 2019) |
| Pt-rGO-TiO$_2$ | Hydrothermal method | β blocker Propranolol | 1000 W xenon lamp | 4 h, 94% | (Shinde et al., 2018) |
| TiO$_2$      | - | CAP; paracetamol | Sunlight | 240 min, 98%; 235 min, 100% | (Palma et al., 2020) |
| PbS/TiO$_2$  | Sulfide produced in the UAPB reactor | | | 240 min, 93%; 93% | |
| TiO$_2$-Z    | Solution mixing method (Hosseini et al., 2007) | ACE-codeine | Sunlight | 2 h, 39.2% | (Behravesh et al., 2020) |
| ZnO-Z        | Hydrothermal impregnation method (Byrappa et al., 2006) | | | 2 h, 45.7% | |
| Flower-like BiOCl/BiOCOOH p-n heterojunctions | Solvothermal and in situ anion-exchange methods | TC | 300 W Xe lamp | 60 min, 80.4% | (Liu et al., 2019) |
| AgI/Bi$_{34}$O$_{53}$Cl$_{10}$ | Solvothermal and in situ precipitation methods | TC; Cr (VI) | 300 W xenon lamp | 1 h, 85.34%; 78.26% | (Li, Lai, et al., 2019) |
| (CuC$_{10}$H$_{26}$N$_6$)$_3$(PW$_{12}$O$_{40}$)$_2$/AgCl@Ag | In situ co-precipitation method | TC; DNP | 500 W Xe arc lamp | 2 h, 85%; 65% | (Chen et al., 2019) |
| Flower-like Ag$_3$CO$_3$/BiOCOOH | Solvothermal method | TC | 300 W xenon lamp | 120 min, 93.4% | (Li, Mo, et al., 2018) |
| Bi$_2$O$_3$/CuNiFe LDH | Co-precipitation | LOM | 35 W xenon lamp | 40 min, 84.6% removal rate | (Zhang et al., 2020) |
| MnO@MnO$_x$ | Solvothermal | LEV | 500 W xenon lamp | 30 min, 98.1% degradation and 81.4% mineralization | (Wang, Chen, et al., 2020) |
| Co$_3$(PO$_4$)$_2$/Ag$_3$PO$_4$ | Hydrothermal method | OFX | 300 W Xe lamp | 5 min, 88.8% | (Geng et al., 2019) |
| N-ZnS        | Solvothermal method | MTR; CIP | Sunlight | 150 min, 99%; 42% | (Tie et al., 2019) |
E. coli ATCC 25,922 (E. coli 25922) and Methicillin-resistant *Staphylococcus aureus* (MRSA). The result shows that the bacteria have been completely inactivated after 150 min with up to 98.5% disinfection efficiency. Fernández-Ibáñez et al. (2015) developed TiO$_2$-rGO via a sonochemical method. Importantly, they proved that the concentration of TiO$_2$-rGO may not be proportional to disinfection efficiency. At 500 mg/L of TiO$_2$, only 10 min of solar treatment can completely inactivate *E. coli*. On the contrary, the best *F. solani* inactivation efficiency was observed for 10 mg/L, requiring 30 min of treatment for complete inactivation. Waso et al. (2020) also used the same material by the same preparation method to treat rainwater and removed all *Klebsiella pneumoniae* (from 2.00 x 10$^9$ CFU/ml to below the detection limit [BDL]) with 120 min of natural sunlight exposure after pre-treatment by *Bdellovibrio bacteriovorus*.

ZnO composites have also been extensively investigated. Danwittayakul et al. (2020) synthesized ZnO nanorods on cellulose and polyester substrates, which achieved nearly total disinfection within 15 min. A similar result was achieved by Yadav et al. (2019), where ZnO NPs were applied to enhance solar disinfection for fecal coliforms with compound parabolic concentrators. The result showed that there was complete inactivation within 15 min, which was a 50% improvement without using ZnO (Table 7).

### Other application

Visible light active photocatalyst also applies in many other fields. In agriculture, to deal with the enormous use of pesticides, Balasubramanian et al. (2020) used Ag$_3$PO$_4$/polyaniline@g-C$_3$N$_4$ to treat monocrotophos (MCP), a hazardous pesticide. By using the 150 W Xe arc lamp with a UV (λ > 400 nm) cutoff filter to simulate sunlight, it removed 99.6% MCP. To treat 2, 4-dichlorophenoxy acetic acid (2, 4-D), methyl chlorophenoxy propionic acid (MCPP), and 3, 6-dichloro-2-methoxy benzoic acid (Dicamba), which are present in many of the shelf herbicide products, Heydari et al. (2019) used Buoyant titanium dioxide (TiO$_2$)-coated glass spheres and achieved 99.8%, 100%, and 99.4% removal rate, respectively. To treat chlorpyrifos (CP), thiamethoxam (TH), and tebuconazole (TEB), Rani and Shanker (2018) prepared metal hexacyanoferrate NPs (ZnHCF, CuHCF, NiHCF, and CoHCF), which all have direct low band gap, and the best degradation was achieved by ZnHCF (98% CP; 95% TH; and 91% TEB). Also, combining olive stone activated carbon (OSAC), ozone, and Solar-Simulated Radiation (SSR) system has
been reported can remove the pyridine-based herbicides clopyralid completely (Rajah et al., 2019).

For urban wastewater treatment, Chavez et al. (2020) supported magnetite and TiO₂ onto graphene combined with ozone and successfully treated the effluent of an urban wastewater treatment facility with 10 well-known micropollutants. Similarly, Kaur et al. (2020) used rGO-TiO₂ to remove triclosan totally in actual urban wastewater. In marine conservation, Qiu et al. (2019) deposited the metal semiconductor (BiOI) on the expanded perlite (EP), which is able to degrade 86% of diesel-contaminated seawater within 2 h.

To reduce Cr(VI), Zhang et al. (2019) synthesized Iron(III)-alginate (Fe-SA) hydrogel beads, which reduced Cr(VI) up to 100% within 150 min. Nitrogen–phosphorus-doped fluorescent carbon dots (NP-CD) show high efficiency for Cr(VI) in a linear range from 10 ppm (in approximately 10 min) to 2000 ppm (in approximately 320 min) (Bhati et al., 2019). To treat nitrate (NO₃⁻-N) and ammonia (NH₄⁺-N), Zhao et al. (2018) synthesized 3D/2D Mn₂O₃/g-C₃N₄ and achieved high removal efficiency of 94.5% and 97.4% for NO₃⁻-N and NH₄⁺-N (Table 8).

## PILOT-SCALE TESTS

### Current research

Over the past number of decades, many studies have invested in visible light active photocatalyst for water treatment. However, only a few of them have entered the pilot-scale test. Based on the Scopus database, only approximately 23 papers have been published about pilot-scale tests in water treatment using visible light/solar active photocatalysts, among them only 14 papers in the past 5 years (2018–2022). In this section, this research that has been successfully tested on a pilot scale will be introduced. Compound Parabolic Collector (CPC) (Figure 4) is widely applied in many photocatalyst pilot-scale tests. Other equipment like falling film photoreactor (FFR) (Figure 5), tubular reactor, and self-made reactor are also applied.

Majority of pilot tests carried out in the last 5 years used TiO₂ with its composites as the photocatalyst. Just using the commercial TiO₂ with CPC, Zuniga-Benitez and Penuela (2020) tested their photodegradation ability for Benzophenone-1 and Benzophenone-2 (BP1 and BP2). The pilot scale was tested in the city of Medellín, Colombia, using a solar compound cylinder-parabolic collector; greater than 90% of BP have been removed after 6 h of reaction (between 10:00 and 16:00 h). Using TiO₂ with CPC for carbapenem antibiotics imipenem and meropenem degradation, they can remove 75% of imipenem after 60 min and 75% of meropenem after 45 min (Cabrera-Reina et al., 2019). For degradation of diphenhydramine hydrochloride (DPH), Lopez et al. (2018) achieved 14,889 mg TOC/kWh demineralization efficiency but under black blue lamps has better efficiency (21,141 mg TOC/kWh). On the contrary, also using TiO₂-P25, Haranaka-Funai et al. (2017) reported that the CPC has the best removal performance for valproic acid sodium salt (VA) treatment (91% VAC removal efficiency and 50% TOC degradation rate) compared with three artificial irradiation (black light blue lamps, UVC, and Xe lamp). Also applied CPC and TiO₂-P25, Grilla et al. (2019) found that the TMP degradation is proportional to SPS concentration and inversely proportional to water matrix complexity. Diaz-Angulo et al. (2020) also used them to remove DCF; by applying MR as the photo-sensitizer,
| Photocatalyst | Synthesis method | Pollutants | Illumination | Result | Reference |
|-------------|------------------|------------|--------------|--------|-----------|
| Ag$_3$PO$_4$ /polyaniline@g-C$_3$N$_4$ | Calcination method (Zhang et al., 2018) | MCP | 150 W Xe arc lamp with an ultraviolet ($\lambda > 400$ nm) cutoff filter | 50 min, 99.6% | (Balasubramanian et al., 2020) |
| TiO$_2$ | - | 2, 4-D, MCP, Dicamba | Sunlight | 99.8%, 100%, 99.4% | (Heydari et al., 2019) |
| ZnHCF | Sapindus mukorossi (Jassal et al., 2015) | CP; TH; TEB | Sunlight | 12 h, 98%; 95%; 91% | (Rani & Shanker, 2018) |
| CuHCF | | | | 12 h, 91%; 89%; 85% | |
| NiHCF | | | | 12 h, 85%; 78%; 73% | |
| CoHCF | | | | 12 h, 83%; 76%; 70% | |
| O$_3$/OSAC/SSR | Najar's method (Ouederni et al., 2006) | Clopyralid | 500 W Xe lamp | 30 min, removal rate: 100% | (Rajah et al., 2019) |
| S-rGO/ZnS | Hummer's and hydrothermal method | - | Sunlight | Enhanced the solubilized chemical oxygen demand by 113% after 6 h | (Barakat et al., 2019) |
| 10-MG1-Ti | Solvothermal method (Cao et al., 2015) | Cotinine, caffeine, ciprofloxacin, metoprolol, sulfamethoxazole, N,N-diethyl-m-toluamide, clofibric acid, bezafibrate, tritosulfuron, ibuprofen | Xe arc lamp | 2 h, 70% TOC removal efficiency | (Chavez et al., 2020) |
the mineralization rate can be increased up to 65%, which removes 99% of DCF and 99% of MB.

Also applied CPC, to treat pesticides in wastewater, Vela et al. (2018b) used two commercial TiO2 nanopowders (Degussa P25 and Kronos vlp 7000) for degradation of a mixture of six pesticides (malathion, fenotrothion, quinalphos, vinclozoline, dimethoate, and fenarimol). After optimized operational conditions under laboratory conditions (Vela et al., 2015), they set up a polie scale test at Murcia, SE Spain (3000 h sun per year). The result showed that the use of TiO2 alongside an electron acceptor like Na2S2O8 can strongly enhance the degradation rate and the best result was achieved by TiO2 Kronos vlp 7000 with Na2S2O8, which achieved 90% degradation (DT90) in 32 min. These photocatalysts also have been tested to treat endocrine disruptors (EDs) at a pilot plant scale. Different from pesticides test results, TiO2-P25/Na2S2O8 has the best performance, which achieved a 3 J/cm² half-fluence (H50). They also found that TiO2 (mainly P25) in tandem with Na2S2O8 can avoid recombination of e−/h+ pairs (Vela et al., 2018c). Except for TiO2, they also used ZnO/Na2S2O8 at the pilot plant scale. It can achieve an 83% removal rate for dissolved organic carbon (DOC) for EDs removal (Vela et al., 2018a) and min DT90 for several fungicides and insecticides removal (Vela et al., 2019). Some similar pilot-scale tests using TiO2/ZnO with Na2S2O8 also have been completed (Fenoll et al., 2019; Kushniarou et al., 2019).

TiO2 composites have also been invested under pilot tests. For carbon-based TiO2 composites, Luna-Sanguino et al. (2020) synthesized two TiO2-rGO from commercial TiO2 (P25 and Hombikat UV100, HBK) for several pesticides’ treatments (methomyl, pyrimethanil, isoproturon, and alachlor) and run a pilot-scale test in a 3.2 m² CPC located in the Plataforma Solar de Almería (PSA-CIE-MAT). The TiO2-rGO (P25) has a better performance, which removes all pesticides in 210 min. They also reported that the use of H2O2 can speed up the removal. Also, TiO2/H2O2 has been proved efficient for Curvularia sp. deactivation by using CPC, which achieved completed disinfection in 300 min (Aguas et al., 2017). Shaban et al. (2016) used carbon-modified titanium oxide (CM-n-TiO2) to treat polychlorinated biphenyls (PCBs) in seawater on a pilot-plant scale by a solar falling film reactor (SFFR), which reached completed degradation after 75 min. Vatanpour et al. (2019) modified TiO2 by urea for Reactive Orange 29 (RO29) removal and tested it in a continuous pilot-scale submerged photocatalytic membrane reactor (SPMR). They found that modified TiO2 using urea with a 1:6 ratio (TiO2:urea) under 450°C can achieve 84.2% decolorization efficiency. Recently, Mesa et al. (2021) compared commercial TiO2 with UV/H2O2 in a 120 L CPC for effluents from handicraft factories. Their
result showed that UV/H$_2$O$_2$ is the best treatment for dye and TiO$_2$ achieved a better elimination of coliform bacteria. It is important to mention that TiO$_2$ showed a detrimental effect on the overall elimination of dyes.

Ahmadpour et al. (2020) compared ZnFe$_2$O$_4$@TiO$_2$/Cu nanocomposites removal ability for recalcitrant drug NPX in batch and large-scale systems. In a large-scale experiment, 1000 ml of NPX pollutant solution was treated and reported a 63.14% degradation rate in 120 min, compared with 80.73% for the batch experiment. After optimizing the photocatalyst design in a laboratory-scale experiment, Bibova et al. (2019) designed two pilot-scale tests for SiO$_2$/TiO$_2$/calcined Liapor. One is in Czech Republic to simulate the remediation of contaminated water in rural areas, and another is in Vietnam for a comparative solar experiment. In the Czech Republic, oxalic acid (OA; 3.3 × 10$^{-3}$ mol/dm$^3$) is chosen as a model compound and achieved an 82.1% TOC removal rate in 3 days. In Vietnam, MB as a model compound is used and achieved around 58% degradation in 6 days.

Graywater is a highly reclaimable water source. Saran et al. (2019) prepared TiO$_2$-Ag for a pilot-scale slurry-type tubular photocatalytic reactor to treat actual graywater, with the addition of H$_2$O$_2$ a 99% COD abatement was achieved within 2 h. Tsoumachidou et al. (2017) used commercial TiO$_2$-P25 with H$_2$O$_2$ and Fe$^{3+}$ to treat graywater, which achieved an almost 64% DOC removal rate in a pilot-scale slurry fountain photoreactor. Olga Sacco et al. (2018) set a pilot-scale test for real wastewater disinfection and MB removal using nitrogen-doped TiO$_2$ particles (N-TiO$_2$/PS) immobilized on polystyrene spheres. MB removal pilot-scale test showed a similar result to the laboratory-scale test, which achieve a 90% removal rate in 180 min. However, the disinfection pilot-scale test showed a much worse result, which only inactivates 25%
| Photocatalyst          | Synthesis method | Pollutants                                | Illumination | Location                                      | Result                              | Reference                               |
|-----------------------|------------------|-------------------------------------------|--------------|-----------------------------------------------|--------------------------------------|-----------------------------------------|
| TiO$_2$-P25           | -                | BP                                        | CPC          | Medellán (latitude 6°13'51", longitude 75°35'26") | 6 h; 90% removal rate               | (Zuniga-Benitez & Penuela, 2020)       |
| TiO$_2$-P25           | -                | Imipenem; meropenem                       | CPC          | Solar Energy Research Center, Almería, Spain   | 60 min, 75%                         | (Cabrera-Reina et al., 2019)           |
| TiO$_2$-P25           | -                | DPH                                       | CPC          | University of Barcelona (41.4°N, 2.1°W)       | 14,889 mg TOC/kWh                   | (Lopez et al., 2018)                   |
| TiO$_2$-P25           | -                | VA                                        | CPC          | University of Barcelona (41.4°N, 2.1°W)       | 5 h, 91%                            | (Haranaka-Funai et al., 2017)          |
| TiO$_2$-P25 SPS       | -                | TmP                                       | CPC          | Plataforma Solar de Almeria                   | Complete degradation               | (Grilla et al., 2019)                  |
| TiO$_2$/MB            | -                | DCF                                       | CPC          | Iwaki centrifugal pumps                       | 2 h, 99%                            | (Diaz-Angulo et al., 2020)             |
| TiO$_2$/P25/Na$_2$S$_2$O$_8$ | -   | A mixture of six pesticides               | Sunlight     | Murcia, SE Spain (37°59′N, 1°08′W)            | DT$_{90}$ varied from 79 to 1270 min | (Vela et al., 2018b)                   |
| TiO$_2$ vlp 7000/Na$_2$S$_2$O$_8$ | -   | EDs                                       | Sunlight     | Murcia, SE Spain                              | DT$_{90}$ varied from 32 to 817 min | H$_{50}$: 3–58 J/cm$^2$               | (Vela et al., 2018c)                   |
| TiO$_2$ P25/Na$_2$S$_2$O$_8$ | -    |                                          | Sunlight     | Nobsa, Boyacá, Colombia, coordinates 5°46′11″N, 72°56′24″O | H$_{50}$: 10–117 J/cm$^2$          |                                         | (Mesa et al., 2021)                   |
| Commercial TiO$_2$    | -                | Effluents from handicraft factories       | Sunlight     | Nobsa, Boyacá, Colombia, coordinates 5°46′11″N, 72°56′24″O | 7 h, 70.80% of the discoloration   |                                         |                                         |
| ZnO/Na$_2$S$_2$O$_8$  | -                | EDs                                       | Sunlight     | Murcia, SE Spain                              | 240 min, DOC: 83%                  |                                         | (Vela et al., 2018a)                   |
| ZnO/Na$_2$S$_2$O$_8$  | -                | Vinclozoline; fenarimol; quinalphos; malathion; fenitrothion; dimethoate | Sunlight     | Murcia, SE Spain                              | 240 min, DOC: 83%                  |                                         | (Vela et al., 2019)                   |
| Photocatalyst                  | Synthesis method                          | Pollutants                                      | Illumination          | Location                  | Result                  | Reference                          |
|-------------------------------|-------------------------------------------|------------------------------------------------|-----------------------|---------------------------|-------------------------|------------------------------------|
| TiO$_2$-rGO (P25)             | Hydrothermal method                       | Methomyl, pyrimethanil, isoproturon, and alachlor | CPC                   | PSA-CIEMAT                | 210 min, 100%            | (Luna-Sanguino et al., 2020)      |
| TiO$_2$-rGO (Hombikat UV100) |                                           |                                                 |                       | PSA-CIEMAT                | 240 min, 100%           |                                    |
| TiO$_2$/H$_2$O$_2$            |                                           | Curvularia sp.                                 | CPC                   | Spain                     | 30 min, 100%            | (Aguas et al., 2017)               |
| CM-n-TiO$_2$                  |                                           | PCBs                                           | FFR                   | Jeddah                    | 75 min, 100%            | (Shaban et al., 2016)              |
| TiO$_2$/urea                  | Taguchi methods                           | RO29                                           | SPMR with five 36 W visible lamps | -                        | 5 min, 90.2%             | (Vatanpour et al., 2019)           |
| ZnFe$_2$O$_4$@TiO$_2$/Cu     | Solvothermal (Gu et al., 2016), sonochemical, and Chi’s (Chi et al., 2013) methods | NPX                                            | Sunlight              | -                        | 120 min, 63.14%           | (Ahmadpour et al., 2020)           |
| SiO$_2$/TiO$_2$/calcined Liapor | Utility model (Jirkovsky et al., 2013)methods | OA                                             | Sunlight              | Czech Republic            | 3 days, TOC removal rate: 82.1% | (Bibowa et al., 2019)          |
|                              |                                           | MB                                             |                       | Vietnam                   | 6 days, 58%             |                                    |
| TiO$_2$-Ag                   | Photoreduction methods (Ubonchonlakate et al., 2012) | Graywater                                     | Slurry-type tubular photocatalytic reactor | Pondicherry University (12.01°N, 79.85°E) | 2 h, 99% COD              | (Saran et al., 2019)              |
| TiO$_2$/H$_2$O$_2$/Fe$^3$+    |                                           | Pilot-scale slurry fountain photoreactor       | -                     | Outside the Laboratory of Sanitary and Environmental Engineering, University of Salerno (40°N, 14°E) | 120 min, 91% discoloration, 180 min, 90% TOC removal rate, 120 min, 25% | (Sacco et al., 2018) |
| N-TiO$_2$/PS                 | Solvent cast method                       | MB                                             | Sunlight              | Outside the Laboratory of Sanitary and Environmental Engineering, University of Salerno (40°N, 14°E) | 120 min, 91% discoloration, 180 min, 90% TOC removal rate, 120 min, 25% | (Sacco et al., 2018) |
| PANi-TiO$_2$                  | In situ deposition oxidative polymerization method | 1,2-DCE                                       | Pilot-scale packed bed recirculating | -                        | 360 min, 100%            | (Mohsenzadeh et al., 2019)         |

(Continues)
| Photocatalyst | Synthesis method | Pollutants      | Illumination                  | Location                           | Result               | Reference                        |
|--------------|------------------|-----------------|-------------------------------|------------------------------------|----------------------|----------------------------------|
| TiO₂−Ag      | Sol-gel method   | Microorganisms  | Fixed bed tubular reactor     | Pondicherry University             | 120 min, 100%        | (Saran et al., 2018)             |
|              |                  |                 | under sunlight                | (12.01°N and 79.85°E)              |                      |                                  |
| N-TiO₂/FC    | Aforementioned   | Trichlorfon     | Sunlight                      | -                                  | 2 weeks, 100%        | (Li et al., 2016)                |
|              | mixing procedure |                 |                               |                                     |                      |                                  |
| TiO₂WO₃      | Sol-gel method   | Amoxicillin     | CPC                           | Cali, Colombia                     | Maximum 64.4%        | (Arce-Sarria et al., 2018)       |
|              | (Ramos-Delgado et al., 2013) |                 |                               |                                     |                      |                                  |
| Nano ZnO     | Precipitation–thermal decomposition method (Velmurugan & Swaminathan, 2011) | Dye industry effluent | FFR                           | Annamalai University            | 4 h, 95%              | (Dhatshnamurthi et al., 2017)   |
| Ag/BiVO₄     | Homogeneous precipitation and photodeposition methods (Booshehri et al., 2014) | E. coli; E. faecalis; F. solani | CPC                          | Plataforma Solar de Almeria (Almeria, Spain) | 160 min, 100%; 300 min, 90%; 270 min, 60% | (Booshehri et al., 2017) |
|              |                  |                 |                               | (37°34′N, 2°34′W)                 |                      |                                  |
of E. coli in 120 min. Mohsenzadeh et al. (2019) used the composition of polyaniline (PAni) and TiO$_2$ on glass beads to remove 1,2-dichloroethane (1,2-DCE) in a pilot-scale packed bed recirculating photocatalytic reactor, which achieves complete degradation after 360 min. Saran et al. (2018) tested TiO$_2$-Ag for rainwater disinfection using a pilot-scale solar photocatalytic fixed bed tubular reactor and achieved complete disinfection in addition to COD removal within 120 min. Y. Li et al. (2016) fabricated foam concrete incorporated with nitrogen-doped TiO$_2$ (N-TiO$_2$/FC) and tested its removal performance for trichlorfon in a pilot-scale experiment, which reported that 6% N-TiO$_2$/FC can remove almost 100% of trichlorfon in 2 weeks. However, the TiO$_2$ composite is not always better than commercial TiO$_2$. Arce-Sarria et al. (2018) modified TiO$_2$ by WO$_3$ and tested its photocatalytic performance for antiobiotic amoxicillin by CPC, which achieved maximum 64.4% removal rate but still underperformed compared with the commercial TiO$_2$-P25.

Except for the TiO$_2$ composite, some other composites also have been invested under pilot-scale tests. For example, Dhatshanamurthi et al. (2017) coated ZnO on fevicol and found that it is more efficient than the catalysts made by commercial ZnO and TiO$_2$-P25 catalysts for really dye industry effluent treatment in a pilot-scale FFR, which achieved around 95% COD removal rate in 4 h. Booshehri et al. (2017) synthesized Ag-modified BiVO$_4$ for E. coli, E. faecalis, and spores of F. solani inactivation and tested its photocatalytic disinfection by CPC, which achieved almost total degradation for E. coli after around 160 min, although its performance is still worse than TiO$_2$-P25 (Table 9).

Summary

Currently, only very limited researchers have explored the pilot-scale application of visible light photocatalysis. Although there are many visible light photocatalysts that have been developed and tested in the laboratory, the majority of the pilot-scale test still focused on TiO$_2$ and its composites.

The most common reactor used in pilot-scale tests is CPC. It is a non-imaging concentrator for solar energy collection (Kalogirou, 2014). Some studies use very simple reactors without proper design; some of them even put the water directly into a giant water vat. These reactors, including CPC, need further optimizations for real-world visible light photocatalysis treatments: (1) the attachment of photocatalyst; (2) the mixture and separation of photocatalyst; (3) energy consumption of the reactor; and (4) durability.

CONCLUSION AND PERSPECTIVES

Visible light active photocatalyst for water treatment has been widely examined due to its unique advantages. In this review, we have reviewed the current state of the art with a focus on materials, application, and pilot-scale investigations. In addition, we have outlined the mechanisms of photocatalysis and reviewed a variety of synthesis, doping, and modification methods.

Significant progress in visible light active photocatalyst has been made during the past number of years. Many composite materials have been designed as well as the development of some new facile synthesis methods. Many studies have proved this technology as a promising advanced oxidation process (AOP) that has extensive application in urban, industrial, agricultural, and pharmaceutical wastewater treatment as well as natural water and drinking water treatment with potential for future further research. Visible light active photocatalyst can remove persistent organic pollutants, in addition to metallic ion reduction and microorganism degradation. Concurrent to water treatment applications, the visible light active photocatalyst is also used in air purification (J. U. Choi et al., 2019; Pichat, 2019), hydrogen production (Lee et al., 2019; Reddy et al., 2020), and chlorine production (Chehade et al., 2020). Notwithstanding, visible light active photocatalyst still faces many challenges that have to be addressed in future and are summarized below:

1. There is a lack of theoretical research on the photocatalyst modification mechanism. It is common knowledge that some widely used photocatalysts (i.e., TiO$_2$) are not suitable for visible light active photocatalysis. Researchers have tried to modify it by shifting the absorption spectrum, reducing band gap energy, and slowing down the speed of charge recombination. Common methods include optimizing the photocatalyst’s structure, doping other materials, and using support materials. However, the lack of a theoretical guide leads to unorganized modification studies, with some of them even having reported modified photocatalysts to be less effective than previous.

2. Research in photocatalysis-enhanced solar disinfection is relatively limited despite millions of people having to use untreated drinking water in parts of the world with extensive solar exposure, and most solar disinfection studies did not apply photocatalyst. The majority of research in photocatalysis-enhanced solar disinfection is only applied to common TiO$_2$ and ZnO photocatalyst composite materials and very few of these have progressed to the pilot-scale phase.

3. Many new visible light photocatalysts have been developed over the last few decades, but few have
made it to the pilot-scale application stage. Following laboratory and bench-scale proof of concept, ability, and function, pilot-scale experimental trials should be carried out before eventual application. Only a small number of pilot-scale experimental trials have been documented in the literature with the majority using commercial TiO$_2$ or other common composites. More pilot-scale experimental trials are needed to expand the currently laboratory-scale results for the full-scale application of this promising sustainable technology.

ACKNOWLEDGMENTS
This research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors. Open access funding provided by IReL.

DATA AVAILABILITY STATEMENT
The data that support the findings of this study are available on request from the corresponding author. The data are not publicly available due to privacy or ethical restrictions.

ORCID
David W. O’Connell https://orcid.org/0000-0002-1974-8145

REFERENCES
Abukhadra, M. R., Shaban, M., Sayed, F., & Saad, I. (2018). Efficient photocatalytic removal of saffarin-O dye pollutants from water under sunlight using synthetic bentonite/polyaniline@Ni$_2$O$_3$ photocatalyst of enhanced properties. *Environmental Science and Pollution Research*, 25, 33264–33276.

Adamek, E., Baran, W., Ziemiańska-Blaszczyk, J., & Sobczak, A. (2019). Immobilisation of TiO$_2$-P25 on a glass fibre mat: Preparation, photocatalytic activity and stability. *Solar Energy*, 188, 1232–1242.

Agüas, Y., Hincapié, M., Fernandez-Ibanez, P., & Polo-Lopez, M. I. (2017). Solar photocatalytic disinfection of agricultural pathogenic fungi (*Curvularia* sp.) in real urban wastewater. *Science of the Total Environment*, 607, 1213–1224.

Ahmad, U. M., Pu, Y., Qi, W. K., Foster, N. R., Chen, J. F., & Wang, D. (2017). Efficient treatment of actual pharmaceutical wastewater by wet oxidation process in subcritical water apparatus. *Canadian Journal of Chemical Engineering*, 95, 2056–2062.

Ahammadpour, N., Sayadi, M. H., Sobhani, S., & Hajiani, M. (2020). A potential natural solar light active photocatalyst using magnetic ZnFe$_2$O$_4$@TiO$_2$/Cu nanocomposite as a high performance and recyclable platform for degradation of naproxen from aqueous solution. *Journal of Cleaner Production*, 268, 122023.

Ahmed, A., Usman, M., Yu, B., Ding, X., Peng, Q. H., Shen, Y. Q., & Cong, H. L. (2020). Efficient photocatalytic degradation of toxic Alizarin yellow R dye from industrial wastewater using biosynthesized Fe nanoparticle and study of factors affecting the degradation rate. *Journal of Photochemistry and Photobiology B: Biology*, 202, 13.

Alenizi, M. A., Alseroury, F. A., Kumar, R., Aslam, M., & Barakat, M. A. (2020). Removal of trichlorophenol from wastewater using NiS/RGO/TiO$_2$ composite as an efficient photocatalyst under sunlight. *Desalination and Water Treatment*, 173, 267–273.

Ali, N., Yeoh, C. B., Lau, S., & Tay, M. G. (2019). An enhanced treatment efficiency for diluted palm oil mill effluent using a photo-electro-Fenton hybrid system. *Journal of the Serbian Chemical Society*, 84, 517–526.

Alseroury, F. A. (2018). The effect of using photocatalytic to decontaminate wastewater in natural sunlight exposure. *International Journal of Pharmaceutical Research and Allied Sciences*, 7, 74–80.

Ameta, R., Solanki, M. S., Benjamin, S., & Ameta, S. C. (2018). Chapter 6—Photocatalysis. In S. C. Ameta & R. Ameta (Eds.), *Advanced oxidation processes for waste water treatment* (pp. 135–175). Academic Press.

Amini, Z., Givianrad, M. H., Saber-Tehrani, M., Azar, P. A., & Husain, S. W. (2019). Synthesis of N-doped TiO$_2$/SiO$_2$/Fe$_3$O$_4$ magnetic nanocomposites as a novel purple LED illumination-driven photocatalyst for photocatalytic and photoelectrocatalytic degradation of naproxen: Optimization and different scavenger agents study. *Journal of Environmental Science and Health Part a-Toxic/Hazardous Substances & Environmental Engineering*, 54, 1254–1267.

Ani, I. J., Akpan, U. G., Olutoye, M. A., & Hameed, B. H. (2018). Photocatalytic degradation of pollutants in petroleum refinery wastewater by TiO$_2$- and ZnO-based photocatalysts: Recent development. *Journal of Cleaner Production*, 205, 930–954.

Arce-Sarria, A., Machuca-Martinez, F., Bustillo-Lecompte, C., Hernandez-Ramirez, A., & Colina-Marquez, J. (2018). Degradation and loss of antibacterial activity of commercial amoxicillin with TiO$_2$/WO$_3$-assisted solar photocatalysis. *Catalysts*, 8, 222.

Babuponnusami, A., & Muthukumar, K. (2012). Advanced oxidation of phenol: A comparison between Fenton, electro-Fenton, sono-electro-Fenton and photo-electro-Fenton processes. *Chemical Engineering Journal*, 183, 1–9.

Balasubramanian, J., Ponnaiyah, S. K., Periakaruppan, P., & Kamaraj, D. (2020). Accelerated photodeterioration of class I toxic monocrotophos in the presence of one-pot constructed Ag$_3$PO$_4$/polyaniline@g-C$_3$N$_4$ nanocomposite: Efficacy in light harvesting. *Environmental Science and Pollution Research*, 27, 2328–2339.

Barakat, M. A. E., Kumar, R., Al-Makishah, N. H., Neamtallah, A. A., & Alafif, Z. O. (2019). S-rGO/ZnS nanocomposite-mediated photocatalytic pretreatment of dairy wastewater to enhance aerobic digestion. *Korean Journal of Chemical Engineering*, 36, 1281–1290.

Barbosa, A. A., de Aquino, R. V. S., Oliveira, A. F. B., Dantas, R. F., Silva, J. P., Duarte, M., & da Rocha, O. R. S. (2019). Development of a new photocatalytic reactor built from recyclable material for the treatment of textile industry effluents. *Desalination and Water Treatment*, 151, 82–92.

Barbosa, A. A., de Aquino, R. V. S., Silva, M. G., Nascimento, W. J., Duarte, M., Dantas, R. F., & da Rocha, O. R. S. (2020). New aluminum mesh from recyclable material for immobilization of TiO$_2$ in heterogeneous photocatalysis. *Canadian Journal of Chemical Engineering*, 98, 1124–1138.

Basheer, E. A. M., Abdulbari, H. A., & Mahmood, W. K. (2020). Enhanced titanium dioxide photocatalyst emphasized on
micropores silicon wafer: An experimental approach. *Journal of Chemical Technology and Biotechnology*, 95, 2730–2738.

Batista, L. M. B., Bezerra, F. A., Oliveira, J. L. F., Araujo, A. M. D., Fernandes, V. J., Araujo, A. S., Gondim, A. D., & Alves, A. P. M. (2019). PYROLYSIS of glyceral with modified vermiculite catalysts Kinetic and PY-GC/MS. *Journal of Thermal Analysis and Calorimetry*, 137, 1929–1938.

Behravesh, S., Mirghaffari, N., Alemrajabi, A. A., Davar, F., & Soleimani, M. (2020). Photocatalytic degradation of acetaldehyde and codeine medicines using a novel zeolite-supported TiO₂ under UV and sunlight irradiation. *Environmental Science and Pollution Research*, 27, 26929–26942.

Ben, Y. J., Fu, C. X., Hu, M., Liu, L., Wong, M. H., & Zheng, C. M. (2019). Human health risk assessment of antibiotic resistance associated with antibiotic residues in the environment: A review. *Environmental Research*, 169, 483–493.

Berger, T. E., Regmi, C., Schafer, A. I., & Richards, B. S. (2020). Photocatalytic degradation of organic dye via atomic layer deposited TiO₂ on ceramic membranes in single-pass flow-through operation. *Journal of Membrane Science*, 604, 118015.

Bhati, A., Anand, S. R., Saini, D., & Gunture; Sonkar, S. K. (2019). Sunlight-induced photoreduction of Cr (VI) to Cr(III) in wastewater by nitrogen-phosphorus-doped carbon dots. *Npj Clean Water*, 2, 1–9, 12.

Bibova, H., Hykrdova, L., Hoang, H., Elias, M., & Jirkovsky, J. (2019). SiO₂/TiO₂ composite coating on light substrates for photocatalytic decontamination of water. *Journal of Chemistry*, 2019, 11.

Bokare, A. D., & Choi, W. (2014). Review of iron-free Fenton-like systems for activating H₂O₂ in advanced oxidation processes. *Journal of Hazardous Materials*, 275, 121–135.

Booshehri, A. Y., Chun-Kiat Goh, S., Hong, J., Jiang, R., & Xu, R. (2014). Effect of depositing silver nanoparticles on BiVO₄ in enhancing visible light photocatalytic inactivation of bacteria in water. *Journal of Materials Chemistry A*, 2, 6209–6217.

Booshehri, A. Y., Polo-Lopez, M. I., Castro-Alferez, M., He, P. F., Xu, R., Rong, W., Malato, S., & Fernandez-Itanex, P. (2017). Assessment of solar photocatalysis using Ag/BiVO₄ at pilot solar Compound Parabolic Collector for inactivation of pathogens in well water and secondary effluents. *Catalysis Today*, 281, 124–134.

Bora, L. V., & Mewada, R. K. (2017). Photocatalytic treatment of dye wastewater and parametric study using a novel Z-scheme Ag₂CO₃/SiC photocatalyst under natural sunlight. *Journal of Environmental Chemical Engineering*, 5, 5556–5565.

Bora, L. V., Rathod, M., Kapadia, K., Thakkar, S., Reddy, R. N., Chougule, S. S., & Bora, N. V. (2022). Trash GGBFS-based geopolymers as a novel sunlight-responsive photocatalyst for dye discoloration. *Journal of the Indian Chemical Society*, 99, 100560.

Byrappa, K., & Adschiri, T. (2007). Hydrothermal technology for nanotechnology. *Progress in Crystal Growth and Characterization of Materials*, 53, 117–166.

Byrappa, K., Subramani, A. K., Ananda, S., Rai, K. M. L., Sunita, M. H., Basavalingu, B., & Soga, K. (2006). Impregnation of ZnO onto activated carbon under hydrothermal conditions and its photocatalytic properties. *Journal of Materials Science*, 41, 1355–1362.
Choi, J. U., Kim, Y. G., & Jo, W. K. (2019). Multiple photocatalytic applications of non-precious Cu-loaded g-C3N4/hydrogenated black TiO2 nanofiber heterostructure. Applied Surface Science, 473, 761–769.

Chong, M. N., Jin, B., Chow, C. W., Saint, C. J. W., & r. (2010). Recent developments in efficient dye solar treatment technology: A review. Water Research, 44, 2997–3027.

Choucnehe, B., Ben Chaabane, T., Balan, L., Girot, E., Mozet, K., Medjahdi, G., & Schneider, R. (2016). High performance Ce-doped ZnO nanorods for sunlight-driven photocatalysis. Beilstein Journal of Nanotechnology, 7, 1338–1349.

Chu, Y. B., Wan, L. X., Guo, X. P., Yu, D. Q., Yu, Z. Y., & Cao, L. Q. (2014). Synthesis of ZnO nanowires by solvothermal method and fabrication of ZnO nanowires film via microfiltration method. Optoelectronics and Advanced Materials, Rapid Communications, 8, 1125–1128.

Cong, Y., Li, X. K., Qin, Y., Dong, Z. J., Yuan, G. M., Cui, Z. W., & Lai, X. J. (2011). Carbon-doped TiO2 coating on multiwalled carbon nanotubes with higher visible light photocatalytic activity. Applied Catalysis B: Environmental, 107, 128–134.

Cubas, P. D., Semkiw, A. W., Monteiro, F. C., Los Weinert, P., Monteiro, J., & Fujiwara, S. T. (2020). Synthesis of CuCr2O4 by self-combustion method and photocatalytic activity in the degradation of Azo Dye with visible light. Journal of Photochemistry and Photobiology A: Chemistry, 401, 8.

Cui, D. D., Wang, L., Xu, K., Ren, L., Wang, L., Yu, Y. X., Du, Y., & Hao, W. C. (2018). Band-gap engineering of BiOCl with oxygen vacancies for efficient photooxidation properties under visible-light irradiation. Journal of Materials Chemistry A, 6, 2193–2199.

Cunha, D. L., Kushnetsov, A., Araujo, J. R., Neves, R. S., Anchanjo, B. S., Canela, M. C., & Marques, M. (2019). Optimization of benzodiazepine drugs removal from water by heterogeneous photocatalysis using TiO2-activated carbon composite. Water, Air, and Soil Pollution, 230, 1–7, 141.

Czok, M., & Golonka, L. (2016). Sol-gel layers for ceramic microsystems application. In P. Jasinski (Ed.), 14th International Conference on Optical and Electronic Sensors (pp. 89–94).

da Silva, L. J. V., Fioletto, E. L., Dorneles, L. S., Paz, D. S., Frantz, T. S., & Gundel, A. (2013). ZnO electrodeposition onto gold from recordable compact discs and its use as photocatalyst under solar irradiation. Brazilian Journal of Chemical Engineering, 30, 155–158.

Danwittayakul, S., Songnagam, S., & Sukkasi, S. (2020). Enhanced solar water disinfection using ZnO supported photocatalysts. Environmental Technology, 41, 349–356.

Das, S., & Mahalingam, H. (2019). Dye degradation studies using immobilized pristine and waste polystyreneTiO2/rGO/g-C3N4 nanocomposite photocatalytic film in a novel airlift reactor under solar light. Journal of Environmental Chemical Engineering, 7, 10.

Davididou, K., Nelson, R., Monteagudo, J. M., Duran, A., Exposit, A. J., & Chatzisymeon, E. (2018). Photocatalytic degradation of bisphenol-A under UV-LED, blacklight and solar irradiation. Journal of Cleaner Production, 203, 13–21.

de Barros, A. L., Domingos, A. A. Q., Fechine, P. B. A., de Keukeleire, D., & do Nascimento, R. F. (2014). PET as a support material for TiO2 in advanced oxidation processes. Journal of Applied Polymer Science, 131, 9.

Dey, S., Bhattacharjee, S., Chaudhuri, M. G., Bose, R. S., Halder, S., & Ghosh, C. K. (2015). Synthesis of pure nickel (III) oxide nanoparticles at room temperature for Cr (VI) ion removal. RSC Advances, 5, 54717–54726.

Dhatshanumurthi, P., Shanthi, M., & Swaminathan, M. (2017). An efficient pilot scale solar treatment method for dye industry effluent using nano-ZnO. Journal of Water Process Engineering, 16, 28–34.

Diaz-Angulo, J., Lara-Ramos, J., Mueses, M., Hernandez-Ramirez, A., Li Puma, G., & Machuca-Martinez, F. (2020). Enhancement of the oxidative removal of diclofenac and of the TiO2 rate of photon absorption in dye-sensitized solar pilot scale CPC photocatalytic reactors. Chemical Engineering Journal, 381, 122520.

Djearamane, S., Lim, Y. M., Wong, L. S., & Lee, P. F. (2018). Cytoxic effects of zinc oxide nanoparticles on cyanobacterium Spirulina (Arthospira platensis). PeerJ, 6, e4682.

Djellabi, R., Ali, J., Yang, B., Haider, M. R., Su, P. D., Bianchi, C. L., & Zhao, X. (2020). Synthesis of magnetic recoverable electronic-rich TCTA@PVP based conjugated polymer for photocatalytic water remediation and disinfection. Separation and Purification Technology, 250, 7.

Domingues, E., Gomes, J., Assuncao, N., Gmurek, M., Quina, M. J., Quinta-Ferreira, R. M., & Martins, R. C. (2020). Iron-based catalysts under solar and visible radiation for contaminants of emerging concern removal. Energy Reports, 6, 711–716.

Dong, S., Feng, J., Fan, M., Pi, Y., Hu, L., Han, X., Liu, M., Sun, J., & Sun, J. (2015). Recent developments in heterogeneous photocatalytic water treatment using visible light-responsive photocatalysts: A review. RSC Advances, 5, 14610–14630.

Dong, S. Y., Xia, L. J., Zhang, F. Y., Li, F. Z., Wang, Y. Y., Cui, L. F., Feng, J. L., & Sun, J. H. (2019). Effects of pH value and hydrothermal treatment on the microstructure and natural-sunlight photocatalytic performance of ZnSn(OH)6 photocatalyst. Journal of Alloys and Compounds, 810, 12.

dos Santos, A. J., Batista, L. M. B., Martinez-Huitle, C. A., Alves, A. P. D., & Garcia-Segura, S. (2019). Niobium oxide catalysts as emerging material for textile wastewater reuse: Photocatalytic decolorization of azo dyes. Catalysts, 9, 15.

Duan, J. H., Liu, M. Y., Guo, Y., Wang, W. W., Zhang, Z. S., & Li, C. J. (2020). High photocatalytic activity of 2D sheet structure ZnO/Bi2WO6 Z-scheme heterojunction under simulated sunlight. Journal of Physics D: Applied Physics, 53, 165101.

Dutta, V., Sharma, S., Raizada, P., Kumar, R., Thakur, V. K., Nguyen, V.-H., Asiri, A. M., Khan, A. A. P., & Singh, P. (2020). Recent progress on bismuth-based Z-scheme semiconductor photocatalysts for energy and environmental applications. Journal of Environmental Chemical Engineering, 8, 104505.

El-Sheshtawy, H. S., El-Hosainy, H. M., Shouier, K. R., El-Mhesabe, I. M., & El-Kemary, M. (2019). Facile immobilization of Ag nanoparticles on g-C3N4/V2O5 surface for enhancement of post-illumination, catalytic, and photocatalytic activity removal of organic and inorganic pollutants. Applied Surface Science, 467, 268–276.

Feng, H., Tang, N., Zhang, S. B., Liu, B., & Cai, Q. Y. (2017). Fabrication of layered (CdS-Mn/MoS2/CdTe)-promoted TiO2 nano-tube arrays with superior photocatalytic properties. Journal of Colloid and Interface Science, 486, 58–66.
Feng, H., Zhou, W. H., Zhang, Y. Y., Zhang, S. B., Liu, B., & Zhen, D. S. (2019). Synthesis of Z-scheme Mn-Cds/ MoS2/TiO2 ternary photocatalysts for high-efficiency sunlight-driven photocatalysis. Advanced Composites Letters, 28, 10.

Feng, J. J., Liao, Q. C., Wang, A. J., & Chen, J. R. (2011). Mannite reactions and oxide minerals as catalysts and nanocatalysts in Fenton processes. Chemical Engineering Journal, 261, 36–44.

Fujishima, A., Zhang, X., & Tryk, D. A. (2008). TiO2 photocatalysis and related surface phenomena. Surface Science Reports, 63, 515–582.

Garcia-Gil, A., Valverde, R., Garcia-Munoz, R. A., McGuigan, K. G., & Murugan, J. (2020). Solar photocatalytic disinfection of water using titanium dioxide graphene composites. Chemical Engineering Journal, 361, 12–20.

Garcia-Segura, S., Ocon, J. D., & Chong, M. N. (2018). Electrochemical oxidation remediation of real wastewater effluents—A review. Process Safety and Environmental Protection, 113, 48–67.

Garrido, I., Flores, P., Hellin, P., Vela, N., Navarro, G., Garcia-Garcia, J., & Navarro, S. (2019). Implementation of a new modular facility to detoxify agro-wastewater polluted with neonicotinoid insecticides in farms by solar photocatalysis. Energy, 175, 722–729.

Fernández-Ibañez, P., Polo-López, M. I., Malato, S., Wadhwa, S., Hamilton, J. W. J., Dunlop, P. S. M., O’Shea, K., Dionysiou, D. D., & Byrne, J. A. (2015). Solar photocatalytic disinfection of water using titanium dioxide graphene composites. Chemical Engineering Journal, 261, 36–44.

Guo, Q., Yi, L., Wang, C., & Liu, Y. Z. (2017). A review on advanced treatment of pharmaceutical wastewater. In D. Binlin (Ed.), 2017 International Conference on Environmental and Energy Engineering (012025). IOP Publishing Ltd.

Han, Q. (2020). Advances in preparation methods of bismuth-based photocatalysts. Chemical Engineering Journal, 414, 127877.

Hasan, S. N., Xu, M., & Asselin, E. (2019). Electrodeposition of metallic molybdenum and its alloys—A review. Canadian Metallurgical Quarterly, 58, 1–18.

He, K., Borthwick, A. G., Lin, Y. C., Li, Y. N., Fu, J., Wong, Y. J., & Liu, W. (2020). Sale-based estimation of pharmaceutical concentrations and associated environmental risk in the Japanese wastewater system. Environment International, 139, 10.
enhanced full-spectrum photocatalytic activity for the degradation of toxic pollutants. *Nanomaterials*, 8, 914.

Li, S. J., Xue, B., Wu, G. Y., Liu, Y. P., Zhang, H. Q., Ma, D. Y., & Zuo, J. C. (2019). A novel flower-like Ag/AgCl/BiOOCOH ternary heterojunction photocatalyst: Facile construction and its superior photocatalytic performance for the removal of toxic pollutants. *Nanomaterials*, 9, 14.

Li, T., Zhao, L., He, Y., Cai, J., Luo, M., & Lin, J. (2013). Synthesis of g-C_3N_4/SmVO_4 composite photocatalyst with improved visible light photocatalytic activities in RhB degradation. *Applied Catalysis B: Environmental*, 129, 255–263.

Li, Y., Gao, Q., Xing, T., Wang, D. W., Zhang, W. L., & Wang, Q. (2016). Sorption and photocatalytic degradation of trichloroform by foam concrete blended with nitrogen-doped titanium dioxide. *Journal of Materials in Civil Engineering*, 28, 8.

Li, Y. F., Zhong, Y., Chang, J. Q., Hu, C. H., & Iop. (2018). Synthesis and effects on visible light photocatalytic activity of Bi_2Ti_3O_9 photocatalyst. International Conference on Mechanical Engineering and Applied Composite Materials. Iop Publishing Ltd, Bristol.

Liang, Y. H., Shao, M. Y., Cui, W. Q., Liu, L., & McEvoy, J. G. (2013). Photocatalytic degradation of Rhodamine B by CdS-loaded K_2Nb_2O_7 nanocomposites prepared via reverse microemulsion. *Journal of Molecular Catalysis A: Chemical*, 370, 87–94.

Lim, G. T., Kim, Y. H., Jeong, H. G., Woo, H. G., Ohk, S. H., & Kim, D. H. (2008). Synthesis of carbon containing TiO_2 nano powders by aerosol flame deposition for photocatalyst. *Journal of Nanoscience and Nanotechnology*, 8, 4603–4606.

Lim, P. F., Leong, K. H., Sim, L. C., Abd Aziz, A., & Saravanan, P. (2019). Amalgamation of N-graphene quantum dots with nanocubic like TiO_2: An insight study of sunlight sensitive photocatalysis. *Environmental Science and Pollution Research*, 26, 3455–3464.

Liu, T., Li, B., Hao, Y., & Yao, Z. (2014). MoO_3-nanowire membrane and Bi_2MoO_6O_2/MoO_3 nano-heterostructural photocatalyst for wastewater treatment. *Chemical Engineering Journal*, 244, 382–390.

Liu, Y., Tian, L., Tan, X., Li, X., & Chen, X. (2017). Synthesis, properties, and applications of black titanium dioxide nanomaterials. *Science Bulletin*, 62, 431–441.

Liu, Z. J., Hao, J. Y., Wang, Y., Sun, Q., Zhang, D., & Gan, Y. (2019). Decorating Ag_3PO_4 nanodots on mesoporous silica-functionalized NaYF_4:Yb,Tm@NaLuF_4 for efficient sunlight-driven photocatalysis: Synergy of broad spectrum absorption and pollutant adsorption-enrichment. *Inorganic Chemistry Frontiers*, 6, 3529–3538.

Long, R. Q., & Yang, R. T. (2002). Selective catalytic oxidation of ammonia to nitrogen over Fe_2O_3–TiO_2 prepared with a sol–gel method. *Journal of Catalysis*, 207, 158–165.

Lopez, N., Marco, P., Gimenez, J., & Espugras, S. (2018). Photocatalytic diphenylhydramine degradation under different radiation sources: Kinetic studies and energetic comparison. *Applied Catalysis B: Environmental*, 220, 497–505.

Lu, J., Li, L., Wang, Z., Wen, B., & Cao, J. (2013). Synthesis of visible-light-active TiO_2-based photo-catalysts by a modified sol–gel method. *Materials Letters*, 94, 147–149.

Luna-Sanguino, G., Ruiz-Delgado, A., Tolosana-Moranchel, A., Pascual, L., Malato, S., Bahamonde, A., & Faraldos, M. (2020). Solar photocatalytic degradation of pesticides over TiO₂-rGO nanocomposites at pilot plant scale. *Science of the Total Environment*, 737, 140286.

Malato, S., Fernandez-Ibanez, P., Maldonado, M. I., Blanco, J., & Gernjak, W. (2009). Decontamination and disinfection of water by solar photocatalysis: Recent overview and trends. *Catalysis Today*, 147, 1–59.

Malik, S. N., Ghosh, P. C., Vaidya, A. N., & Mudliar, S. N. (2020). Hybrid ozonation process for industrial wastewater treatment: Principles and applications: A review. *Journal of Water Process Engineering*, 35, 101193.

Marcano, D. C., Kosynkin, D. V., Berlin, J. M., Sinitskii, A., Sun, Z., Slesarev, A., Alemay, L. B., Lu, W., & Tour, J. M. (2010). Improved synthesis of graphene oxide. *ACS Nano*, 4, 4806–4814.

Martins, R. C., Domingues, E., Bosio, M., Quina, M. J., Gmurek, M., Quinta-Ferreira, R. M., & Gomes, J. (2019). Effect of different radiation sources and noble metal doped onto TiO₂ for contaminants of emerging concern removal. *Water*, 11, 894.

Matamura, Y., Ikenoue, T., Miyake, M., & Hirato, T. (2020). Mist chemical vapor deposition of MoO₂ thin films. *Journal of Crystal Growth*, 548, 125862.

Meena, S., Anantharaju, K. S., Vidya, Y. S., Renuka, L., Malini, S., Sharma, S. C., & Nagabhushana, H. (2020). MnFe₂O₄/ZrO₂ nanocomposite as an efficient magnetically separable photocatalyst with good response to sunlight: Preparation, characterization and catalytic mechanism. *SN Applied Sciences*, 2, 1–2, 328.

Mesa, J. J. M., Nino, J. S. H., Gonzalez, W., Rojas, H., Hidalgo, M. C., & Navio, J. A. (2021). Photocatalytic treatment of stained wastewater coming from handicraft factories. A case study at the pilot plant level. *Water*, 13, 10.

Miklos, D. B., Remy, C., Jekel, M., Linden, K. G., Drewes, J. E., & Hubner, U. (2018). Evaluation of advanced oxidation processes for water and wastewater treatment—A critical review. *Water Research*, 139, 118–131.

Mishra, A., Panigrahi, A., Mal, P., Penta, S., Padmaja, G., Bera, G., Das, P., Rambabu, P., & Turpu, G. R. (2020). Rapid photodegradation of methylene blue dye by rGO-V₂O₅ nano composite. *Journal of Alloys and Compounds*, 842, 7.

Mohszenzadeh, M., Mirbagheri, S. A., & Sabbagh, S. (2019). Degradation of 1,2-dichloroethane by photocatalysis using immobilized PANi-TiO₂ nano-photocatalyst. *Environmental Science and Pollution Research*, 26, 31328–31343.

Moncayo-Lasso, A., Sanabria, J., Pulgarin, C., & Benitez, N. (2009). Simultaneous E. coli inactivation and NOM degradation in river water via photo-Fenton process at natural pH in solar CPC reactor. A new way for enhancing solar disinfection of natural water. *Chemosphere*, 77, 296–300.

Moo, J. G. S., Khezri, B., Webster, R. D., & Pumera, M. (2014). Graphene oxides prepared by Hummers’, Hofmann’s, and Staudenmaier’s methods: Dramatic influences on heavy-metal-ion adsorption. *Chemosphere*, 15, 2922–2929.

Mota, H. P., Quadrado, R. F. N., Iglesias, B. A., & Fajardo, A. R. (2020). Enhanced photocatalytic degradation of organic pollutants mediated by Zn (II)-porphyrin/poly (acrylic acid) hybrid microparticles. *Applied Catalysis B: Environmental*, 277, 119208.

Muthukrishnaraj, A., Kalaivani, S. S., Manikandan, A., Kavitha, H. P., Srinivasan, R., & Balasubramanian, N. (2020). Chemical vapor deposition of MoO₂ thin films. *Journal of Crystal Growth*, 548, 125862.
synthesis and visible light induced photocatalytic property of reduced graphene oxide@ZnO hexagonal hollow rod nanocomposite. *Journal of Alloys and Compounds*, 836, 9.

Nevarez-Martinez, M. C., Mazierski, P., Kobylanski, M. P., Szczepanska, G., Trykowski, G., Malankowska, A., Kozak, M., Espinoza-Montero, P. J., & Zaleska-Medynska, A. (2017). Growth, structure, and photocatalytic properties of hierarchical V2O5-TiO2 nanotube arrays obtained from the one-step anodic oxidation of Ti-V alloys. *Molecules*, 22, 580.

Nozaki, T., Shoji, R., Kobayashi, Y., & Sato, K. (2018). Feasibility of macroporous CeO2 photocatalysts for removal of lead ions from water. *Bulletin of Chemical Reaction Engineering & Catalysis*, 13, 256–261.

Oh, W.-D., Dong, Z., & Lim, T.-T. (2016). Generation of sulfate radical through heterogeneous catalysis for organic contaminants removal: Current development, challenges and prospects. *Applied Catalysis B: Environmental*, 194, 169–201.

Oliva, J., Martinez, A. I., Oliva, A. I., Garcia, C. R., Martinez-Luevanos, A., Garcia-Lobato, M., Ochoa-Valiente, R., & Berlanga, A. (2018). Flexible graphene composites for removal of methylene blue dye-contaminant from water. *Applied Surface Science*, 436, 739–746.

Ouederni, A., Souissi-Najar, S., & Ratel, A. (2006). Activated carbon from olive stones by a two step process: Influence of production parameters on textural characteristics. *Annales de Chimie-Science des Matériaux*, 31, 151–167.

Palma, T. L., Vieira, B., Nunes, J., Lourenço, J. P., Monteiro, O. C., & Costa, M. C. (2020). Photodegradation of chloramphenicol and paracetamol using PbS/TiO2 nanocomposites produced by green synthesis. *Journal of the Iranian Chemical Society*, 17, 2013–2031.

Pang, Y. L., Abdullah, A. Z., & Bhatia, S. (2011). Review on sonochemical methods in the presence of catalysts and chemical additives for treatment of organic pollutants in wastewater. *Desalination*, 277, 1–14.

Pardeshi, S. K., & Patil, A. B. (2008). A simple route for photocatalytic degradation of phenol in aqueous zinc oxide suspension using solar energy. *Solar Energy*, 82, 700–705.

Pena, M. E., Korfias, G. P., Patel, M., Lippincott, L., & Meng, X. G. (2005). Adsorption of As(V) and As (III) by nanocrystalline titanium dioxide. *Water Research*, 39, 2327–2337.

Perez-Osorio, G., Hernandez-Gomez, F. D., Arriola-Morales, J., Castillo-Morales, M., & Mendoza-Hernandez, J. C. (2020). Blue dye degradation in an aqueous medium by a combined photocatalytic and bacterial biodegradation process. *Turkish Journal of Chemistry*, 44, 180–193.

Perović, K., Dela Rosa, F. M., Kovačić, M., Kusić, H., Štangar, U. L., Fresno, F., Dionysiu, D. D., & Loncaric Bozic, A. (2020). Recent achievements in development of TiO2-based composite photocatalytic materials for solar driven water purification and water splitting. *Materials*, 13, 1338.

Pichat, P. (2019). A brief survey of the practicality of using photocatalysis to purify the ambient air (indoors or outdoors) or air effluents. *Applied Catalysis B: Environmental*, 245, 770–776.

Polat, K. (2020). Thin film photocatalyst made from Fe2O3/2D graphene/Cu working in the visible region of the solar spectrum. *Solid State Communications*, 319, 6.

Priyanka, R. N., Joseph, S., Abraham, T., Plathanam, N. J., & Mathew, B. (2020). Rapid sunlight-driven mineralisation of dyes and fungicide in water by novel sulphur-doped graphene oxide/Ag2VO4 nanocomposite. *Environmental Science and Pollution Research*, 27, 9604–9618.

Qi, H. X., Hu, J. W., Zhang, R., Gong, W. T., Yu, Y. C., & Gao, H. W. (2019). The photocatalytic degradation of diesel by solar light-driven floating BioI/EP composites. *Colloids and Surfaces a-Physicochemical and Engineering Aspects*, 583, 9.

Rachna, Rani, M., & Shanker, U. (2020). Sunlight assisted degradation of toxic phenols by zinc oxide doped prussian blue nanocomposite. *Journal of Environmental Chemical Engineering*, 8, 104040.

Rafie, A., Bhatti, I. A., Tahir, A. A., Ashraf, M., Bhatti, H. N., & Zia, M. A. (2019). Solar photocatalytic treatment of textile effluent for its potential reuse in irrigation. *Pakistan Journal of Agricultural Sciences*, 56, 993–1001.

Rahbar, M., Mehrzad, M., Behpour, M., Mohammadi-Aghdam, S., & Ashrafi, M. (2019). N Co-doped carbon quantum dots/TiO2 nanocomposite as highly efficient visible light photocatalyst. *Nanotechnology*, 30, 16.

Rajah, Z., Guiza, M., Solís, R. R., Rivas, F. J., & Ouederni, A. (2019). Catalytic and photocatalytic ozonation with activated carbon as technologies in the removal of aqueous micropollutants. *Journal of Photochemistry and Photobiology A: Chemistry*, 382, 9.

Rajaraman, T. S., Parikh, S. P., & Gandhi, V. G. (2020). Black TiO2: A review of its properties and conflicting trends. *Chemical Engineering Journal*, 389, 29.

Raman, C. D., & Kannmani, S. (2019). Decolorization of monoazo dye and textile wastewater using nano iron particles. *Environmental Progress & Sustainable Energy*, 38, S366–S376.

Ramos-Delgado, N. A., Hinojos-Reyes, L., Guzman-Mar, I. L., Gracia-Pinilla, M. A., & Hernández-Ramírez, A. (2013). Synthesis by sol–gel of WO3/TiO2 for solar photocatalytic degradation of malathion pesticide. *Catalysis Today*, 209, 35–40.

Rani, M., & Shanker, U. (2018). Removal of chlorpyrifos, thiamethoxam, and tebuconazole from water using green synthesized metal hexacyanoferrate nanoparticles. *Environmental Science and Pollution Research*, 25, 10878–10893.

Reddy, N. R., Bhargav, U., Kumari, M. M., Cheralathan, K. K., Shankar, M. V. R., Reddy, K. R., Saleh, T. A., & Aminabhavi, T. M. (2020). Highly efficient solar light-driven photocatalytic hydrogen production over Cu/FCN-Ts-titania quantum dots-based heterostructures. *Journal of Environmental Management*, 254, 8.

Ren, J., Wu, Y. Z., Zou, H., Dai, Y., Sha, D. W., Chen, M., Wang, J. J., Pan, J. M., & Yan, X. H. (2016). Synthesis of a novel CeVO4/graphitic C3N4 composite with enhanced visible-light photocatalytic property. *Materials Letters*, 183, 219–222.

Rodriguez-Chueca, J., Giannakis, S., Marjanovic, M., Kohantorbii, M., Gholami, M. R., Grandjean, D., de Alencastro, L. F., & Pulgarin, C. (2019). Solar-assisted bacterial disinfection and removal of contaminants of emerging concern by Fe2+-activated HSO3− vs. S2O82− in drinking water. *Applied Catalysis B: Environmental*, 248, 62–72.

Roongraung, K., Chuangchote, S., & Laosiripojana, N. (2020). Enhancement of photocatalytic oxidation of glucose to value-added chemicals on TiO2 photocatalysts by a zeolite (type Y) support and metal loading. *Catalysts*, 10, 16.

Rubia, A. A., Johny, L. M., Jothi, N. S. N., & Sagayaraj, P. (2019). Solvothermal synthesis, characterization and photocatalytic...
activity of ZnO nanoparticle. *Materials Today: Proceedings*, 8, 94–98.

Sabaghi, V., Davar, F., & Fereshteh, Z. (2018). ZnS nanoparticles prepared via simple reflux and hydrothermal method: Optical and photocatalytic properties. *Ceramics International*, 44, 7545–7556.

Sacco, O., Stoller, M., Vaiano, V., Ciambelli, P., Chianese, A., & Sannino, D. (2012). Photocatalytic degradation of organic dyes under visible light on N-doped TiO\textsubscript{2} photocatalysts. *International Journal of Photoenergy*, 2012.

Sacco, O., Vaiano, V., Rizzo, L., & Sannino, D. (2018). Photocatalytic activity of a visible light active structured photocatalyst developed for municipal wastewater treatment. *Journal of Cleaner Production*, 175, 38–49.

Sacco, O., Vaiano, V., Rizzo, L., & Sannino, D. (2019). Intensification of ceftriaxone degradation under UV and solar light irradiation in presence of phosphors based structured catalyst. *Chemical Engineering and Processing: Process Intensification*, 137, 12–21.

Sahu, M., & Biswas, P. (2011). Single-step processing of copper-doped titania nanomaterials in a flame aerosol reactor. *Nanoscale Research Letters*, 6, 441.

Saran, S., Arunkumar, P., & Devipriya, S. P. (2018). Disinfection of roof harvested rainwater for potable purpose using pilot-scale solar photocatalytic fixed bed tubular reactor. *Water Science and Technology: Water Supply*, 18, 49–59.

Saran, S., Arunkumar, P., Manjari, G., & Devipriya, S. P. (2019). Reclamation of grey water for non-potable purposes using pilot-scale solar photocatalytic tubular reactors. *Environmental Technology*, 40, 3190–3199.

Sautina, N. V., Rybakova, A. I., & Galyametdinov, Y. G. (2019). Kinetics of lysine mass transfer in reverse microemulsions, stabilized by AOT. *Liquid Crystals Applications*, 19, 26–32.

Scott, T., Zhao, H. L., Deng, W., Feng, X. H., & Li, Y. (2019). Photocatalytic degradation of phenol in water under simulated sunlight by an ultrathin MgO coated Ag/TiO\textsubscript{2} nanocomposite. *Chemosphere*, 216, 1–8.

Senthilnathan, A., Dissanayake, D., Chandrakumara, G. T. D., Mantilaka, M., Rajapakse, R. M. G., Pitawala, H., & de Silva, K. M. N. (2019). Akaganeite nanorices deposited muscovite mica surfaces as sunlight active green photocatalyst. *Royal Society Open Science*, 6, 182212.

Serra, A., Gomez, E., & Philippe, L. (2019). Bioinspired ZnO-based solar photocatalysts for the efficient decontamination of persistent organic pollutants and hexavalent chromium in wastewater. *Catalysts*, 9, 974.

Serra, A., Zhang, Y., Sepulveda, B., Gomez, E., Nogues, J., Michler, J., & Philippe, L. (2019). Highly active ZnO-based biomimetic fern-like microleaves for photocatalytic water decontamination using sunlight. *Applied Catalysis B: Environmental*, 248, 129–146.

Serra, A., Zhang, Y., Sepulveda, B., Gomez, E., Nogues, J., Michler, J., & Philippe, L. (2020). Highly reduced ecotoxicity of ZnO-based micro/nanostructures on aquatic biota: Influence of architecture, chemical composition, fixation, and photocatalytic efficiency. *Water Research*, 169, 12.

Shaban, Y. A., El Sayed, M. A., El Maradny, A. A., Al Farawati, R. K., Al Zobidi, M. I., & Khan, S. U. M. (2016). Laboratory and pilot-plant scale photocatalytic degradation of polychlorinated biphenyls in seawater using CM-n-TiO\textsubscript{2} nanoparticles. *International Journal of Photoenergy*, 2016, 8471960.

Shahid, S., Fatima, U., Rasheed, M. Z., Asghar, M. N., Zaman, S., & Sarwar, M. N. (2020). Enhanced sunlight-driven photocatalytic performance of Ag-ZnO hybrid nanoflowers. *Applied Nanoscience*, 10, 187–197.

Shang, Z. C., Yang, Z. X., Xiao, Y., & Wang, X. H. (2020). Ordered mesoporous Ag/CeO\textsubscript{2} nanocrystalline via silica-templated solution combustion for enhanced photocatalytic performance. *Colloids and Surfaces a-Physicochemical and Engineering Aspects*, 604, 9.

Shaniba, C., Akbar, M., Ramseena, K., Raveendran, P., Narayanan, B. N., & Ramakrishnan, R. M. (2020). Sunlight-assisted oxidative degradation of cefixime antibiotic from aqueous medium using TiO\textsubscript{2}/nitrogen doped holey graphene nanocomposite as a high performance photocatalyst. *Journal of Environmental Chemical Engineering*, 8, 102204.

Sharma, G., Dionysiou, D. D., Sharma, S., Kumar, A., Al-Muhtaseb, A. H., Naushad, M., & Stadler, F. J. (2019). Highly efficient Sr/Ce/activated carbon bimetallic nanocomposite for photoinduced degradation of rhodamine B. *Catalysis Today*, 335, 437–451.

Sharmila, J., Saravananan, P., Sivasankar, S., & Chamundeeswarri, M. (2020). A novel and an eco-friendly approach for organic dyes degradation using *Spirulina platensis* cultivated water. *Catalysis Today*, 340, 245–252.

Shen, L., Xing, Z., Zou, J., Li, Z., Wu, X., Zhang, Y., Zhu, Q., Yang, S., & Zhou, W. (2017). Black TiO\textsubscript{2} nanobelts/g-C\textsubscript{3}N\textsubscript{4} nanosheets laminated heterojunctions with efficient visible-light-driven photocatalytic performance. *Scientific Reports*, 7, 41978.

Shen, Y., Wu, Y., Li, X., Zhao, Q., & Hou, Y. (2013). One-pot synthesis of MgFe\textsubscript{2}O\textsubscript{4} nanospheres by solvothermal method. *Materials Letters*, 96, 85–88.

Shinde, Y., Wadhai, S., Ponkshe, A., Kapoor, S., & Thakur, P. (2018). Decoration of Pt on the metal free RGO TiO\textsubscript{2} composite photocatalyst for the enhanced photocatalytic hydrogen evolution and photocatalytic degradation of pharmaceutical pollutant β blocker. *International Journal of Hydrogen Energy*, 43, 4015–4027.

Shuang, S., Xie, Z., & Zhang, Z. J. (2016). Enhanced visible light photocatalytic performance by nanostructured semiconductors with glancing angle deposition method. Intech Europe.

Shwetharani, R., & Balakrishna, R. G. (2014). Comparative study of homogeneous and heterogeneous photoxidative treatment on bacterial cell via multianalytical techniques. *Journal of Photochemistry and Photobiology A: Chemistry*, 295, 11–16.

Sohrabi, P., & Ghabadi, N. (2019). Optical and photocatalytic behaviors of iron selenide thin films grown by chemical bath deposition versus deposition time and annealing temperature. *Applied Physics A: Materials Science and Processing*, 125, 11.

Song, Z., Dong, X., Wang, N., Zhu, L., Luo, Z., Fang, J., & Xiong, C. (2017). Efficient photocatalytic defluorination of perfluorooctanoic acid over BiOCl nanosheets via a hole direct oxidation mechanism. *Chemical Engineering Journal*, 317, 925–934.

Stan, C. D., Cretescu, I., Pastravanu, C., Poulios, I., & Dragan, M. (2012). Treatment of pesticides in wastewater by heterogeneous
and homogeneous photocatalysis. *International Journal of Photoenergy*, 2012, 6.

Subramani, A. K., Byrappa, K., Kumaraswamy, G. N., Ravikumar, H. B., Ranganathaiah, C., Lokanatha Rai, K. M., Ananda, S., & Yoshimura, M. (2007). Hydrothermal preparation and characterization of TiO2:AC composites. *Materials Letters, 61*, 4828–4831.

Sujatha, G., Shanthakumar, S., & Chiampo, F. (2020). UV light-irradiated photocatalytic degradation of coffee processing wastewater using TiO2 as a catalyst. *Environments, 7*, 47.

Sun, Y. Y., Li, G. Y., Wang, W. J., Gu, W. Q., Wong, P. K., & An, T. C. (2019). Photocatalytic defluorination of perfluorooctanoic acid by surface defective BiOCl: Fast microwave solvothermal synthesis and photocatalytic mechanisms. *Journal of Environmental Sciences, 84*, 69–79.

Taherinia, M., Nasiri, M., Abedini, E., & Pourretedal, H. R. (2019). Influence of calcination temperature and solvent of titanium precursor on the photocatalytic activity of N-doped TiO2 nanoparticles in H2 evolution under visible radiation. *Environment, Development and Sustainability, 21*, 1963–1975.

Tahir, M. B., Iqbal, T., Rafique, M., Rafique, M. S., Nawaz, T., & Sagir, M. (2020). Chapter 5—Nanomaterials for photocatalysis. In M. B. Tahir, M. Rafique, & M. S. Rafique (Eds.), *Nanotechnology and photocatalysis for environmental applications* (pp. 65–76). Elsevier.

Tan, L., Yu, C. F., Wang, M., Zhang, S. Y., Sun, J. Y., Dong, S. Y., & Sun, J. H. (2019). Synergistic effect of adsorption and photocatalysis of 3D g-C3N4−agar hybrid aerogels. *Applied Surface Science, 467*, 286–292.

Thorat, J. H., Kanade, K. G., Nikam, L. K., Chaudhari, P. D., Panmand, R. P., & Kale, B. B. (2012). Self-aligned nanocrystalline ZnO hexagons by facile solid-state and co-precipitation route. *Journal of Nanoparticle Research, 14*, 10.

Tie, L. N., Sun, R. Y., Jiang, H., Liu, Y. M., Xia, Y., Li, Y. Y., Chen, H., Yu, C. F., Dong, S. Y., Sun, J. Y., & Sun, J. H. (2019). Facile fabrication of N-doped ZnS nanomaterials for efficient photocatalytic performance of organic pollutant removal and H2 production. *Journal of Alloys and Compounds, 807*, 151670.

Titouhi, H., & Belgaied, J.-E. (2016). Removal of ofloxacin antibiotic using heterogeneous Fenton process over modified alginate beads. *Journal of Environmental Sciences, 45*, 84–93.

Tobajas, M., Belver, C., & Rodriguez, J. J. (2017). Degradation of emerging pollutants in water under solar irradiation using novel TiO2-ZnO/clay nanoarchitectures. *Chemical Engineering Journal, 309*, 596–606.

Tong, Z. W., Yang, D., Shi, J. F., Nan, Y. H., Sun, Y. Y., & Jhang, Z. Y. (2015). Three-dimensional porous aerogel constructed by g-C3N4 and graphene oxide nanosheets with excellent visible-light photocatalytic performance. *ACS Applied Materials & Interfaces, 7*, 25693–25701.

Tran, N. H., Li, J. H., Hu, J. Y., & Ong, S. L. (2014). Occurrence and suitability of pharmaceuticals and personal care products as molecular markers for raw wastewater contamination in surface water and groundwater. *Environmental Science and Pollution Research, 21*, 4727–4740.

Tsoumachidou, S., Velegraki, T., Antoniadis, A., & Poullos, I. (2017). Greywater as a sustainable water source: A photocatalytic treatment technology under artificial and solar illumination. *Journal of Environmental Management, 195*, 232–241.

Ubonchonlakate, K., Sikong, L., & Saito, F. (2012). Photocatalytic disinfection of *P. aeruginosa* bacterial Ag-doped TiO2 film. *Procedia Engineering, 32*, 656–662.

Vatangpour, V., Karami, A., & Sheydaei, M. (2019). Improved visible photocatalytic activity of TiO2 nanoparticles to use in submerged membrane photoreactor for organic pollutant degradation. *International Journal of Environmental Science and Technology, 16*, 2405–2414.

Vela, N., Calin, M., Yanez-Gascon, M. J., el Aatik, A., Garrido, I., Perez-Lucas, G., Fenoll, J., & Navarro, S. (2019). Removal of pesticides with endocrine disruptor activity in wastewater effluent by solar heterogeneous photocatalysis using ZnO/Na2S2O8. *Water, Air, and Soil Pollution, 230*, 1–11, 134.

Vela, N., Calin, M., Yanez-Gascon, M. J., Garrido, I., Perez-Lucas, G., Fenoll, J., & Navarro, S. (2018a). Photocatalytic oxidation of six endocrine disruptor chemicals in wastewater using ZnO at pilot plant scale under natural sunlight. *Environmental Science and Pollution Research, 25*, 34995–35007.

Vela, N., Calin, M., Yanez-Gascon, M. J., Garrido, I., Perez-Lucas, G., Fenoll, J., & Navarro, S. (2018b). Photocatalytic oxidation of six pesticides listed as endocrine disruptor chemicals from wastewater using two different TiO2 samples at pilot plant scale under sunlight irradiation. *Journal of Photochemistry and Photobiology A: Chemistry, 353*, 271–278.

Vela, N., Calin, M., Yanez-Gascon, M. J., Garrido, I., Perez-Lucas, G., Fenoll, J., & Navarro, S. (2018c). Solar reclamation of wastewater effluent polluted with bisphenols, phthalates and parabens by photocatalytic treatment with TiO2/Na2S2O8 at pilot plant scale. *Chemosphere, 212*, 95–104.

Velmurugan, R., & Swaminathan, M. (2011). An efficient nanostructured ZnO for dye sensitized degradation of Reactive Red 120 dye under solar light. *Solar Energy Materials and Solar Cells, 95*, 942–950.

Villaluz, F. D. A., de Luna, M. D. G., Colades, J. I., Garcia-Segura, S., & Lu, M. C. (2019). Removal of 4-chlorophenol by visible-light photocatalysis using ammonium iron (II) sulfate-doped nano-titania. *Process Safety and Environmental Protection, 125*, 121–128.

Vivar, M., Fuentes, M., Pichel, N., Lopez-Vargas, A., Rodrigo, M. J., & Srithar, K. (2020). Photovoltaic and solar disinfection technology meeting the needs of water and electricity of a typical household in developing countries: From a Solar Home System to a full-functional hybrid system. *Science of the Total Environment, 747*, 16.

Vlazan, P., Irina-Moisescu, C., Miron, I., Sfirloaga, P., Grozescu, I. J. O., & Communications, A. M.-R. (2015). Structural characterization of ZnO nanoparticles synthesized by co-precipitation and sol-gel method. *Optoelectronics and Advanced Materials, Rapid Communications, 9*, 1139–1142.

Walsh, F. (2013). The multiple roles of antibiotics and antibiotic resistance in nature. *Frontiers in Microbiology, 4*, 1.
Wang, A. Q., Chen, Z., Zheng, Z. K., Xu, H., Wang, H., Hu, K., & Yan, K. (2020). Remarkably enhanced sulfate radical-based photo-Fenton-like degradation of levofloxacin using the reduced mesoporous MnO@MnO2 microspheres. *Chemical Engineering Journal*, 379, 11.

Wang, J. H., Zhu, H. F., Tang, S. H., Li, M., Zhang, Y. P., Xing, W., Xue, Q. Z., & Yu, L. Q. (2020). Sandwich structure MoO3/-MoS2/TiO2 photocatalyst for superb hydrogen evolution. *Journal of Alloys and Compounds*, 842, 5.

Wang, S. Y., Li, F., Dai, X. H., Wang, C. J., Lv, X. T., Waterhouse, G. I. N., Fan, H., & Ai, S. Y. (2020). Highly flexible and stable carbon nitride/cellulose acetate porous films with enhanced photocatalytic activity for contaminants removal from wastewater. *Journal of Hazardous Materials*, 384, 10.

Wang, Y., He, Y., Lai, Q., & Fan, M. (2014). Review of the progress in preparing nano TiO2: An important environmental engineering material. *Journal of Environmental Sciences*, 26, 2139–2177.

Waso, M., Khan, S., Singh, A., McMichael, S., Ahmed, W., Fernandez-Ibanez, P., Byrne, J. A., & Khan, W. (2020). Predatory bacteria in combination with solar disinfection and solar photocatalysis for the treatment of rainwater. *Water Research*, 169, 10.

Wei, P. F., Yu, X. H., & Li, Y. (2019). Preparation of Fe3O4/ZnO/ZnS composites with enhanced photoperformance under solar irradiation. *Journal of Electronic Materials*, 48, 4877–4885.

Wei, S., Zhang, R., Liu, Y., Ding, H., & Zhang, Y. L. (2016). Graphene quantum dots prepared from chemical exfoliation of multwall carbon nanotubes: An efficient photocatalyst promoter. *Catalysis Communications*, 74, 104–109.

Weon, S., He, F., & Choi, W. J. E. S. N. (2019). Status and challenges in photocatalytic nanotechnology for cleaning air polluted with volatile organic compounds: Visible light utilization and catalyst deactivation. *The Royal Society of Chemistry*, 6, 3185–3214.

Wetchakun, N., Incessungvorn, B., Wetchakun, K., & Phanchinphat, S. (2012). Influence of calcination temperature on anatase to rutile phase transformation in TiO2 nanoparticles synthesized by the modified sol–gel method. *Materials Letters*, 82, 195–198.

World Health Organization & Unicef. (2015). Progress on sanitation and drinking water—2015 update and MDG assessment.

World Health Organization & Unicef. (2017). Progress on drinking water, sanitation and hygiene: 2017 update and SDG baselines. *World Health Organization*.

Xu, J., Zhang, L. W., Shi, R., & Zhu, Y. F. (2013). Chemical exfoliation of graphitic carbon nitride for efficient heterogeneous photocatalysis. *Journal of Materials Chemistry A*, 1, 14766–14772.

Xu, Q. J., Wang, Y., Chi, M., Hu, W. B., Zhang, N., & He, W. W. (2020). Porous polymer-titanium dioxide/copper composite with improved photocatalytic activity toward degradation of organic pollutants in wastewater: Fabrication and characterization as well as photocatalytic activity evaluation. *Catalysts*, 10, 310.

Yadav, A. A., Hunge, Y. M., & Kulkarni, S. B. (2019). Synthesis of multifunctional FeCo2O4 electrode using ultrasonic treatment for photocatalysis and energy storage applications. *Ultrasonics Sonochemistry*, 58, 7.

Yadav, A. A., Hunge, Y. M., Mathe, V. L., & Kulkarni, S. B. (2018). Photocatalytic degradation of salicylic acid using BaTiO3 photocatalyst under ultraviolet light illumination. *Journal of Materials Science - Materials in Electronics*, 29, 15069–15073.

Yamamoto, M., Minoura, Y., Akatsuka, M., Ogawa, S., Yagi, S., Yamamoto, A., Yoshida, H., & Yoshida, T. (2020). Comparison of platinum photodeposition processes on two types of titanium dioxide photocatalysts. *Physical Chemistry Chemical Physics*, 22, 8730–8738.

Yan, H. L., Liu, L. Z., Wang, R., Zhu, W. X., Ren, X. Y., Luo, L. P., Zhang, X., Luo, S. J., Ai, X. L., & Wang, J. L. (2020). Binary composite MoS2/TiO2 nanotube arrays as a recyclable and efficient photocatalyst for solar water disinfection. *Chemical Engineering Journal*, 401, 9.

Yan, Y., Sun, H. P., Zhang, L., Zhang, J., Mu, J., & Kang, S. Z. (2011). Effect of multivall carbon nanotubes on the photocatalytic degradation of methyl orange in aqueous solution under visible light irradiation. *Journal of Dispersion Science and Technology*, 32, 1332–1336.

Yan, Z., Gao, J., Li, Y., Zhang, M., & Guo, M. (2015). Hydrothermal synthesis and structure evolution of metal-doped magnesium ferrite from saponite laterite. *RSC Advances*, 5, 92778–92787.

Yang, G., & Park, S. J. (2019). Conventional and microwave hydrothermal synthesis and application of functional materials: A review. *Materials*, 12, 18.

Yazdani, A., Rahmani, K., Rahmani, H., Sarafraz, M., Tahmasebipour, M., & Rahmani, A. (2019). Inactivation of Fecal coliforms during solar and photocatalytic disinfection by zinc oxide (ZnO) nanoparticles in compound parabolic concentrators (CPCs). *Iranian Journal of Catalysis*, 9, 339–346.

Yin, Q., Cao, Z. Z., Wang, Z. Y., Zhai, J. M., Li, M. L., Guan, L., Fan, B. B., Liu, W., Shao, G., Xu, H. L., Wang, H. L., Zhang, R., & Lu, H. X. (2021). Z-scheme TiO2@Ti3C2/Co3O4/ZnO nanocomposites with efficient photocatalytic performance via one-step hydrothermal route. *Nanotechnology*, 32, 11.

You, Y., Zhang, S., Wán, L., & Xu, D. (2012). Preparation of continuous TiO2 fibers by sol-gel method and its photocatalytic degradation on formaldehyde. *Applied Surface Science*, 258, 3469–3474.

Yu, X. J., Yang, X. Y., & Li, G. (2016). The enhanced photoluminescence of CeO2-g-C3N4 mixed particles due to the mutual synergetic effect. *Journal of Materials Science - Materials in Electronics*, 27, 12174–12177.

Yusuff, A. S., Popoola, L. T., & Aderibigbe, E. I. (2020). Solar photocatalytic degradation of organic pollutants in textile industry wastewater using ZnO/pumice composite photocatalyst. *Journal of Environmental Chemical Engineering*, 8, 103907.

Zeng, X. K., Liu, Y., Xia, Y., Uddin, M. H., Xia, D. H., McCarthy, D. T., Deletic, A., Yu, J. G., & Zhang, X. W. (2020). Cooperatively modulating reactive oxygen species generation and bacteria-photocatalyst contact over graphitic carbon nitride by polyethyleneimine for rapid water disinfection. *Applied Catalysis B: Environmental*, 274, 8.

Zhang, H. X., Nengzi, L. C., Wang, Z. J., Zhang, X. Y., Li, B., & Cheng, X. W. (2020). Construction of Bi2O3/CuNiFe LDHs composite and its enhanced photocatalytic degradation of lomefloxacin with persulfate under simulated sunlight. *Journal of Hazardous Materials*, 383, 121236.

Zhang, W. F., Liu, F., Sun, Y. G., Zhang, J., & Hao, Z. P. (2019). Simultaneous redox conversion and sequestration of chromate (VI) and arsenite (III) by iron (III)-alginic based photocatalysis. *Applied Catalysis B: Environmental*, 259, 11.
Zhang, X., Liu, Y., Dong, S., Ye, Z., & Guo, Y. (2017). One-step hydrothermal synthesis of a TiO2-Ti3C2Tx nanocomposite with small sized TiO2 nanoparticles. Ceramics International, 43, 11065–11070.

Zhang, Y., Zhou, J., Feng, Q., Chen, X., & Hu, Z. (2018). Visible light photocatalytic degradation of MB using UIO-66/g-C3N4 heterojunction nanocatalyst. Chemosphere, 212, 523–532.

Zhao, H., Chen, J., Rao, G., Deng, W., & Li, Y. (2017). Enhancing photocatalytic CO2 reduction by coating an ultrathin Al2O3 layer on oxygen deficient TiO2 nanorods through atomic layer deposition. Applied Surface Science, 404, 49–56.

Zhao, J., Li, N., Yu, R., Zhao, Z., & Nan, J. (2018). Magnetic field enhanced denitrification in nitrate and ammonia contaminated water under 3D/2D Mn2O3/g-C3N4 photocatalysis. Chemical Engineering Journal, 349, 530–538.

Zhao, J. H., Nan, J., Zhao, Z. W., & Li, N. (2017). Facile fabrication of novel Mn3O4 nanocubes with superior light-harvesting for ciprofloxacin degradation. Catalysis Communications, 102, 5–8.

Zheng, Q., Durkin, D. P., Elenewski, J. E., Sun, Y. X., Banek, N. A., Hua, L. K., Chen, H. N., Wagner, M. J., Zhang, W., & Shuai, D. M. (2016). Visible-light-responsive graphitic carbon nitride: Rational design and photocatalytic applications for water treatment. Environmental Science & Technology, 50, 12938–12948.

Zheng, Q. M., Xu, E. S., Park, E., Chen, H. N., & Shuai, D. M. (2019). Looking at the overlooked hole oxidation: Photocatalytic transformation of organic contaminants on graphitic carbon nitride under visible light irradiation. Applied Catalysis B: Environmental, 240, 262–269.

Zhou, A. N., Wang, X. Q., Qu, J. L., Wang, Y. D., Li, Y. G., & Wang, G. G. (2011). C, S & N-doped TiO2 photocatalyst prepared by the reverse-microemulsion method. In X. H. Liu, Z. Y. Jiang, & J. T. Han (Eds.), Manufacturing processes and systems, Pts 1-2 (pp. 1007–1010). Trans Tech Publications Ltd.

Zhou, G. D., Zhao, T., Qian, R. F., Xia, X., Dai, S. Y., Alsaedi, A., Hayat, T., & Pan, J. H. (2019). Decorating (001) dominant anatase TiO2 nanoflakes array with uniform WO3 clusters for enhanced photoelectrochemical water decontamination. Catalysis Today, 335, 365–371.

Zinatloo-Ajabshir, S., Baladi, M., Amiri, O., & Salavati-Niasari, M. (2020). Sonochemical synthesis and characterization of silver tungstate nanostructures as visible-light-driven photocatalyst for waste-water treatment. Separation and Purification Technology, 248, 11.

Zuniga-Benítez, H., & Penuela, G. A. (2020). Solar-induced removal of benzophenones using TiO2 heterogeneous photocatalysis at lab and pilot scale. Topics in Catalysis, 63, 976–984.

How to cite this article: Sun, Y., & O’Connell, D. W. (2022). Application of visible light active photocatalysis for water contaminants: A review. Water Environment Research, 94(10), e10781. https://doi.org/10.1002/wer.10781