Recent advances, influencing factors, and future research prospects using photocatalytic process for produced water treatment

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ABSTRACT

Oilfield-produced water is the primary by-product generated during oil and gas extraction operations. Oilfield-produced water is often severely toxic and poses substantial health, safety, and environmental issues; adequate treatment technologies must bring these streams to a quality level. Photocatalysis is a photochemical catalytic reaction that is a highly promising tool for environmental remediation due to its efficiency in mineralizing persistent and potentially toxic contaminants. However, there is limited understanding of its application to treating oilfield-produced water with a complex and highly variable water composition. This review article discusses the mechanisms and current state of heterogeneous photocatalytic systems for oilfield-produced water treatment, highlighting impediments to knowledge transfer, including the feasibility of practical applications and the identification of essential research requirements. Additionally, the effects of significant variables such as catalyst quantity, pH, organic compound concentration, light intensity, and wavelength were discussed in detail. Some solutions are proposed for scientists and engineers interested in advancing the development of industrial-scale photocatalytic water treatment technologies.

Key words: photocatalysis, photocatalytic reactors, produced water, titanium dioxide (TiO\textsubscript{2}), water treatment

HIGHLIGHTS

- photocatalysis; produced water; treatment; affecting factors; produced water; prospects

1. INTRODUCTION

Advanced oxidation process (AOP), using photocatalytic oxidation, are gaining importance in the area of wastewater treatment (Gogate & Pandit 2004; Raut-Jadhav & Bagal 2020) since this process results in the degradation of pollutants with operation at mild conditions of temperature and most importantly sunlight or ultraviolet radiation for the generation of radicals capable of reacting with a wide range of priority pollutants. The advantages of photocatalytic water treatment over homogeneous-phase AOPs are well documented. For example, photocatalysis has been effectively used to degrade a wide range of organic compounds, including dyes (Dong 2015b; Shoneye \textit{et al.} 2021) endocrine and mutagenic damaging chemicals (Al-Ghouti \textit{et al.} 2019) and for degradation of pollutants in petroleum refinery wastewater (Rincon & Pulgarin 2004; Ani \textit{et al.} 2018). Photocatalysis as a treatment system obviates the necessity for constant demand of precursor chemicals, which is a significant advantage for specific applications, especially those in isolated or resource-limited areas. This promise is reflected in a recent surge of scholarly publications on photocatalytic water treatment over 5,500 results papers from 2002 to 2021 (Figure 1).

Despite extensive research during the last few years, photocatalysis's applicability in produced water has been quite limited. In light of these facts, how might photocatalysis be efficiently scaled up or approved for oilfield-produced water treatment?

We examine the current state of heterogeneous semiconductor photocatalytic water treatment in this review, highlighting barriers to technology transfer, assessing the feasibility of practical applications, and identifying critical research needs for overcoming obstacles, in order to find answers to this question.

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1.1. Mechanism and procedure for heterogeneous photocatalytic processes

Photocatalysis represents a unique class of chemical transformations capable of completely decomposing nearly all organic molecules in the presence of a photocatalyst, solar, or Ultraviolet light energy (Bharagava 2020). as shown in Figure 2 and summarised from (Equations (1)–(5)), photocatalysts absorb energy equal to or above their bandgap energy of the photocatalyst when the solution is subjected to a UV light across the catalyst’s surface in an aqueous solution. This exposure leads to the production of electrons and holes pairs in the conduction band and valence band (Equation (1)). Thus, The entire...
occurrence in photocatalytic processes requires the presence of water and dissolved oxygen which gives room to the formation of reactive radicals.

As shown on Figure 2, the electrons (e\(^-\)) which are excited by the light spectrum (photons), migrate from the valence band to the conduction band, leaving behind an empty unfilled valence band, and thus creating the electron-hole pair (h\(^+\)) (Chong et al. 2010). As shown on Equations (2) and (3), the electron-hole pair h\(^+\) at the valency band reacts with OH\(^-\) or H\(_2\)O to form hydroxyl radical (OH\(^-\)). While Equation (4) illustrates the reaction at the conduction band, here O\(_2\) as an oxidizing agent, accepts the photogenerated electron e\(^-\) to become reduced. The reduction of molecular oxygen O\(_2\) produces superoxide radicals O\(_2\)^{\cdot-}\.

Thus photogenerated reactive species O\(_2\)^{\cdot-} and OH\(^-\) are mainly responsible for the degradation of the pollutants or mineralized to nontoxic states (Chong et al. 2010; Ala‘a & Khraisheh 2015).

During the reaction process, challenges encountered include the recombination of the electrons and holes (Equation (5)), resulting in the emission of heat within nanoseconds and hinders the activity of radicals and results to a low quantum yield (Dong et al. 2015b; Bloh 2019).

Photocatalyst + hv \rightarrow (e\(_{cb}\) and h\(_{vb}\)) (1)

\[ \text{OH}^- + h^+ \rightarrow \text{OH} \] (2)

Oxidation of H\(_2\)O molecules: h\(^+\) + H\(_2\)O \rightarrow H\(^+\) + OH\(^-\) (3)

O\(_2\) + e\(^-\) \rightarrow (O\(_2\)^{-}) (4)

Electrons – holes recombination: e\(^-\) + h\(^+\) \rightarrow heat (5)

However, the degradation pathway of pollutants to final photocatalytic products involves some specific sequence of steps as depicted in the reaction procedure in Figure 2 (Su et al. 2008; Chong et al. 2010).

I. Mass transfer of reactants from the bulk fluid phase to the external surface of the solid photocatalyst through diffusion

II. Internal mass transfer of the reactants from the external surface of the photocatalyst through the pores to the surface of the photocatalyst and settling on an active site through adsorption

III. Reaction in the absorbed phase, with a re-arrangement of electron taking place in the reaction

IV. Product is released from the external surface of the photocatalyst to the fluid media.

1.1.1. Factors influencing photocatalytic reaction process

The oxidation rates and performance of the photocatalytic system are strongly reliant on some factors such as pH of the reaction, light intensity, reaction time, wavelength and catalytic loading and concentration of pollutants (Loeb et al. 2018). Aside from the irradiation source, and the photocatalyst material, the photoreactor design have an impact on photocatalytic performance as measured by pollutant removal efficiency.

1.1.1.1. pH. pH is one of the most significant operational factors in heterogeneous photocatalytic water systems because it affects the charge on the catalyst particles, the size of the catalyst aggregates, and the locations of the conductance and valence bands. Because of the nature of the semiconductor catalyst employed, any change in operational pH is reported to stimulate the isoelectric point or surface charge of the photocatalyst (Gnanaprakasam et al. 2015). Many reports have used the point of zero charge (PZC) to study the pH impact on the photocatalytic oxidation performance (Ochuma et al. 2007; Chong et al. 2009). The PZC is a condition where the surface charge of photocatalyst is zero or neutral that lies in the pH range of 4.5–7.0 depending on the catalysts used (Sacco et al. 2012; Chanu et al. 2019).

1.1.1.2. Catalytic loading. The amount of catalyst also affects photocatalytic degradation. The rate of photodegradation increased as the quantity of catalyst in the photocatalytic process increased. This may be explained by the fact that increasing the quantity of catalyst generally increases the number of active sites on the surface of the photocatalyst, resulting in an increase in the number of OH\(^-\) radicals formed, which can participate in the real discoloration of dye solution. Beyond a certain quantity of catalyst, the solution becomes turbid and so prevents UV rays for the reaction to continue, resulting in a decrease in percentage degradation (Coleman et al. 2007) for instance as shown on Figure 3.
the absence of TiO$_2$, no significant degradation was observed. The degradation rate increased with increasing catalyst loading until 0.7 gL$^{-1}$, after which a decrease in degradation was observed. The reduction of photocatalytic activity at higher catalyst loading is attributed to the effects of light scattering and shielding by the suspended catalysts (Jamali et al. 2013).

1.1.1.3. Light wavelength. Depending on the kind of photocatalysts used, the photochemical impacts of light sources with various wavelength emission ranges, will have a significant impact on the photocatalytic process (Molinari et al. 2020). UV light used in the process needs to have sufficient energy to promote electron hole formation (Ameta & Ameta 2018). The corresponding electromagnetic spectrum for UV irradiation is categorised as UV-A, UV-B, and UV-C, based on the wavelength of light that it emits. The UV-A range has its light wavelength range from 315 to 400 nm (3.10–3.94 eV). UV-B has wavelength range of 280–315 nm (3.94–4.43 eV) and the UV-C ranges from 100 to 280 nm (4.43–12.4 eV) (Janssens et al. 2019).

In most of the previous studies, the UV ranges at 254 nm–315 nm provides light photons sufficient for photonic activation of titanium dioxide (TiO$_2$) and zinac oxide (ZnO). TiO$_2$ has a band gap with an optical absorption in the 310–400 nm-wavelength region, while CeO$_2$ lies in the corresponding wavelengths of 388 nm (3.2 eV) and 381 nm (3.25 eV) respectively. ZnO with a wide band gap ($E_g = 3.37$ eV, corresponding to 387 nm and has unique electro optical properties and efficient UV absorptivity (Becheri et al. 2008; Rajendran et al. 2016; Ghamsari et al. 2017) However, some studies have used 253 nm during photocatalysis reaction (Lu et al. 2008; Ali et al. 2010).

1.1.1.4. Concentration of pollutants. The concentration of the photocatalyst has a significant effect on the pace of the photocatalytic process. It is well established that heterogeneous photocatalytic processes exhibit a proportionate rise in photodegradation with increasing catalyst loading (Krysa et al. 2004; Kumar & Pandey 2017). Generally, the optimal catalyst concentration for every specific photocatalytic application must be established in order to minimise excess catalyst and assure complete absorption of efficient photons (Krysa et al. 2004). This is because excessive photocatalyst loading results in unfavourable light scattering and a decrease in light penetration into the solution (Saquib & Muneer 2003).

1.1.1.5. Temperature. Temperature this variable has little or no effect on the photocatalytic reaction rate. However, it was shown that an increase in photocatalytic reaction temperature (>80 °C) promoted the recombination of electron hole charges (Gaya & Abdullah 2008) Moreover; temperatures below 80 °C actually favour adsorption of contaminants on the TiO$_2$ surface and operating at this temperature can reduced the heating capacity of water (Herrmann 2005). Puma et al. (2002) reported that temperatures between 20–80 °C seem to be more effective for organic reactions with UV light (Li Puma & Yue 2002).

Figure 3 | Effect of TiO$_2$ catalyst loading on phenol degradation (Jamali et al. 2013).
1.1.1.6. **Light Intensity.** When increased light intensity results in much greater energy waste rather than degradation, the increase in light intensity results in a significant rise in costs (Guozheng et al. 2010). A significant portion of light energy is lost so it is difficult to have an extensive application. When light intensity is not logically controlled, which is one of the most significant photocatalytic components. Light energy losses occur when the photon with less energy than threshold photon energy (hνₒ) is unable to ignite an electron–hole pair, and its energy is lost as heat hv<hνₒ and when hνₒ is absorbed by a photocatalyst, hνₒ energy is used to excite an electron–hole pair and the remaining energy hνₒ−hνₒ is lost as heat leading to energy waste (Yang & Liu 2007; Guozheng et al. 2010). It has been reported that sometimes the higher light intensity, causes much more energy waste instead of much more degradation of organic compounds. It is critical to establish suitable light intensities in order to reduce energy losses caused by electron–hole recombination and, to some extent, to ensure similar values in all the measurements at different times (Dillert et al. 2013).

1.1.1.7. **Reactor design.** Photocatalytic reactors for water treatment can be categorised into those reactors using suspended photocatalyst particles and photocatalyst are immobilised on a continuous inert carrier as shown on figure Figure 4. Photocatalytic reactors can run in batch, batch with recirculation, or continuous mode and their geometry should be designed to optimise the collection of light emitted by the selected sources (Cassano & Alfano 2000). According to Pareek et al. (2008), the most critical parameters to consider when designing a photocatalytic reactor are the total irradiation surface area of the catalyst per unit volume and the light dispersion inside the reactor (Pareek et al. 2008).

Recent studies by Enesca (2021) reported that using the inappropriate photoreactor design may significantly increase energy consumption, improperly distribute photons, or cause the catalyst to deactivate, all of which have an adverse effect.

![Figure 4 | Photocatalytic water treatment reactor designs (Loeb et al. 2018).](http://iwaponline.com/wst/article-pdf/doi/10.2166/wst.2021.641/984385/wst2021641.pdf)
on photocatalytic efficiency. (Enesca 2021). Thus the main obstacle in the development of highly efficient photocatalytic reactors is the establishment of effective reactor designs for intermediate and large-scale use, as demanded for the purpose of industrial or commercial applications (Abhang et al. 2011). A Scale up for industrial applications will offer opportunities to increase the performance of photocatalytic water treatment systems through improved reactor design. The importance of additional research in the areas of reactor design have been emphasised by (Chong et al. 2010; Loeb et al. 2018). According to Hossain (2018) a compact photocatalytic reactor will enable efficient decomposition of organic compounds in a liquid or gas phase, incorporating a flexible and light-dispersive capacity (Hossain 2018).

1.2. Challenges and prospects for photocatalytic application in water treatment

The photocatalytic process has shown significant promise as a low-cost, ecologically friendly, and sustainable treatment method that is compatible with the water/wastewater industry’s ‘zero’ waste policy; This advanced oxidation technology’s effectiveness to eliminate persistent organic contaminants and microorganisms in wastewater has been extensively proven. Table 1 gives an overview of the organic compounds treated, the conditions of the catalytic process, as well as the new advances in this technology for each study.

However, the application of photocatalysis systems to water treatment is limited by some technical problems that need further research (Foteinis & Chatzisymeon 2020).

According to (Lin et al. 2020), the relatively slow transfer of photocatalysis treatment techniques from bench to industrial scale is likely due to the system’s design currently used in water treatment; another key challenge identified as a constraint for photocatalysis application is the treatment scope for contaminants (Lin et al. 2020). That ben said Kang et al. (2019) reported a poor quantum yield due to the very effective recombination processes acting in the bulk solid and at the solid/electrolyte interface using UV-irradiated semiconductors (Kang et al. 2019). Also Jiang et al. (2021) reported that obtaining selective oxidation of the target pollutant or pollutants in the presence of other oxidizable organic substrates is relatively complex (Jiang et al. 2021) which has become a major set back for photocatalysis systems.

Selectivity is the oxidants’ capacity to distinguish between the multiple compounds present in solution (in heterogeneous photocatalytic reactions, h+, vb and OH). For example, recent reports had shown that it is challenging to oxidize benzene or other BTEX chemicals selectively in the presence of a high concentration of DOM dissolved organic matter (Coha et al. 2021; Giannakis et al. 2021; Marco et al. 2021).

In terms of intermediates produced during treatment not much studies has reported the management or handling of these compounds; in reality these intermediates may be more dangerous to humans and the the environment in the short run (Jamjoum et al. 2021).

1.2.1. Evaluation photocatalytic treatment systems and oilfield produced water

A photocatalytic treatment process can be more efficient in the removal of organics from oilfield-produced water. The most mature and feasible processes, such as ozonation and Fenton, are also associated with lower efficiency in oilfield-produced water. This assessment was based on the comprehensive report by (Coha et al. 2021), who classified the various AOPs based on their current developmental stage.

A search of the Scopus database using the keywords ‘produced water’ and ‘photocatalysis’ indicated that there were fewer than 90 peer-reviewed articles on the subject (Figure 1). Thus applications of photocatalysis techniques to treat oilfield-produced water and, more specifically, aromatic and polyaromatic compounds are still understudied (Ani et al. 2018).

In environmental remediation, limited reports depict the use of photocatalytic studies for the simultaneous degradation of organic compounds such as BTEX, PAHs, and phenols, contained in OPW and co-existing together. Although research in the literature shows that petroleum wastewaters have been studied using a heterogeneous photocatalysis method (Table 2). Nevertheless, most of the studies have primarily focused on the degradation of a single pollutant (Jain et al. 2007; Mu et al. 2017).

However, wastewater on an industrial scale contains a mixture of organic and inorganic compounds in different classifications co-existing, such as produced water during oil and gas extraction. Scaling up from laboratory to industrial-scale applications will require additional scientific research, including the fabrication and modification of semiconducting photocatalysts and the treatment of multiple pollutants, as well as process optimization studies to reduce the cost of treatment, as conceptualized in Figure 5.
| Class contaminants         | Target compound                      | Highlights on experimental and findings                                                                                                                                                                                                 | Reference                  |
|---------------------------|--------------------------------------|----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|-----------------------------|
| Dye pollutants            | Methyl orange dye                    | Bi$_2$O$_3$/CoFe$_2$O$_4$ heterojunctions have shown a high efficiency for decomposing organic dye under light irradiation. The nanocomposite with 1:1 Bi$_2$O$_3$/CoFe$_2$O$_4$ composition showed the highest photodegradation efficiency. The Bi$_2$O$_3$/CoFe$_2$O$_4$ is environmentally friendly, the synthesis is simple, and, if it were scaled up, the manufacturing cost would be low. Further studies on photocatalytic activities against other dye/drug pollutants and its water splitting potential is necessary. | Naveed et al. (2021)        |
| Phenolic compound         | Phenol                               | Photodegradation can be used for complete mineralization of phenol. Experimental results showed that under optimized conditions the phenol removal efficiency was 98 and 100% for the TiO$_2$/UV and TiO$_2$/UV/H$_2$O$_2$ system. | Saadati et al. (2016)       |
| Dye pollutants            | Methylene blue and Malachite green   | ZnO NPs degraded 94 and 92% of methylene blue (MB) and malachite green (MG), respectively. The biosynthesized ZnO NPs proved as an effective antibacterial agent and photocatalyst. | Vasantharaj et al. (2021)   |
| aromatic and aliphatic    | 4-Chlorophenol, chlorobenzene, 1,4-  | Wide variety of aromatic and aliphatic chlorocompounds as contaminants present in water can quench the fluorescence from ZnO-nano. Should examine the effectiveness of this catalyst in degrading real industrial effluents, in which numerous organic contaminants are present. | Hariharan (2006)            |
| chlorocompounds           | dichlorobenzene and benzene.         |                                                                                                                                                                                                                                         |                             |
| Dye pollutants            | Methylene blue                       | There is a highly nonlinear behaviour of the catalyst properties and their adsorption efficiencies. These results give some insight into the limiting factors in the thin film technique for photocatalysis. | Gupta et al. (2015)         |
| Dye pollutants            | Methyl Orange                        | There are presently no ways of producing graphene derivatives in huge amounts which are scalable and affordable despite their remarkable applicability. The synthesis and design of the new graphene-based nanocomposites for photocatalyst still require integral thinking. | Jamjoum et al. (2021)       |
| Aromatic compounds        | Phenol                               | Prolonged lifetime of photogenerated charges over the C-TiO$_2$ NPs caused the formation of the larger amount of OH with strong oxidizing power for the phenol degradation. The findings show the new prospect for designing an efficient visible light responsive nano-photocatalytic material. | Yu et al. (2014)            |
| Dye pollutants            | Methylene blue (MB)                  | Titanium oxide coupled with bismuth oxide (TiO$_2$/Bi$_2$O$_3$) nanocomposite was synthesized by seed extract of Sapindus mukorossi. TiO$_2$/Bi$_2$O$_3$ showed maximum degradation (MB: 94% and BPA: 91%) at a minimum concentration of pollutant (50 mg L$^{-1}$) with catalyst amount (55 mg), neutral pH and reduces half-life of pollutants (BPA: 1 h, MB: 0.5 h) | Rani & Shanker (2021)       |
| Chromophoric dye derivatives | AY-29, CBBG-250 and AG-25            | Rare earth metal doped bismuth oxide different chromophoric dye derivatives, such as AY-29, CBBG-250 and AG-25 in aqueous suspension. Bi$_2$O$_3$. The enhancements in the photocatalytic activity is | Raza et al. (2018)          |

(Continued.)
Hong et al. (2018) investigated the degradation of biocides such as Glutaraldehyde (GA) considered one of the most harmful contaminants in produced water which restricts biological activities making biological treatment a non-viable alternative for produced water treatment. GA was performed under ultraviolet (UV) irradiation with removal efficiency ranging from 52 to 85% within one hour irradiation (Hong et al. 2018). Also, in the study carried out by Andreozzi et al. (2017), linear plot of Ln(C/Co) versus the treatment time for the organic constituents of saline produced water in presence of reduced graphene oxide/titania rGO(10%)/TiO2-P25 shows that organic constituents removal was influenced by the rGO/TiO2 weight ratio. Among rGO/TiO2-P25 photocatalysts with different weight ratios (1, 5, 10 and 20%), the highest photocatalytic efficiency was achieved with a ratio of 10:1. As depicted on (Figure 6).

| Class contaminants          | Target compound                                                                 | Highlights on experimental and findings                                                                 | Reference                          |
|-----------------------------|---------------------------------------------------------------------------------|----------------------------------------------------------------------------------------------------------|------------------------------------|
| Aromatic compounds          | Benzene, toluene and xylene                                                     | Mn-TiO2 showed superior BTX removal efficiency under UV and visible irradiation in the presence of O2. The conversion percentage of benzene, toluene, and xylene to CO2 were 63.6%, 56.4%, 51.8%, and to CO 29%, 26.5%, 23.2%, respectively | Binas et al. (2019)               |
| Aromatic compounds          | Benzene, toluene and xylene ethylbenzene                                        | Investigation of photocatalytic degradation of BTEX by ZnO nanorods as visible light photocatalyst exhibited formation of benzyl alcohol, benzoaldehyde, phenol and benzoic acid as intermediate byproducts | Al-Sabahi et al. (2017)            |
| Aromatic compounds          | Benzene, toluene, ethylbenzene, m, p-xylene and o-xylene                       | At steady-state operation, above 79, 79, 99, 98, and 98% removal efficiencies were achieved for benzene, toluene, ethylbenzene, m, p-xylene and o-xylene, respectively, under optimal conditions (2.0 U mf of superficial gas velocity and 1.43 of height/diameter ratio)..The experimental results can lead to the development of an efficient photocatalytic treatment system that utilizes solar energy and TiO2/SiO2 photocatalysts | Park et al. (2011)                |
| Pharmaceuticals             | Tetracycline                                                                     | Compound was resistant to photolysis. Photocatalysis over 0.5 g/l TiO2 suspension showed rapid rate of degradation. The irradiated solution inhibits the activity of microorganisms | Reyes et al. (2006)               |
| Carboxylic acids            | Phenoxy acetic acid and 2,4,5-phenoxyacetic acid                                | The effect of pH, catalyst, BrO3− and H2O2 to degradation was significant in all cases. Degussa P-25 was more efficient photocatalyst than Hombicat UV 100. Millenium Inorganic PC500 and Travancore | Singh et al. (2007)               |
| Isoproturon                 | Hericides                                                                        | Degradation rate over Degussa TiO2 was faster than Hombicat 100 and was increased by the addition of electron acceptors. Degradation was slower under solar illumination | Haque & Muneer (2003)             |
| Toxic aquatic pollutants    | Cr(VI) and bisphenol A                                                           | shows the better degradation over Cr(VI) and BPA pollutants. At pH 2 and 5.64, Cr(VI) and BPA pollutants were degraded | Santhosh et al. (2018)            |
| Pesticides                  | Pesticides in aqueous solutions                                                  | demonstrated that the photocatalytic processes are promising for the degradation of pesticides from aqueous solutions using photocatalyst includingTiO2/Fe2O3/UV,rGO/Fe2O3/ZnO. However further studies suggested meeting key criteria such as cost-effectiveness, reactor design, and treatment of real effluents | (Yeganeh et al. (2021)            |
The photocatalytic reaction rates increase as follows: acetic acid < phenols < naphthalene < xylenes < toluene (Andreozzi et al. 2018). Sheikholeslami et al. (2018) studied the removal efficiency of BTEX compounds using γ-Fe₂O₃ nanoparticles. At the optimal catalyst concentration of 150 mg/L and pH 3, a 97% decrease in COD was achieved after 90 min of irradiation. Thus
optimizing the three principal independent parameters as depicted on Figure 7, can have significant impact on BTEX removal (Sheikholeslami et al. 2018).

Photocatalysis experiments were also performed to test the influence of the wavelength and intensity. Jimenez et al. (2019) reported a low removal of phenol with 50% degradation; results shows that the configuration and geometry of the equipment, can affect the profit of the light (Jimenez et al. 2019). Taghizadeh et al. (2020) using a combination of forward osmosis and photocatalyst system for simultaneous salt removal and treatment of produced water demonstrated that benzene, toluene, ethylbenzene, and xylene (BTEX) removal efficiency in the cellulose triacetate with TiO₂ and TiO₂/GO membrane under UVC radiation was 62 and 78% (Figure 8), respectively, results shows that the use of TiO₂ and TiO₂/GO membranes significantly improved the permeability, water flux, photocatalytic degradation of pollutants and desalination of produced water. The result for CT (cellulose triacetate and CTG membranes in comparison with the C membrane showed that the presence of TiO₂ and GO nanoparticles improved the permeability, increased hydrophilicity and enhanced the FO efficiency furthermore the best BTEX removal efficiency obtained was 80% in membrane CTG under visible light (Taghizadeh et al. 2020).

1.3. Photocatalyst application and challenges
There is a direct correlation between organic pollutant and surface coverage of photocatalyst (Dong et al. 2015b) as organic pollutants that can attach properly to the photocatalyst surface, are more likely to be oxidized directly. The photoinduced transfer of electrons that take place with adsorbed species over semiconductor photocatalyst depends on the band gap

Figure 7 | The nexus between pH, light intensity, catalyst concentration and BTEX removal (Sheikholeslami et al. 2018).

Figure 8 | BTEX compounds removal efficiency by membranes CT and CTG (Taghizadeh et al. 2020).
energy of the semiconductor (Kang et al. 2019) and so the activation energy must be enough to transfer electrons from the valence band to the conduction band (Schneider et al. 2014).

Figure 9, displays the bandgap energy ($E_{bg}$) for the photexcitation of different photocatalysts. However besides band gap, other factors play an important role in photocatalytic reactions; as the advancement of photocatalytic technology in the water treatment sector will require the use of photocatalyst exhibiting some ideal features such as high adsorption and surface area, light absorption, efficient charge separation and high mobility of charge carriers.

Different authors (Zhou et al. 2012; Neat et al. 2014) agree about the main factors of an ideal photocatalyst for instance, the size and shape of the catalyst influence its surface structure including its adsorption capacity and then resulting in various photocatalytic performance (Rani et al. 2018; Li et al. 2020a). Because adsorption of pollutants is a key phase, the surface area of the photocatalysts materials, also has a significant impact on photocatalytic activity thus, a large surface area contain more active sites and display improved photocatalytic activity (Tian et al. 2014). Thus, the selection of photocatalyst directly determines the utilization of UV, visible light. According to the findings by Correa et al.(2010) O3/UV/TiO2O3/UV/TiO2 combination was very effective for phenol reduction. reductions in contaminants were obtained after 60 min of oxidation treatment: phenols 99.9%, O&G 98.2%, sulfide 97.2%, COD 89.2%, and ammonia 15% proved that O3/UV/TiO2 seems to be a good option for cost effective treatment of produced water streams (Correa et al. 2010).

Silva et al.(2019) used real sample of OPW collected from an oil company located in Rio Grande do Norte, Brazil. The photocatalytic processes were effective for the removal of dissolved organic matter in OPW, the best treatment was at pH 7, this was attributed to the calcination effect on the photocatalyst during treatment. Thus an increase in the kinetic energy of reaction resulting in a higher oxidation rate of phenol (Silva et al. 2019).

Andreozzi et al. (2018) reported that titania coupled with reduced graphene oxide shows higher activity than bare TiO2 nanoparticles for reducing the TOC of saline produced water (SPW). The higher photoactivity of rGO/TiO2-HM pristine TiO2-HM compared to commercial bare P25 can be related to the specific surface area of rGO/TiO2-HM which is three times higher than TiO2-P25. On the other hand, the differences in shape, phase and particle size demonstrated to play a role in the photoactivity of these materials (Andreozzi et al. 2018).

Other studies carried out for treating produced water by photocatalytic processes demonstrated that high rate of photogenerated ($e^-$ and $h^+$) recombination, poor adsorption capacity of pollutants and high concentration of chloride ions in SPW compete with organic substrates and reduces the effect of pristine TiO2 which is frequently associated with low efficiency and a lack of reduction in the toxicity of treated SPW (Santos et al. 2006; Li et al. 2007; Gouma & Lee 2014). Also a more crystalize photocatalyst is capable of re-positioning of light-generated carriers to its originated state thereby preventing

**Figure 9** | Band gap energies of various semiconductor photocatalysts. (Nahar et al. 2017; Rani et al. 2018).
recombination (Kim & Kwak 2007) and in some occasion more energy can be absorbed (Marotti et al. 2006). And the surface charge properties of the photocatalyst under acidic or alkaline condition of some photocatalyst can result to a higher oxidizing activity at lower pH but excess H⁺ at very low pH, and can decrease reaction rate (Horvath 2003; Sun et al. 2006).

Furthermore, in a study conducted by Marzouk et al. (2021) shows that dip coating commercial TiO₂ membranes with different concentrations of SiO₂ (Figure 10); tested for oil rejection from raw PW. The TOC content in the SPW filtered through Mu was as low as 28 mg/l giving a removal efficiency of 72%. However, further enhancement with SiO₂ reported 89, 91, 90 and 87% for membrane (M1, M2, M3 and M4); respectively, which can be attributed to the pore size of the membranes within the NF range.

Research has also been performed to incorporate photocatalysts into inert substrates, such as glass or polymers, most notably to resolve post-treatment catalysts recovery problems. Liu et al. (2016) compared the removal efficiency of naphthalene in real offshore PW achieved by the catalyst suspended or immobilized on glass slides. Even if naphthalene reduction after 12 h was around 85%, immobilized TiO₂ promoted a larger removal rate, mainly due to a much lower increase in system turbidity upon catalyst addition (Liu et al. 2016).

1.3.1. Modification routes towards augmenting the photoactivity of photocatalyst materials

Given that photocatalyst can be deficient as regards to its main factors, various modification routes such as doping, thermal treatment and optimisation of application process towards augmenting or improving the optical and material response (performance) of photocatalysts exist.

The justification for using these material engineering methods is to maximize rates of the photocatalytic reaction by introducing electron acceptors or changing the catalyst shape and composition through different mechanism as reported by (Chong et al. 2010). Metallic materials such as copper (Cu), tin (Sn), nickel (Ni), platinum (Pt), gold (Au), silver (Ag) Vanadium (V) may elicit an appropriate bandgap change and stimulate effective degradation.

For instance, Gao et al. (2015) studied the effect of metal ion-doping on the photocatalytic activity of TiO₂ for rhodamine B removal. Ag⁺, Al³⁺, Mn²⁺, Ni²⁺ and Zn²⁺, were investigated. Result shows that Zn²⁺ could exhibit an excellent photocatalytic reduction efficiency because of the effects of the weight fractions of the anatase phase, S_bet, and Band gap (E_g). The use of Mn²⁺ and Ni²⁺ as dopants decreased photocatalytic activity (Gao et al. 2015).

**Figure 10** | Raw produced water treated pristine TiO₂ and TiO₂/SiO₂ coated membranes (Marzouk et al. 2021).
The application of non-metal dopants such as fluorine nitrogen, sulphur, carbon, (F, C, S, N and P) can enhance the photoactivity and feasibility of catalysts for industrial application through the introduction of impurities in the bandgap of photocatalyst and thus, reduces the photonic energy requirements, narrowing the bandgap and promoting the adsorption between photocatalyst and pollutants. Increased conductivity within photocatalyst and the mobility of charge carriers (Fujishima et al. 2008; Niu et al. 2018). The choice of phosphorus as a dopant allows the possibility of both cationic (P$^{5+}$) and anionic P$^{3-}$ doping of anatase TiO$_2$ (Yu et al. 2003) and there are several reports on high activity of P-doped TiO$_2$ nanoparticles (Gopal et al. 2012). Ganesh (2017) studied the influences of solution pH, band-gap energy, structural, surface and photocatalytic characteristics of different amounts of P-doped TiO$_2$ nano-powders. Result shows that 1 wt.% P-doped TiO$_2$ nano-powder calcined at 400 °C exhibits the highest rate of reaction for photocatalytic methylene blue (MB) degradation. P-doped TiO$_2$ nano-powder photocatalysts prefer a solution pH of 5.5 for improved activity in the MB degradation reaction. Nitrogen as a dopant have numerous potentials. Nitrogen doping improves optical absorption and photocatalytic degradation capability significantly (Ansari et al. 2016).

1.3.2. Photocatalysts types and environmental impact

According to prior research, the effectiveness of photocatalysts in degrading environmental pollutants is influenced by variables such as the photocatalyst type and the influence of light in photocatalytic reactions depends on the type of photocatalyst (Dong et al. 2015b).

A disadvantage of large-scale application would be the incorrect choice of catalyst for pollutant degradation. That is, utilizing a photocatalyst that is ineffective or incompatible with the contaminants (Hlongwane et al. 2019; Zhang et al. 2019; Quesada-Cabrera & Parkin 2020). Xu et al. (2019), as shown on Figure 11. categorised photocatalyst into nitrides based photocatalysts, metal oxide based photocatalysts and chalcogenides based photocatalysts (Xu et al. 2019).

1.3.2.1. Nitrides based Photocatalysts. Nitrides based Photocatalysts are well suited for catalytic applications as they have good electrical conductivity and Pt-like band structures, thus showing catalytic activity in hydro-denitrogenation and hydro-desulfurization (Rao et al. 2021). Also Nitrides nanostructures possess good mechanical toughness, including an outstanding stability in aqueous solution during electrochemical reactions (Qureshi et al. 2017). For example, the application of Gallium nitride (GaN) as a photocatalyst recorded immense success in sensing fields due to high mechanical strength and chemical stability compared to chalcogenides and oxides based photocatalysts (Yonenaga 2001) and Tantalum nitride (TaN$_3$) was effectively used for solar water splitting, due to its suitable band edge potential and narrow direct band gap (2.1 eV) (Tabata et al. 2010).

1.3.2.2. Chalcogenides based nanomaterials. Chalcogenides based nanomaterials had shown tremendous progress in the photocatalytic hydrogen evolution; hydrogen production from water splitting under visible light (Li et al. 2020b) among the chalcogenides, CdS CuS and ZnS semiconductors are well applied for photocatalytic reactions, such as water
decomposition and CO₂ reduction (Zhang et al. 2019). CuS/ZnS composites constructed by (Zhang et al. 2011) showed excellent photocatalytic hydrogen evolution activity under visible light, and the best H₂-production rate reached 4,147 μmol h⁻¹ g⁻¹ with quantum efficiency of 20% at 420 nm. Chen et al. (2016) constructed CuS/CdIn₂S₄/ZnIn₂S₄ photocatalysts, compared to P25, CuS/CdIn₂S₄/ZnIn₂S₄ presents more outstanding photocatalytic activity to degrade MO under simulated sunlight and visible light. As a result of the large surface area 239.5 (m²/g) and effective visible light response with an absorption edge of 670 nm (Chen et al. 2016).

1.3.2.3. Metal oxide based photocatalysts. Metal oxides play a significant role in environmental remediation technology. Most metal oxides may be used as photocatalysts due to their promising light absorption capabilities, electronic configuration, and charge transport characteristics. The most important characteristics of the photocatalytic system includes high surface property, suitable material properties such as high crystallinity and electronic properties for enhanced absorption behaviour (Hernández-Ramírez & Medina-Ramírez 2016). Metal oxides are largely considered effective photocatalyst for degradation of toxic organic compounds (as pollutant) present in wastewater (Khan et al. 2015) and regarded as low cost photocatalyst with good application prospect in photocatalysis. Murthy et al. (2015) reported that TiO₂, ZnO and CeO₂ are suitable photocatalyst for the degradation of mutagenic compounds which induces heritable change in cells or organisms) and carcinogenic compounds which induces unregulated growth processes in cells or tissues of multicellular organisms (Akbari-Fakhrabadi et al. 2015; Murthy et al. 2015).

1.4. Further strategies for improving photocatalytic treatment process

At present, It is difficult to make comparative evaluation not only across photocatalytic systems but also between photocatalysts (Hoque & Guzman 2018). The vast majority of the approaches are based on the use of TiO₂ semiconductors (Dong et al. 2015a), but further research should be carried out; as the upscale of photocatalytic processes may be challenging without adequate studies on more economical and available materials also the designing of more reliable photocatalyst through coating or doping on fixed supports would allow for the simultaneous degradation and separation of contaminants from the effluent stream.

To the best of our knowledge, there has been no report on a systematic comparison of appropriate semiconductors in literature. Moreover, the degradation of the wide range of organic compounds as pollutants has been reported using TiO₂, ZnO, and CeO₂ due to their exceptional stability in a variety of conditions and capability to generate charge carriers when stimulated with the required amount of light energy.

To the best of our knowledge, there has been no report on a systematic comparison of appropriate semiconductors photocatalyst. although the application of photocatalysts such as TiO₂, ZnO, and CeO₂ has been reported due to their exceptional capability to generate charge carriers when stimulated with the required amount of light energy (Chen et al. 2012; Kalathil et al. 2013; Ansari et al. 2014).

Murthy et al. (2015) reported that TiO₂, ZnO, and CeO₂ are suitable photocatalysts for the degradation of mutagenic compounds, which induces a heritable change in cells or organisms) and carcinogenic compounds, which causes unregulated growth processes in cells or tissues of multicellular organisms (Akbari-Fakhrabadi et al. 2015; Murthy et al. 2015) thus systematic comparative studies have not been reported in the treatment of oilfield produced water with photocatalysis processes, according to Scopus data (Figure 1). According to research, there is a rise of scientifically appealing but inappropriate materials that are brittle, chemically undesirable, costly, and potentially hazardous. WO₃ and CdS, for example, are visible light photocatalysts that are relatively effective, but the toxicity nature of CdS is incompatible with safe and sustainable water treatment practices (Nyamukamba et al. 2018). Also, the application of nanostructured materials to water treatment; if discharged to the environment could possibly lead to further environmental pollution (Pietroiusti et al. 2018) and so concerns about the fate of environmental behaviour, and toxicity of various nanomaterials cast doubt on the long-term viability of nanotechnology for wastewater treatment and purification (Hlongwane et al. 2019). Thus, a system scale of for photocatalytic process should put into consideration biotoxicity and environmental hazards associated with nanomaterials.

In this regard, Wang et al. (2021) using a life cycle assessment (LCA), as shown on Figure 12, evaluated the environmental impact of CdS, ZnFe₂O₄, and NiFe₂O₄ under visible light irradiation. After 4 h of photocatalysis treatment, the removal efficiency of MB was greatest for CdS followed by NiFe₂O₄ and ZnFe₂O₄. Moreover, based on the results of this study, ZnFe₂O₄ and NiFe₂O₄ have lower environmental impacts than CdS, both show promise as photocatalysts, as shown on (Figure 12(a)) CdS had a higher environmental impact with high respiratory effect, climate change and carcinogenic effects compared to
ZnFe$_2$O$_4$, and NiFe$_2$O$_4$. Thus CdS will not be recommended as a treatment catalyst. Additionaly, NiFe$_2$O$_4$ and ZnFe$_2$O$_4$ are recommended for further studies according in a pilot treatment system due low environmental impacts (Wang et al. 2021).

In another work the LCA between heterogeneous photocatalysis photo-fenton treatment process shows that an industrial wastewater treatment facility based on heterogeneous photocatalysis has a greater environmental effect than the photo-Fenton option, which scores 80–90% lower in the majority of impact categories evaluated. Further materials engineering studies was recommended to be carried out as the combination of heterogeneous photocatalysis process to the existing biological wastewater treatment can reduced the eutrophication potential, but require higher site area and electricity consumption (Chong et al. 2010).

In terms of environmental applications, photocatalysis has promising importance in wastewater treatment, including applications in the oil and gas industry, as shown by the recent growth in relevant research. Furthermore, the discharge water quality may be as high as required in light of the aim and allowable discharge concentration under various laws in different parts of the world. The present state of photocatalysis does not take into account intermediates generated during treatment; these intermediates may be more dangerous to humans and the the environment in the short run. As a result, future technical progress should put into consideration best ways of intermediates formed as well as increase material efficiency.

### 2. CONCLUSIONS AND PROSPECTS

Environmental pollution caused by oilfield-produced water is a threat to the human race and the environment at large due to the inability to eliminate non-biodegradable and persistent pollutants from OPW before discharge due to the conventional treatment methods used in the majority of oil and gas companies. As a result, this review article discussed the most current advancements in the treatment of OPW based photocatalysis systems. The primary benefit of photocatalytic therapy is its capacity to degrade contaminants to mineral end products without conveying contaminants through one phase to another, as is usual for conventional treatment methods. To upscale photocatalysis systems for water treatment, photocatalysis has to be competitive with other AOP technologies. A systematic comparison between photocatalyst in photocatalytic degradation research should be a primary method to identify appropriate photocatalyst before further modification to achieving high activity photocatalyst, suitable for industrial applications. The scope of treatment should consider vast contaminants. Also, studies on the life cycle assessment of photocatalyst at the preparatory and application stage should be intensified. Using life cycle assessment (LCA) concepts may aid in developing environmentally friendly and sustainable green synthesis techniques.

### DATA AVAILABILITY STATEMENT

All relevant data are included in the paper or its Supplementary Information.
REFERENCES

Abhang, R., Kumar, D. & Taralkar, S. 2011 Design of photocatalytic reactor for degradation of phenol in wastewater. *International Journal of Chemical Engineering and Applications* 2 (5), 337.

Akbari-Fakhraabadi, A., Saravanan, R., Jamshidiham, M., Mangalaraja, R. V. & Gracia, M. 2015 Preparation of nanosized yttrium doped CeO2 catalyst used for photocatalytic application. *Journal of Saudi Chemical Society* 19 (5), 505–510.

Ala’a, H. & Khraisyhe, M. J. J. o. w. p. e. 2015 Photocatalytic removal of phenol from refinery wastewater: catalytic activity of Cu-doped titanium dioxide. 8, 82–90.

Al-Ghouti, M. A., Al-Kaabi, M. A., Ashfaq, M. Y. & Da’na, D. A. 2019 Produced water characteristics, treatment and reuse: a review. *Journal of Water Process Engineering* 28, 222–239.

Ali, A. M., Emanuelsen, E. A. & Patterson, D. A. 2010 Photocatalysis with nanostructured zinc oxide thin films: the relationship between morphology and photocatalytic activity under oxygen limited and oxygen rich conditions and evidence for a Mars Van Krevelen mechanism. *Applied Catalysis B: Environmental* 97 (1–2), 168–181.

Al-Sabahi, J., Bora, T., Al-Abri, M. & Dutta, J. 2017 Efficient visible light photocatalysis of benzene, toluene, ethylbenzene and xylene (BTEX) in aqueous solutions using supported zinc oxide nanorods. *PloS one* 12 (12), e0189276.

Ameta, S. & Ameta, R. 2018 *Advanced Oxidation Processes for Wastewater Treatment: Emerging Green Chemical Technology*. Academic press.

Andreozzi, M., Álvarez, M. G., Contreras, S., Medina, F., Clarizio, L., Vitiello, G. & Marotta, R. 2018 Treatment of saline produced water through photocatalysis using rGO-TiO2 nanocomposites. *Catalysis Today* 315, 194–204.

Ani, I., Akpan, U., Olutoye, M. & Hameed, B. 2018 Photocatalytic degradation of pollutants in petroleum refinery wastewater by TiO2-and ZnO-based photocatalysts: recent development. *Journal of Cleaner Production* 205, 930–954.

Ansari, S. A., Khan, M. M., Ansari, M. O., Kalathil, S., Lee, J. & Cho, M. H. 2014 Band gap engineering of CeO2 nanostructure using an electrochemically active biofilm for visible light applications. *Rsc Advances* 4 (52), 16782–16791.

Ansari, S. A., Khan, M. M., Ansari, M. O. & Cho, M. H. 2016 Nitrogen-doped titanium dioxide (N-doped TiO 2) for visible light photocatalysis. *New Journal of Chemistry* 40 (3), 3000–3009.

Becheri, A., Dürr, M., Nostro, P. L. & Baglioni, P. 2008 Synthesis and characterization of zinc oxide nanoparticles: application to textiles as UV-absorbers. *Journal of Nanoparticle Research* 10 (4), 679–689.

Bharagava, R. N. 2020 *Emerging Eco-Friendly Green Technologies for Wastewater Treatment*. Springer.

Binas, V., Stefanopoulos, V., Kiriakidis, G. & Papagiannakopoulos, P. 2019 Photocatalytic oxidation of gaseous benzene, toluene and xylene under UV and visible irradiation over Mn-doped TiO2 nanoparticles. *Journal of Materiomics* 5 (1), 56–65.

Bloh, J. Z. 2019 A holistic approach to model the kinetics of photocatalytic reactions. *Frontiers in Chemistry* 7, 128.

Cassano, A. E. & Alfano, O. M. 2000 Reaction engineering of suspended solid heterogeneous photocatalytic reactors. *Catalysis Today* 58 (2–3), 167–197.

Chahu, L. A., Singh, W. J., Singh, K. J. & Devi, K. N. 2019 Effect of operational parameters on the photocatalytic degradation of Methylene blue dye solution using manganese doped ZnO nanoparticles. *Results in Physics* 12, 1230–1237.

Chen, H., Nanayakkara, C. E. & Grassian, V. H. 2012 Titanium dioxide photocatalysis in atmospheric chemistry. *Chemical Reviews* 112 (11), 5919–5948.

Chen, X., Li, L., Zhang, W., Li, Y., Song, Q. & Dong, L. 2016 Fabricate globular flower-like CuS/CdIn2S4/ZnIn2S4 with high visible light response via microwave-assisted one-step method and its multipathway photoelectron migration properties for hydrogen evolution and pollutant degradation. *ACS Sustainable Chemistry & Engineering* 4 (12), 6680–6688.

Chong, M. N., Jin, B., Zhu, H., Chow, C. & Saint, C. 2009 Application of H-titanate nanofibers for degradation of Congo Red in an annular slurry photoreactor. *Chemical Engineering Journal* 150 (4), 49–54.

Chong, M. N., Jin, B., Chow, C. W. & Saint, C. 2010 Recent developments in photocatalytic water treatment technology: a review. *Water Research* 44 (10), 2997–3027.

Coha, M., Farinelli, G., Tiraferri, A., Minella, M. & Vione, D. 2021 Advanced oxidation processes in the removal of organic substances from produced water: potential, configurations, and research needs. *Chemical Engineering Journal*, 128668.

Coleman, H., Vimones, V., Leslie, G. & Amal, R. 2007 Degradation of 1, 4-dioxane in water using TiO2 based photocatalytic and H2O2/UV processes. *Journal of Hazardous Materials* 146 (3), 496–501.

Correa, A. X., Tiepo, E. N., Somensi, C. A., Sperb, R. M. & Radetski, C. M. 2010 Use of ozone-photocatalytic oxidation (O 3/UV/TiO 2) and biological remediation for treatment of produced water from petroleum refineries. *Journal of Environmental Engineering* 136 (1), 40–45.

Dillert, R., Engel, A., Grobe, J., Lindner, P. & Bahnemann, D. W. 2013 Light intensity dependence of the kinetics of the photocatalytic oxidation of nitrogen (ii) oxide at the surface of TiO 2. *Physical Chemistry Chemical Physics* 15 (48), 20876–20886.

Dong, H., Zeng, G., Tang, L., Fan, C., Zhang, C., He, X. & He, Y. 2015a An overview on limitations of TiO2-based particles for photocatalytic degradation of organic pollutants and the corresponding countermeasures. *Water Research* 79, 128–146.

Dong, S., Feng, J., Fan, M., Pi, Y., Hu, L., Han, X. & Sun, J. 2015b Recent developments in heterogeneous photocatalytic water treatment using visible light-responsive photocatalysts: a review. *Rsc Advances* 5 (19), 14610–14630.

Enesca, A. 2021 The influence of photocatalytic reactors design and operating parameters on the wastewater organic pollutants removal – a mini-review. *Catalysts* 11 (5), 556.
Foteinis, S. & Chatzigeorgiou, E. 2020 Heterogeneous photocatalysis for water purification. In: Nanostructured Photocatalysts. Elsevier, pp. 75–97.

Fujishima, A., Zhang, X. & Tryk, D. A. 2008 TiO2 photocatalysis and related surface phenomena. Surface Science Reports 63 (12), 515–582.

Gao, X., Zhou, B. & Yuan, R. 2015 Doping a metal (Ag, Al, Mn, Ni and Zn) on TiO2 nanotubes and its effect on Rhodamine B photocatalytic oxidation. Environmental Engineering Research 20 (4), 329–335.

Gaya, U. I. & Abdullah, A. H. 2008 Heterogeneous photocatalytic degradation of organic contaminants over titanium dioxide: a review of fundamentals, progress and problems. Journal of Photochemistry and Photobiology C: Photochemistry Reviews 9 (1), 1–12.

Ghamsari, M. S., Alamdari, S., Han, W. & Park, H.-H. 2017 Impact of nanostructured thin ZnO film in ultraviolet protection. International Journal of Nanomedicine 12, 207.

Giannakis, S., Lin, K.-Y. A. & Ghanbari, F. 2021 A review of the recent advances on the treatment of industrial wastewaters by Sulfate Radical-based Advanced Oxidation Processes (SR-AOPs). Chemical Engineering Journal 406, 127083.

Gnanaprakasam, A., Sivakumar, V. & Thirumarimurugan, M. 2015 Influencing parameters in the photocatalytic degradation of organic effluent via nanometal oxide catalyst: a review. Indian Journal of Materials Science 2015.

Gogate, P. R. & Pandit, A. B. 2004 A review of imperative technologies for wastewater treatment I: oxidation technologies at ambient conditions. Advances in Environmental Research 8 (3–4), 501–531.

Gopal, N. O., Lo, H.-H., Ke, T.-F., Lee, C.-H., Chou, C.-C., Wu, J.-D. & … Ke, S.-C. 2012 Visible light active phosphorus-doped TiO2 nanoparticles: an EPR evidence for the enhanced charge separation. The Journal of Physical Chemistry C 116 (30), 16191–16197.

Gouma, P. & Lee, J. 2014 Photocatalytic nanomats clean up produced water from fracking. In Paper Presented at the 2010 International Conference on Digital Manufacturing & Automation.

Gupta, A., Saurav, J. R. & Bhattacharya, S. 2015 Solar light based degradation of organic pollutants using ZnO nanobrushes for water filtration. Rsc Advances 5 (87), 71472–71481.

Haque, M. & Muneer, M. 2003 Heterogeneous photocatalysed degradation of a herbicide derivative, isoproturon in aqueous suspension of titanium dioxide. Journal of Environmental Management 69 (2), 169–176.

Haririhan, C. 2006 Photocatalytic degradation of organic contaminants in water by ZnO nanoparticles: revisited. Applied Catalysis A: General 304, 55–61.

Hernández-Ramírez, A. & Medina-Ramírez, I. 2016 Photocatalytic Semiconductors. Springer.

Herrmann, J. G. 2005 Research to protect water infrastructure: EPA’s water security research program. In: Paper Presented at the Optics and Photonics in Global Homeland Security.

Hlongwane, G. N., Sekoai, P. T., Meyyappan, M. & Moothi, K. 2019 Simultaneous removal of pollutants from water using nanoparticles: an EPR evidence for the enhanced charge separation. Surface Science Reports 63 (12), 515–582.

Jamali, A., Vanraes, R., Hanselaer, P. & Van Gerven, T. 2013 A batch LED reactor for the photocatalytic degradation of phenol. Chemical Engineering and Processing: Process Intensiﬁcation 71, 43–50.

Jamjoum, H. A. A., Umar, K., Adnan, R., Razali, M. R. & Ibrahim, M. N. M. 2021 Synthesis, characterization, and photocatalytic activities of graphene oxide/metal oxides nanocomposites: a review. Frontiers in Chemistry 9.

Janssens, R., Cristóvão, B. M., Bronze, M. R., Crespo, J. G., Pereira, V. J. & Luis, P. 2019 Photocatalysis using UV-A and UV-C light sources for water treatment. In Paper Presented at the 2010 International Conference on Digital Manufacturing & Automation.

Jiang, D., Otitoju, T. A., Ouyang, Y., Shoparwe, N. F., Wang, S., Zhang, A. & Li, S. 2021 A review on metal ions modiﬁed TiO2 for photocatalytic degradation of organic pollutants. Catalysts 11 (9), 1039.

Jimenez, S., Andreozzi, M., Mico, M. M., Alvarez, M. G. & Contreras, S. 2019 Produced water treatment by advanced oxidation processes. 666, 12–21.

Kalathil, S., Khan, M. M., Ansari, S. A., Lee, J. & Cho, M. H. 2015 Band gap narrowing of titanium dioxide (TiO2) nanocrystals by electrochemically active bioﬁlms and their visible light activity. Nanoscale 5 (14), 6323–6326.

Kang, X., Liu, S., Dai, Z., He, Y., Song, X. & Tan, Z. 2019 Titanium dioxide: from engineering to applications. Catalysts 9 (2), 191.

Khan, M. M., Adil, S. F. & Al-Mayouf, A. 2015 Metal Oxides as Photocatalysts. Elsevier.

Kim, D. S. & Kwak, S.-Y. 2007 The hydrothermal synthesis of mesoporous TiO2 with high crystallinity, thermal stability, large surface area, and enhanced photocatalytic activity. Applied Catalysis A: General 325, 110–118.
Rani, A., Reddy, R., Sharma, U., Mukherjee, P., Mishra, P., Kuila, A. & ... Saravanan, P. 2018 A review on the progress of nanostructure materials for energy harnessing and environmental remediation. *Journal of Nanostructure in Chemistry* 8 (3), 255–291.

Rao, T., Cai, W., Zhang, H. & Liao, W. 2021 Nanostructured metal nitrides for photocatalysts. *Journal of Materials Chemistry C.*

Raut-Jadhav, S. & Bagal, M. 2020 Advanced graphene-transition metal-oxide-based nanocomposite photocatalysts for efficient degradation of pollutants present in wastewater. In: *Multifunctional Nanostructured Metal Oxides for Energy Harvesting and Storage Devices*. CRC Press, pp. 129–167.

Raza, W., Bahmann, D. & Muneer, M. 2018 A Green approach for degradation of organic pollutants using rare earth metal doped bismuth oxide. *Catalysis Today* 300, 89–98.

Reyes, C., Fernandez, J., Freer, J., Mondaca, M., Zaror, C., Malato, S. & Mansilla, H. 2006 Degradation and inactivation of tetracycline by TiO2 photocatalysis. *Journal of Photochemistry and Photobiology A: Chemistry* 184 (1–2), 141–146.

Rincon, A.-G. & Pulgarin, C. 2004 Effect of pH, inorganic ions, organic matter and H2O2 on E. coli K12 photocatalytic inactivation by TiO2: implications in solar water disinfection. *Applied Catalysis B: Environmental* 51 (4), 283–302.

Saadati, F., Keramati, N. & Ghazi, M. M. 2016 Influence of parameters on the photocatalytic degradation of tetracycline in wastewater: a review. *Critical Reviews in Environmental Science and Technology* 46 (8), 757–782.

Sacco, O., Stoller, M., Vaiano, V., Ciambelli, P., Chianese, A. & Sannino, D. 2012 Photocatalytic degradation of organic dyes under visible light on n-doped photocatalysts. *International Journal of Photoenergy* 2012.

Santhosh, C., Malathi, A., Daneshvar, E., Kollu, P. & Bhatnagar, A. 2018 Photocatalytic degradation of toxic aquatic pollutants by novel magnetic 3D-TiO2@HPGA nanocomposite. *Scientific Reports* 8 (1), 1–15.

Santos, F., Azevedo, E. & Dezotti, M. 2006 Photocatalysis as a tertiary treatment for petroleum refinery wastewaters. *Brazilian Journal of Chemical Engineering* 23, 451–460.

Saquib, M. & Muneer, M. 2003 TiO2-mediated photocatalytic degradation of a triphenylmethane dye (gentian violet), in aqueous suspensions. *Dyes and Pigments* 56 (1), 37–49.

Schneider, J., Matsuoka, M., Takeuchi, M., Zhang, J., Horiuchi, Y., Anpo, M. & Bahmann, D. W. 2014 Understanding TiO2 photocatalysis: mechanisms and materials. *Chemical Reviews* 114 (19), 9919–9986.

Sheikholeslami, Z., Kebría, D. Y. & Qaderi, F. 2018 Nanoparticle for degradation of BTEX in produced water; an experimental procedure. *Journal of Molecular Liquids* 264, 476–482.

Shoneye, A., Sen Chang, J., Chong, M. N. & Tang, J. 2021 Recent progress in photocatalytic degradation of chlorinated phenols and reduction of heavy metal ions in water by TiO2-based catalysts. *International Materials Reviews*, 1–18.

Silva, P. C., Ferraz, N. P., Perpetuo, E. A. & Asencios, Y. J. O. 2019 Oil produced water treatment using advanced oxidative processes: heterogeneous photocatalysis and photo-Fenton. *Journal of Sedimentary Environments* 4 (1), 99–107.

Singh, H. K., Saquib, M., Haque, M. M., Muneer, M. & Bahmann, D. W. 2007 Titanium dioxide mediated photocatalysed degradation of phenoxyacetic acid and 2, 4, 5-trichlorophenoxyacetic acid, in aqueous suspensions. (1–2), 66–72.

Su, Y., Han, S., Zhang, X., Chen, X. & Lei, L. 2008 Preparation and visible-light-driven photoelectrocatalytic properties of boron-doped TiO2 nanotubes. *Materials Chemistry and Physics* 110 (2–3), 239–246.

Sun, J., Wang, X., Sun, J., Sun, R., Sun, S. & Qiao, L. 2006 Photocatalytic degradation and kinetics of Orange G using nano-sized Sn (IV)/TiO2/AC photocatalyst. *Journal of Molecular Catalysis A: Chemical* 260 (1–2), 241–246.

Tabata, M., Maeda, K., Higashi, M., Lu, D., Takata, T., Abe, R. & Domén, K. 2010 Modified Ta3N5 powder as a photocatalyst for O2 evolution in a two-step water splitting system with an iodate/iodide shuttle redox mediator under visible light. *Langmuir* 26 (12), 9161–9165.

Taghizadeh, M., Kebría, D. Y. & Qaderi, F. 2020 Effect of biosurfactant as a novel draw solution on photocatalytic treatment and desalination of produced water by different forward osmosis membranes. *Water Supply* 20 (1), 240–250.

Tian, J., Zhao, Z., Kumar, A., Boughton, R. I. & Liu, H. 2014 Recent progress in design, synthesis, and applications of one-dimensional TiO2 nanostructured surface heterostructures: a review. *Chemical Society Reviews* 43 (20), 6920–6937.

Vasantharaj, S., Sathiyavimal, S., Senthilkumar, P., Kalpana, V., Rajalakshmi, G., Alsahi, M. & ... Pugazhendhi, A. 2021 Enhanced photocatalytic degradation of water pollutants using bio-Green synthesis of zinc oxide nanoparticles (ZnO NPs). *Journal of Environmental Chemical Engineering*, 105772.

Wang, X., Masten, S. J. & Esfahanian, E. 2021 Comparison of the photocatalytic efficacy and environmental impact of CdS, ZnFe2O4, and NiFe2O4 under visible light irradiation. *Water Science and Technology* 83 (5), 993–1004.

Xu, C., Anusuyadevi, P. R., Aymoner, C., Luque, R. & Marre, S. 2019 Nanostructured materials for photocatalysis. *Chemical Society Reviews* 48 (14), 3868–3902.

Yang, L. & Liu, Z. 2007 Study on light intensity in the process of photocatalytic degradation of indoor gaseous formaldehyde for saving energy. *Energy Conversion and Management* 48 (5), 882–889.

Yeganeh, M., Charkhloeo, E., Sobhi, H. R., Esrafil, A. & Gholami, M. 2021 Photocatalytic processes associated with degradation of pesticides in aqueous solutions: systematic review and meta-analysis. *Chemical Engineering Journal*, 130081.

Yonenaga, I. 2001 Thermo-mechanical stability of wide-bandgap semiconductors: high temperature hardness of SiC, AlN, GaN, ZnO and ZnSe. *Physica B: Condensed Matter* 308, 1150–1152.
Yu, J. C., Zhang, L., Zheng, Z. & Zhao, J. 2003 Synthesis and characterization of phosphated mesoporous titanium dioxide with high photocatalytic activity. *Chemistry of Materials* **15** (11), 2280–2286.

Yu, S., Yun, H. J., Kim, Y. H. & Yi, J. 2014 Carbon-doped TiO2 nanoparticles wrapped with nanographene as a high performance photocatalyst for phenol degradation under visible light irradiation. *Applied Catalysis B: Environmental* **144**, 893–899.

Zhang, J., Yu, J., Zhang, Y., Li, Q. & Gong, J. R. 2011 Visible light photocatalytic H2-production activity of CuS/ZnS porous nanosheets based on photoinduced interfacial charge transfer. *Nano Letters* **11** (11), 4774–4779.

Zhang, F., Wang, X., Liu, H., Liu, C., Wan, Y., Long, Y. & Cai, Z. 2019 Recent advances and applications of semiconductor photocatalytic technology. *Applied Sciences* **9** (12), 2489.

Zhou, H., Qu, Y., Zeid, T. & Duan, X. 2012 Towards highly efficient photocatalysts using semiconductor nanoarchitectures. *Energy & Environmental Science* **5** (5), 6732–6743.

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