

Photocatalysis technology for treating petroleum wastewater and the potential application of tapered bubble column (TBC): a review

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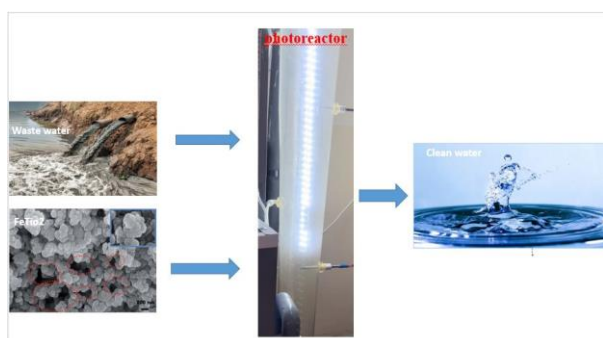
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Graphical abstract



Abstract

The photocatalytic oxidation of organic and petroleum wastewater treatment is an advanced oxidation process (AOP) with several benefits. It operates at normal temperatures and pressure, is inexpensive, does not produce secondary waste, and is easily accessible. Many studies have employed bubble columns, slurry bubble columns, and three-phase fluidized reactors in the photocatalytic process for wastewater treatment. Pure TiO₂ and Fe-doped TiO₂ are considered the most promising catalysts. The aim of this work is to review the main factors affecting the photocatalytic process of organic pollutants and petroleum wastewater (produced water) treatment, photocatalysts type, with a special focus on pure TiO₂ and Fe-doped TiO₂, light source, and reactor type.

Keywords: Photocatalysis, produced water, Fe doped TiO₂, Tapered bubble column.

1. Introduction

Produced water (petroleum wastewater) consists of a wide variety of pollutants, including oil and grease; alkanes; olefins; polycyclic aromatic hydrocarbons (PAHs); benzene, toluene, and xylene (BTX); mercaptans; phenol; ammonia; and many other organic compounds, in addition to a high level of total solids, and high biochemical oxygen demand (BOD) and chemical oxygen demand (COD) (Varjani *et al.* 2019; Al-Nuaim *et al.* 2022; Al-Nuaim *et al.* 2023).

Treating petroleum refinery wastewater or produced water (PW) requires numerous steps. Figure 1 shows these treatment steps with their objectives (Diya'uddeen *et al.* 2011; Varjani *et al.* 2019).

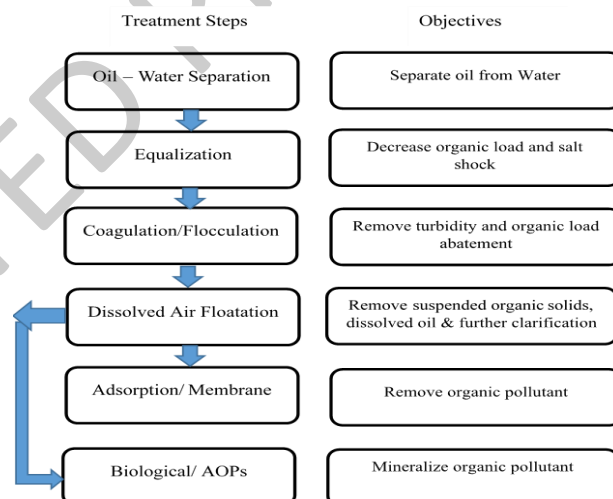


Figure 1. General steps and objectives for treating petroleum wastewater (Diya'uddeen *et al.* 2011; Varjani *et al.* 2019).

The four advanced final wastewater treatment processes are adsorption, membrane, biological, and advanced oxidation processes (AOPs). Adsorption and membrane processes transfer the pollutants to different concentrated forms, whereas biological and advanced oxidation processes can mineralize most of the pollutants (Kaur *et al.* 2016; Li *et al.* 2022; Oliveira *et al.* 2022). Table 1 likely provides a comprehensive overview of the four pollution-control methods, highlighting the advantages and disadvantages of each (Chen *et al.* 2020).

Comparing photocatalytic wastewater treatment with other processes, it is considered a promising and it has gained significant attention owing to its many advantages, making it a contemporary and environmentally friendly technology. Some key features of this approach include excellent performance, operation at ambient pressure and temperature, low costs, and the absence of secondary waste formation. Additionally, operating at ambient pressure and

temperature makes it a convenient and energy-efficient method. (Butkovskiy *et al.* 2017; Dewil *et al.* 2017).

Photocatalysis is used to oxidize refractory organic compounds that cannot be oxidized during biological

Table 1. Comparison of the treatment processes for organic pollutants (Chen *et al.* 2020).

Process type	Strength	Weakness
Biological treatment	1. Cost-effective the environmentally friendly 4nct.	1. It is not sufficiently copiable to remove a significant amount of organic waste.
	2. Excellent odor and color reduction.	2. Biosocial systems are difficult to control.
	3. maximum output.	3. It maintains the chemical oxygen demand values at their current levels.
Chemical precipitation	1. Energy use control.	4. Some organic compounds, such as day, have a weak capacity for biodegradation.
	2. Easy process.	1. High chemical consumption (e.g., lime, oxidants, H ₂ S, etc.)
	3. There is a wide range of compounds that are readily available in commerce.	2. The pH level must be checked.
	4. Efficient removal of absorbable organic halogen and total organic carbon, particularly in the pulp and paper industries.	3. There is a lot of sludge produced
Membrane filtration	1. Quick and effective.	4. The addition of non-recyclable chemicals (coagulants, flocculants, and chemicals) was necessary.
	2. Eco-friendly. Safe for plants and animals, non-toxic, and non-corrosive.	1. Relatively high operation and maintenance costs
	3. a high constituent removal rate.	2. Restricted feeding rate
Traditional photocatalysis	1. It is ecologically sound.	3. Membrane fouling reduces permeating flux and production.
	2. Excellent susceptibility, high energy efficiency, and low process cost.	1. Recovering and regenerating materials is challenging
	3. Catalyst loading adjustments are simple.	2. Because there are too many pollutants, degradation efficiency decreases.
		3. Potential photocatalyst losses in long-term use.

The main advantages of the photocatalytic oxidation can be summarized as follows: (Gogate and Pandit 2004) :

1. Operation occurs at room temperature and pressure.
2. TiO₂ is inexpensive, and sunlight can be used with considerable economic savings.
3. TiO₂ in aqueous media is chemically stable at a wide range of pH levels (i.e., 0-14).
4. The system requires only low concentrations of TiO₂ and no additives.
5. There is a high capacity for recovering noble metals.
6. Many pollutants successfully attain total mineralization.
7. This process is effective with chemicals containing halogens, which are extremely hazardous to bacteria when used in biological water treatment.

The disadvantages of photocatalytic oxidation are outlined in below: (Gogate and Pandit 2004):

1. Reactors cannot be used effectively at industrial scales due to a lack of engineering design and operation procedures. Being unable to evenly irradiate the entire catalyst surface with the same incident intensity presents the greatest challenge when developing large-scale reactors. Opacity, light scattering, depth of

treatment. Many research articles of photolytic degradation performed for treating petroleum wastewater and organic effluents (Varjani *et al.* 2019).

radiation penetration, and volumetric light absorption are all factors that limit the scale-up.

2. Chemical reactions during photocatalysis are often slower than with traditional methods, necessitating the use of additional active catalysts in the reactor. The quantity of active catalyst that can be contained in supported reactors is only limited by the thickness of the coating that can be applied to their surface; the more coating, the lower the total conversion efficiency.
3. Separation is very difficult in the suspended catalyst process.
4. There have been few applications to real industrial effluents with high destruction efficiency using photocatalytic oxidation alone.
5. Over time, the degradation rates decrease because the photocatalyst becomes corroded from prolonged use.

The photocatalytic process is made up of three main related components: the photocatalyst, the light source, and the photocatalytic reactor as depicted in Figure 2.

In the context of water treatment, photocatalysis involves the use of photocatalysts, often semiconductor materials like titanium dioxide, which, when illuminated with light, generate reactive oxygen species capable of breaking down pollutants in water. This process is particularly effective

against organic pollutants and can contribute to the degradation of various contaminants (Sajda *et al.* 2024).

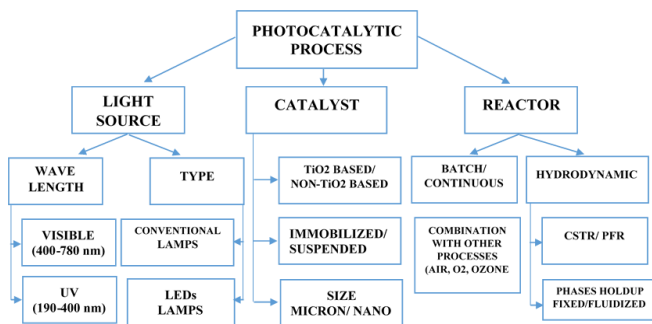


Figure 2. General outline of the photocatalytic process.

TiO₂-based photocatalysts are commonly used to treat organic pollutants and petroleum industry wastewater. Due to its high catalytic efficiency, stability, and nontoxicity, the TiO₂/UV technique has generated a great deal of attention in the field of photocatalysis. It provides the complete mineralization of wastewater from the petroleum industry while maintaining low costs, quick reaction times, no sludge generation, and ease of operation (Al-Nuaim *et al.* 2022; Elmobarak *et al.* 2021; Varjani *et al.* 2019; Ani *et al.* 2018; Aljuboury *et al.* 2017).

Pure TiO₂ has a bandgap of 3.2 and 3.6 eV for the crystal types anatase and rutile, respectively. The efficiency of absorption of sunlight is very low, and photocatalysis requires UV light. Doping with different transition metal ions (i.e., Cr, Fe, V, Mn, Co, and Ni) enhances the electrochemical and photochemical activities, introducing new energy levels into the bandgap and decreasing the gap to the visible range (Jeon *et al.* 2000; Zhang *et al.* 2009; Singh *et al.* 2016; Peng *et al.* 2012; Nair *et al.* 2014; Devi *et al.* 2017; Manzoor *et al.* 2018; Marami *et al.* 2018; Xu *et al.* 2018; Drozd *et al.* 2019; Sacco *et al.* 2019a; Chatrnoor *et al.* 2023; Heda *et al.* 2023). Hence, TiO₂ based photocatalysts can be divided according to their composition into pure TiO₂ and element doped-TiO₂ or composite catalyst. The catalyst TiO₂ doping with Fe enhances electrochemical and photochemical activities (Chatrnoor *et al.* 2023; Heda *et al.* 2023).

The pollutant, active catalyst, and effective source of illumination must all be in proximity to one another for the photocatalysis to be effective (Ibhadon and Fitzpatrick 2013; Ahmad *et al.* 2016; Oliveira *et al.* 2022).

Many studies have used bubble columns, slurry bubble columns, and three-phase fluidized reactors in the photocatalytic process for wastewater treatment (Cassano and Alfano 2000; Pozzo *et al.* 2006).

The aim of this work is to highlight the main three factors that effect on photocatalytic oxidation process; catalyst type, light source and reactor type. Furthermore, the article concentrated on the TiO₂-based photocatalytic

oxidation process for organic pollutants and petroleum wastewater (produced water) treatment, with a special focus on pure TiO₂ and Fe-doped TiO₂

2. Photocatalysts

Advanced oxidation processes (AOPs) for wastewater treatment include a wide variety of chemical processes, of which one is the photocatalytic process. It is employed to remove organic (and sometimes inorganic) pollutants from wastewater by oxidizing them through reactions with the generated hydroxyl radicals (*OH) (Ghime and Ghosh 2020).

Among the several semiconductor photocatalysts, TiO₂ is the most widely used. Many scientists are paying closer attention to it because of its many good qualities, which include high oxidation capacity, photo-stability, chemical stability, abundance, low toxicity, low cost, and long-term photostability (Elgohary *et al.* 2021). TiO₂-based photocatalysts can be divided according to their composition into pure TiO₂ and element doped-TiO₂ or composite catalysts. TiO₂ doped with Fe enhances the electrochemical and photochemical activities (Chatrnoor *et al.* 2023; Heda *et al.* 2023).

Rutile, anatase, and brookite are the three forms of crystals found in TiO₂. The creation of TiO₂ particles can be accomplished in a variety of ways, including flame aerosol synthesis (Bettini *et al.* 2016), hydrothermal synthesis (Corradi *et al.* 2005), and sol-gel synthesis (Gotić *et al.* 1996). While retaining the drawbacks of high temperature synthesis, the key benefit of flame aerosol synthesis is its simplicity, but TiO₂ crystalline powder is created by hydrothermal synthesis. The lack of a full understanding of the many factors that have a significant impact on photocatalytic performance (i.e., chemical equilibrium, nucleation kinetics, and phase growth) makes it difficult to regulate the overall process. The porous structure of the TiO₂ materials, which lowers the hydraulic resistance of TiO₂ films and increases their photocatalytic activity, is a crucial component of sol-gel chemistry synthesis (Li *et al.* 2022).

Photocatalytic systems are typically configured in one of the following ways:

2.1. TiO₂ powder suspension photocatalytic process

High-contact surface area, which results in a quicker reaction time and easier operation, is a defining feature of slurry reactors. To guarantee that the photocatalyst stays in suspension in this system, turbulence is needed. But after usage, it is quite challenging to remove TiO₂ from the liquid phase. According to Amir *et al.* (2017), meeting these standards also results in a significant increase in the energy used during the entire water treatment process. The research on the based photocatalytic oxidation process for organic pollutants and petroleum wastewater (produced water) treatment considered in this review is summaries in Tables 2.

Table 2. A summary of the uses of suspended TiO₂ powder in photocatalytic treatment of oil and gas wastewater.

Reference	Catalyst	Light source	Reactor	Degraded material	Notes
Natarajan <i>et al.</i> (2011)	TiO ₂ (free) Powder Suspended	UV-LED $\lambda=390-410$ nm	125 ml glass beaker and 5 UV-LED on acrylic sheet in circular path.	Rhodamine B dye (RhB)	95% RhB degradation for 6 h
Qi <i>et al.</i> (2011)	TiO ₂ (free) Powder	UV light	Annular reactor	Organic pollutants	CFD reactor simulation
Sarasidis <i>et al.</i> (2011)	TiO ₂ (free) Powder Suspended	Three blue light bulbs $\lambda=365$ nm	Photocatalytic reactor with ultrafiltration	Sodium alginate polysaccharides	75% max. total organic carbon (TOC) removal
Jamali <i>et al.</i> (2013)	TiO ₂ (free) Powder Suspended	UV LEDs 375 nm	Mini cylindrical vessel	Phenol	87% Phenol degradation
(Boyjoo <i>et al.</i> 2014)	TiO ₂ /P25 suspension	with 2 or 4 artificial UV lamps	Annular reactor with catalyst suspension	Organic pollutants	CFD Increase in reaction rate 56% and 123% when using 2 and 4 lamps
(Dominguez <i>et al.</i> 2015)	TiO ₂ (Free) powder Suspended	LED 375 nm In 10 strips and 18 units (180 LEDs)	A glass reaction vessel fitted inside PVC cylinder.	Dodecyl benzene sulfonate DBS Surfactants	50% DBS degradation for 3 h
(Sarasidis <i>et al.</i> 2014)	TiO ₂ (free) powder Suspended	Four black light bulbs, encased in acrylic containers	continuous membrane reactor, with hybrid catalysis	Diclofenac drug (DCF)	96% DCF degradation
(Casado, Timmers, <i>et al.</i> 2017)	TiO ₂ (free) powder Suspended	UV-LED 365 nm and UV black light fluorescent lamp 365–370 nm.	Two reactors, optically differential photoreactor annular lab. scale reactor	Methanol	CFD Kinetics of Oxidation methanol to formaldehyde
(B. Liu <i>et al.</i> 2016)	TiO ₂ (free) powder Suspended	UV mercury lamp peak at 254 nm	Cylindrical glass jar covered by a quartz cap and sealed with a (PTFE) o-ring	Produced Water Polycyclic Aromatic Hydrocarbons (PAHs)	PAHs degradation was strongly restricted by the organic composition in OPW
(Turolla <i>et al.</i> 2016)	TiO ₂ /P25 powder Suspended	UV 254-355 nm	Annular reactor with suspension	Oxalic acid (OXA)	90% OXA degradation
(Casado, Marugán, <i>et al.</i> 2017)	TiO ₂ /P25 powder Suspended	UV-LED 365 nm	Annular reactor with Suspension catalyst	Cinnamic acid (CA)	80%, 90% CA degradation for 50, 100 mg/l ca for 1 h
(Casado <i>et al.</i> 2019)	TiO ₂ /P25 powder Suspended	solar simulator xenon lamp or Natural sunlight	Based on a tubular reactor and a compound parabolic collector, the solar reactor	Methanol	Oxidation of methanol to formaldehyde
(Silva <i>et al.</i> 2019)	TiO ₂ (free) powder Suspended	UV lamps (253.7 nm)	glass beaker (500 ml) illuminated from the top	Phenolic in sea water and Produced Water (PW)	99% for phenol elimination, no significant salt concentration

2.2. Immobilization of TiO₂ photocatalytic oxidation process

Immobilized TiO₂ refers to the adhesion of titanium dioxide onto a support material, such as glass, silica, zeolites, or other porous materials the immobilization process usually enhances the practical application of TiO₂ in photocatalysis, offering advantages such as easy recovery and reuse of the catalyst. According to several studies (Srikanth *et al.* 2017), using the photocatalyst supported

(immobilized) by various materials in various reactor configurations has proven to be a good strategy to get around these challenges in recent years. As a catalyst in aqueous matrices, TiO₂ can be immobilized on a variety of inert support materials for use in fixed-film and fixed-bed reactors, or it can be used in a slurry reactor (Manassero *et al.* 2017). Additional significant technical problems include separating photocatalytic nanoparticles after water treatment and integrating them into workable reactor systems (Muritala *et al.* 2020). Before heterogeneous

photocatalytic technology can be applied in industrial processes, it is necessary to develop nanoparticle immobilization strategies that offer both a high photocatalytic activity and an affordable solid-liquid separation (Persico *et al.* 2015) ble 3. The general steps of immobilization strategy involve the following steps:

1. Selection of the suitable support material like glass, silica, metal oxide, etc. The selection method usually depends on the the intended application as well as the compatibility between the TiO₂ and the support material.
2. Ensuring that the selected material surface is clean and with no contamination. In most cases, it is important to enhance the adhesion of TiO₂. This is done by activation the surface of the support material either by cleaning, acid washing, or surface functionalization.
3. Preparing TiO₂ suspension through dispersing the TiO₂ powder in a suitable solvent.
4. Employing an immobilization process and it can be doen in several techniques involving the following:
5. So-gel process in which that a sol-gel solution of TiO₂ was prepared and applied onto the prepared surface support and dried to form the immobilized TiO₂ layer.
6. Dip-Coating in which that the support material submerged into TiO₂ suspension to allow the adsorption and then dried.
7. Chemical Bonding in which a chemical reaction occurred to create a chemical bond between TiO₂ and the support material.
8. Finally, Heat treatment or calcination, in this step the coated support material is subjected to heat in furnace to remove any residual solvents and transfer the coated TiO₂ into stable and crystalline form.

An overview of prior studies employing the immobilized TiO₂ photocatalytic system are provided in Table3.

Table 3. Studies employing the immobilized TiO₂ photocatalytic system.

Reference	Catalyst	Light source	Reactor	Degraded material	Notes
(Duran <i>et al.</i> 2011)	Immobilized TiO ₂ surface	UV 165-207 nm	TiO ₂ surface immobilized on an annular reactor	Benzoic acid and 2,4-Dichlorophenoxy acetic acid	first order rate constant of 0.025 min ⁻¹
(Sampaio <i>et al.</i> 2013)	TiO ₂ -coated glass raschig rings	Simulated solar light irradiation	A glass cylindrical reactor packed with TiO ₂ -coated rings	Phenol	90% Phenol degradation lose activity when reused
(Miranda-García <i>et al.</i> 2014)	Immobilized TiO ₂ on glass spheres	UV range 290–800 nm (9% corresponds to UV radiation in the 290–400 nm range)	a pilot compound collector (CPC) solar plant	Multi contaminants	Regeneration treatments
El Yadini <i>et al.</i> (2014)	Immobilized TiO ₂ on Borosilicate glass plates	UV 350- 400 nm peak 370 nm	Stirred tank reactor	Insecticide Fenamiphos	Degradation rate constants k=0.0183 min ⁻¹
Wang <i>et al.</i> (2015)	Immobilized TiO ₂ on Diatomite	UV 250W Hg lamp.	Mini reactor 100 ml	Rhodamine B (RhB)	90% RhB degradation for 1 h
(Barton <i>et al.</i> 2016)	TiO ₂ -coated glass sheets and optical fibers	UV mercury lamp 30 W/m ²	Reactor glass beaker with side and top light source	Methylene blue (MB) and methyl orange (MO)	1st order rate constant of about 1.55 min ⁻¹ g ⁻¹
(Maculan <i>et al.</i> 2016)	Immobilized TiO ₂ on metal plate coated with polyurethane resin and the catalyst.	UVsolar	Flat plate reactor	Dairy effluent	Reductions in COD (66.5%) and BOD (66.1%).
(Ramasundaram <i>et al.</i> 2016)	Immobilized TiO ₂ on PVDF (poly vinylidene fluoride) coated Steel mesh (SM)	UV six blacklight blue lamps 350–400 nm	SM-TiO ₂ was hung inside a 60-mL quartz reactor	Methylene Blue MB, methyl orange MO, reactive blue 4, sulfamethoxazole, and microcystin-LR	Degradation rate constants of 0.0251, 0.0368, 0.0164, 0.0568, and 0.0725 min ⁻¹ , respectively
Wang <i>et al.</i> (2016)	TiO ₂ Supported Silica nanosheets composite	Visible light irradiation ≥400 nm	Continuous small container supported catalyst sheet	Phenol	90% phenol degradation for 10 h
(Rokhmat <i>et al.</i> 2017)	TiO ₂ nanoparticles coated on plastic granules	Sunlight irradiation wavelength longer than 300 nm	Hollow rectangular reactor with transparent glass	Methylene blue (MB)	96.54% MB Degrading for 48 h

			at the top and a mirror at the bottom		
(Cunha <i>et al.</i> 2018)	TiO ₂ immobilized on glass spheres	UV-Vis's irradiation simulated the solar spectrum	Compound Parabolic Concentrator (CPC) reactor	Methylene blue (MB)	>96% MB degradation for 90 min
(Sraw <i>et al.</i> 2018)	TiO ₂ immobilized clay beads	UV λ_{\max} 365 nm	Fixed bed recirculation catalyst immobilized clay beads	Pesticide Monocrotophos (MCP)	MCP degradation 78.57%
(Tugaoen <i>et al.</i> 2018)	TiO ₂ coated optical fibers	UV- LED lamp 365 nm connected individual fiber bundle of fibers	PVC cylinder magnetic stirring optical fiber bundles at center	Para-chlorobenzoic acid (pCBA)	TiO ₂ coated optical fiber bundles enhanced pollutant removal
(Urkasame <i>et al.</i> 2018)	TiO ₂ -SiO ₂ monolithic straight macropores (microhoney-combs)	UV- LED	Packed bed ground catalyst	Methylene blue (MB)	The conversion of MB reached a maximum at a calcination temperature of 600 °C.
(Cerrato <i>et al.</i> 2019)	Deposited micro-TiO ₂ on glass Raschig rings	UV light	Packed column with coated glass Raschig rings	Ibuprofen (IBP)	Degraded 87 % of IBP in 6 h
Espindola <i>et al.</i> (2019)	TiO ₂ -P25 immobilized	UVA lamps λ_{\max} =365nm	Photocatalytic membrane reactor immobilized catalyst	Oxytetracycline (OTC)	Lower efficiency but stable permeate flux
Sacco <i>et al.</i> (2019)	structured N-doped TiO ₂ supported on polystyrene (PS) spheres	visible light-emitting diodes (LEDs)	packed bed	Methylene Blue (MB)	almost complete decolorization achieved after 2 h
(Satuf <i>et al.</i> 2019)	immobilized TiO ₂ surface	UV max 365 nm	Microfluidic reactor with catalyst films	Clofibrac acid (CA)	50% CA degradation for 8 h
(Pestana <i>et al.</i> 2020)	TiO ₂ pelletized	UV	Packed bed continuous flow reactor	Microcystins (MC)	51% MC degradation was observed.
Zhang <i>et al.</i> (2020)	TiO ₂ -coated glass beads	Xe-lamp	Capillary micro photoreactor packed bed	Methylene blue (MB)	

2.3. Fe doped TiO₂ powder suspension photocatalytic process

Fe-doped TiO₂ powder is titanium dioxide powder that has been loaded with iron (Fe). The doping process is usually used to introduce specific properties enhancing the performance of various applications. This process includes integrating a certain number of iron ions into the TiO₂ crystal lattice. The doping process are done through the following steps

1. Preparing the chemical materials involving titanium dioxide (TiO₂) powder ,iron precursor (e.g., iron chloride, iron nitrate), solvent (e.g., water or organic solvent), reducing agent (if applicable), and surfactants or stabilizers
2. Dissolving the iron precursor with a suitable solvent to form a solution, after mixing that solution with

titanium oxide powder. The doping level is determined by the used ratio of iron to titanium.

3. Mixing the prepared to ensure uniform distribution of the iron precursor.
4. Adjusting the pH level of the solution to control the doping efficiency.
5. Evaporating the solvent to get the dried powder
6. Heat treatment or calcination the dried powder in a furnace in a temperature range 400-800°C. This step helped in crystalline the material and diffusing the iron ions into the TiO₂ lattice.

TiO₂ doped with Fe enhances the electrochemical and photochemical activities (Chatrnoor *et al.* 2023; Heda *et al.* 2023). The research on the Fe-doped TiO₂ powder solution photocatalytic process system utilized for the treatment is listed in Table 4.

TiO₂-based photocatalysts are commonly used to treat organic pollutants and petroleum industry wastewater. Wet impregnation technique (Realpe *et al.* 2016), reactive radio frequency sputtering (Nair *et al.* 2014), sol-gel (Komaraiah *et al.* 2019), mechanical alloying (Ranjit and Viswanathan 1997), co-precipitation (Z. Zhang *et al.* 1998), hydrothermal (Shi *et al.* 2018), microwave approach (Aba-Guevara *et al.* 2017), controlled hydrolysis (Dholam *et al.* 2009), RF plasma-enhanced chemical vapor deposition (Voleský 2015), and reactive magnetron sputtering are some of the methods that have been reported for doping Fe into TiO₂ structure. By drawing contaminants closer to

the catalysts' active sites, immobilizing photocatalysts in the right kind of adsorptive material would make it easier to recover the catalysts and promote photodegradation (Shi *et al.* 2020). Furthermore, for applications where the irradiation source is sunshine, buoyant immobilization material is extremely desirable. Thus, new supporting materials with high catalyst adherence, super adsorption capability, and tunable buoyancy-to-suspension interconversion are required for a variety of photocatalysis applications (Sboui *et al.* 2017). Table 4 illustrates the researcher's used Fe-doped iO₂ powder in photocatalytic process.

Table 4. Studies on the photocatalytic process using Fe-doped TiO₂ powder suspension.

Reference	Catalyst	Light source	Reactor	Degraded material	Notes
(George <i>et al.</i> 2011)	TiO ₂ pure and Fe-Doped TiO ₂ Nanoparticles	UV Xenon arc lamp with a light filter that transmits light in the range 350-450 nm	Well plates	N-acetyl-L tryptophanamide (NATA).	The rate of NATA oxidation increased with Fe content in TiO ₂
(Ganesh <i>et al.</i> 2012)	Fe-doped TiO ₂ powder	UV-Vis three wavelength ranges 400–475 nm, 475–550 nm and 800–1100 nm with three λ_{max} peaks at λ 433 nm, 512 nm and 900 nm	75 mm tall by 150 mm wide glass dish	Methylene blue (MB)	90% MB degradation, at 0.1 wt% Fe-doped TiO ₂
Zhang and Zhu, (2012)	Fe-doped TiO ₂ immobilized on polyamide fabric	sunlight and UV 254 nm light	fabric sample 5.0×6.5 cm was dipped into 50 ml of MB solution container	Methylene blue MB	95% MB decolorization for sunlight at 2.5 h, and for UV at 6 h
Mwangi <i>et al.</i> (2013)	Fe (III)-doped TiO ₂ immobilized on sintered glass	UV-Vis	Lab stirred Continuous circulation beaker with aeration.	Dissolved organic carbon (DOC) Starch solution	Fe-doped TiO ₂ was activated using natural light
(Si <i>et al.</i> 2015)	Fe-doped TiO ₂ catalyst	UV	Fluidized bed	Alizarin Green (AG)	AG Degradation rate constants 0.017 min ⁻¹
(Sood <i>et al.</i> 2015)	Fe-doped TiO ₂ nanoparticles	Philips CFL bulb visible light 400 nm to 520 nm	Double walled batch photo reactor	Para-nitrophenol (PNP)	92% maximum degradation in 5 h with Fe ³⁺ 0.05 mol%
(Moradi <i>et al.</i> 2016)	Fe-doped TiO ₂ nanoparticles	Visible light	Glass beaker under stirring.	Reactive red 198 (RR 198)	40% RR198 decolorization for 5 h with 1 wt% Fe doped TiO ₂
(Ali <i>et al.</i> 2017)	Fe-doped TiO ₂ nanoparticles	Visible light	Pyrex glass well reactor with a magnetic stirring, water circulating jacket and a window for molecular oxygen supply	methylene blue (MB)	75% MB removal at 3% Fe-doped TiO ₂ after 90 min
Foura <i>et al.</i> (2017)	Fe-Doped TiO ₂ Supported on HY Zeolite	UV light at 254 nm	film flow Plexiglass rectangular workable area photocatalyst nanoparticles	Methylene blue (MB)	MB removal (>98%) was achieved after 1 h

			immobilized on the glass plate)		
(Bansal & Verma 2018)	Fe-TiO ₂ composite in free granules form	Sunlight	Non-concentrating solar recirculating fixed-bed reactor	Pentoxifylline (PEN) drug	93% PEN removal after 4 h
Kaur <i>et al.</i> (2018)	Fe-Doped TiO ₂ immobilized on clay beads	sunlight	Flat Plate	Carbendazim CBZ	Degradation 93% ± 4.65 for after 6 h
(El Mragui <i>et al.</i> 2019)	Pure TiO ₂ Fe-doped TiO ₂ Co-doped TiO ₂ nanoparticles	UV-Vis	Pyrex cylindrical beaker 250 ml	Carbamazepine (CBZ)	CBZ removal With UV Fe/TiO ₂ > TiO ₂ TiO ₂ >Co/TiO ₂ With Vis light Fe/TiO ₂ > Co/TiO ₂ >TiO ₂
(Ghorbanpour & Feizi 2019)	Fe-doped TiO ₂	visible light	Rectangular photoreactor 50x50x50 cm made of MDF.	Methyl orange (MO)	The maximum degradation 69% at the Fe doping content of 0.5 wt%.
(Khan <i>et al.</i> 2019)	Fe-doped TiO ₂ nanoparticles	Xenon lamp visible light (λ=400 nm)	stirred cylindrical vessel	methylene blue (MB)	95% MB removal at 10% Fe-doped TiO ₂ after 3 h
(Liang <i>et al.</i> 2019)	Fe-doped TiO ₂ powder	UV mercury lamp 365 nm and fluorescent lamp	10 mL solution treating cell	Methyl orange (MO)	MO degradation 50% for visible 80% for UV at 0.3 mol% Fe ⁺³
(Ahmed 2020)	Fe-TiO ₂ crystals immobilized on fiberglass	LED 395-405 nm	Glass cylinder rectangular bar at center holds 12 LEDs, 3 on each to cover a 360-degree	Phenol	Degradation 85% after 90 min
Wang <i>et al.</i> (2021)	Fe-doped TiO ₂ powder	mercury lamp λ=365 nm and visible fluorescent lamp	slurry container (25-50 ml)	Methyl orange (MO)	Degradation 1327.5 µg/g for UV light and 103.9 µg/g for visible light after 2 h
(Mancuso <i>et al.</i> 2021)	Fe-doped TiO ₂ powder	A strip of visible-LEDs was positioned around the external body of the photoreactor	Pyrex cylindrical batch photoreactor D = 2.6 cm L = 41 cm V= 200 ml	AO7 dye total organic carbon (TOC) Phenol	90% AO7 dye discoloration 40% TOC removal after 3 h
Ellouzi <i>et al.</i> (2022)	Fe-doped TiO ₂	hydrogen lamp Vis-L resource	A rectangular glass reactor filled with cold water. 125 mL quartz tube, installed inside the reactor.	Azo dye methyl orange (MO)	4.2 times higher efficiency compared to pure TiO ₂
Matias <i>et al.</i> (2022)	Fe-Doped TiO ₂ impregnated on porous polymeric platforms	LED solar simulator	Small magnetic agitation beaker	Rhodamine B (RhB)	Degradation 85% after 3.5 h

3. Light source

Effective photocatalysts operate in the ultraviolet (UV) region of the light spectrum, which is expensive and energy consuming. To maximize efficiency, a wavelength in the ultraviolet region (<400 nm) is used for TiO₂-based photocatalyst activation (Oliveira *et al.* 2022). Figure 3 shows the light solar energy distribution received by the

Earth. The amount of UV light that enters the atmosphere is minimal (approximately 5% of solar light). Visible light (vis) and infrared light (IR) make up the majority of the solar energy that the Earth receives (Barzagan 2022).

For the photocatalysis process, light sources are divided into either UV light with a wavelength range of 190-400 nm or visible light with a wavelength range of 400-780 nm.

Additionally, two light source types are employed: conventional lamps and light emitting diode (LED) lamps. Instead of UV lamps, two main types of LEDs—visible LEDs and UV LEDs—have been used for photochemical applications. For the purpose of researching the photocatalytic degradation of bisphenol, visible LED and carbon/nitrogen-doped TiO₂ were used leading to good results (Chen *et al.* 2005; Wang and Ku 2006; Chen and Dionysiou 2005; Wang and Lim 2010; Natarajan *et al.* 2011; Jamali *et al.* 2013).

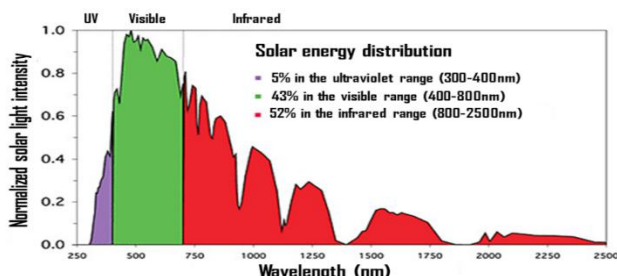


Figure 3. Light solar energy distribution received by the Earth (Barzagan 2022)

An LED is a semiconductor that emits light in a narrow spectrum, with different wavelengths (i.e., infrared, visible, or near ultraviolet) depending on the composition and condition of the semiconducting materials. LED output is directed and linearly correlated to the current flowing through its active region. In addition, LEDs are more cost-effective than traditional ultraviolet sources due to their small size and relatively long lifespan (greater than 50,000 h). Most UV curing, disinfection, sensing, and photocatalysis applications have traditionally employed conventional UV sources. However, LEDs have recently been recognized as an alternative to conventional ultraviolet irradiation sources; additionally, solar light can be utilized alongside LEDs for such applications (Jo & Tayade 2014).

Compared to traditional ultraviolet light irradiation sources, UV-LED technology possesses a number of benefits. These light sources are more energy-efficient and durable, and they have longer lifespans, while avoiding the mercury pollution issue with UV-A black lights and UV-C germicidal lamps. As a result of the homogeneity of the light dispersion found in slurry photoreactors, the reaction rates obtained from photocatalytic processes may be incorrectly analyzed. For catalysts immobilized on a surface, the creation of an effective photocatalytic reactor requires the simultaneous optimization of the light dispersion and the area occupied by the photocatalytic particles (Casado *et al.* 2017b).

4. Photocatalytic reactors

Photocatalytic reactor is the device at which the chemical reaction is facilitated through the use of photocatalysts. Several photocatalytic water treatments reactors have been created and tested during the previous 20 years. They can be categorized in several ways depending on their design and the operation conditions. According to their operating condition they can be classified as slurry photoreactor or immobilized photoreactor. As shown before, photocatalysts can be categorized by (1) form into powder (i.e., nano- or micro-sized particles) and (2) either suspended or immobilized (fixed), in which the catalyst is applied in a film on the wall surface of the reactor and on the supported particles or by pelletizing the powder to a large particle size (P. Liu *et al.* 2009; J. Liu *et al.* 2009). In comparison to suspended photocatalysts, supported photocatalysts have the benefit of not requiring a subsequent filtration step. But suspended photocatalysts often have a higher specific surface area than supported ones, which results in better degrading properties. Tables 5 show the advantages and disadvantages of slurry-type (suspended) and immobilized (fixed) photoreactors (Srikanth *et al.* 2017).

Table 5. Advantages and disadvantages of slurry-type and immobilized photoreactors (Srikanth *et al.* 2017).

Slurry photoreactors	Immobilized photoreactors
<p>Advantages</p> <ul style="list-style-type: none"> The catalysts are dispersed uniformly. Greater illumination of the photocatalytic surface area in relation to the reactor volume Significantly reduced catalyst fouling effects due to the reactor's continual addition and removal of catalyst. A more effective suspension-based particle mixing. <ul style="list-style-type: none"> Lessened reactor-wide pressure drops. There are seldom any mass transfer restrictions. 	<p>Advantages</p> <ul style="list-style-type: none"> Improvement in the removal of organic material from the aqueous phase while applying immobilizing agents with adsorptive qualities. Can offer continuous operation of the reactor. Can offer continuous operation of the reactor. It is quite simple to separate the catalyst from the final treated effluent stream.
<p>Disadvantages</p> <ul style="list-style-type: none"> Requires laborious and expensive post-treatment filtration procedures for the recovery of photocatalyst from the treated wastewater effluent streams. When there is a higher catalyst loading, suspended catalysts have a tendency to scatter light, slowing down photocatalytic activities. Catalytic particle aggregate, especially at greater concentrations. 	<p>Disadvantages</p> <ul style="list-style-type: none"> The potential for catalyst washout and deactivation. <ul style="list-style-type: none"> Less photon accessibility to the catalyst. Considerable external mass transfer restrictions when the pollutant to be treated is flowing at low rates. With an increase in catalyst film thickness, internal mass transfer may play a dominant role by restricting the utilization of the supported photocatalyst, which is due to an increase in the diffusion path length of the reactant from the bulk to the catalyst surface.

Table 6. Typical photocatalytic reactors (Cassano and Alfano 2000).

Systems type	Reactor	Remark
Liquid-solid systems	Well-stirred slurries	Most commonly used as photocatalytic reactors
	Fluidized beds	Less widely used as photocatalytic reactors
	Packed beds	Less widely used as photocatalytic reactors
	Catalytic walls	Include membrane and fiber optic reactors, and Include membrane and fiber optic reactors.
Gas-liquid-solid systems	Trickle beds	Less widely used as photocatalytic reactors
	Packed bubble columns	
	Well-stirred slurries	
	Bubble column slurries	
	Fluidized beds	
	Moving beds	

Cassano and Alfano (2000) have classified reactors for photocatalytic processes for wastewater treatments according to their contact phases, as shown in Table 6.

Depending on the design of the photocatalytic reactor, (Braham & Harris 2009) describe eight types of photocatalytic reactors, as follows:

1. Slurry, Fixed and Fluidized Bed Photoreactors
2. Parabolic Trough Reactors (PTR)
3. Compound Parabolic Collectors
4. Inclined Plate Collectors
5. Double-Skin Sheet Photoreactor
6. Rotating Disk Reactors
7. Water Bell Reactors
8. Optical Fiber Photoreactors

Ballari *et al.* (2019) discusses three types of reactors (i.e., slurry reactors, wall reactors, and fixed-bed reactors), classified according to geometry, modeling, and design purposes. In the cases of simpler geometries, such as continuous annular or flat-plate wall reactors, the design equations are essentially the same. Figure 4 shows the three types of photocatalytic reactors for wastewater treatment that employ artificial light: slurry reactor, packed-bed reactor, and fluidized-bed reactor.

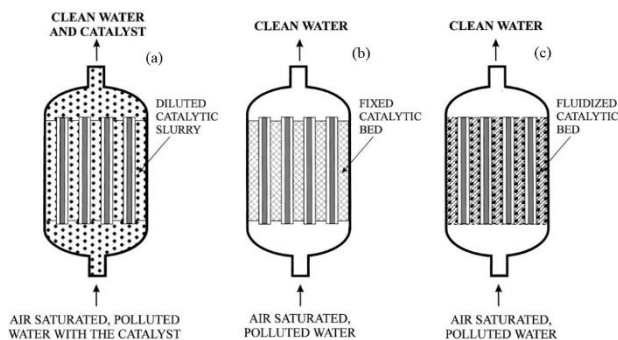


Figure 4. Photocatalytic reactors for wastewater that employ artificial light: (a) slurry reactor, (b) packed-bed reactor, and (c) fluidized-bed reactor (Cassano and Alfano 2000).

In slurry reactors, photocatalysts are suspended as tiny powders or nanoparticles in liquid media. Photocatalyst slurries have a greater surface area, providing a significant benefit. The cost of separating nanometer catalyst particles is a significant barrier to commercializing this technology. The light absorption in slurry systems cannot be separated from scattering, making kinetic analysis problematic. An alternate option involves attaching the catalyst to a clear stationary support that the tainted water travels through. This method can effectively illuminate all photocatalysts installed in the reactor. An early study on slurry reactor had been done on the mineralization of chloroform into chloride and CO₂. Kormann *et al.* found that while chloroform was completely dehalogenated, [Cl⁻] increased over time (Kormann *et al.* 1991). Li Puma and Yue studied the degradation kinetics of both single and multi-component chlorophenols. The researchers investigated the combination of photocatalysis and photolysis using short, medium, and long wavelength ultraviolet light simultaneously (Li Puma G and Yue PL. 1999). A TiO₂ slurry reactor was used to evaluate the adsorption and photocatalytic degradation of Safira HEXL dye (Jone, *et al.* 2005). The researchers found that dye adsorption to the photocatalyst surface was crucial for effective degradation. The process was pH-dependent, with a faster breakdown rate found at low TiO₂ charge.

The study of the photocatalytic degradation of organic wastewater in a laboratory slurry photocatalytic reactor is similar to that used for the degradation of polycyclic aromatic hydrocarbons in produced water ((B. Liu *et al.* 2016), as shown in Figure 5.

The packed-bed reactors use a solid support, often a photocatalyst bed, to flow reactants. The photocatalyst is immobilized on a support structure, and reactants pass over or through the catalyst bed, which is exposed to light for reaction.

Nogueira and Jardim studied the photodegradation of methylene blue utilizing sun irradiation in a fixed bed reactor with TiO₂ immobilized on a flat glass plate. The slope of the plate affects methylene blue

photodegradation due to two factors: fluid thickness and light intensity. The study indicated that 95.8% of the model compound deteriorated at a 22° slope and 89% at a 25° angle (Nogueira and Jardim 1996). Feitz et al. studied two fixed bed photocatalytic reactors: a packed bed reactor and a coated mesh reactor, utilizing solar illumination. The processing rate for 2 mg L⁻¹ phenol solutions was computed as 140 mg m⁻² h⁻¹ for the packed bed reactor and 20 mg m⁻² h⁻¹ for the coated mesh reactor. The coated mesh reactor showed decreased activity due to inadequate photocatalyst surface contact, low TiO₂ levels, and a small reactor-to-tank volume ratio. The packed bed unit demonstrated 40% lower photonic efficiencies than suspension systems while decomposing 100 mg⁻¹ dichloroacetic acid solutions. The authors suggested that this approach was highly successful (Feitz et al. 200). A tubular photocatalytic TiO₂ coating produced via sol-gel was used by (Lin et al. 2003). They studied a reactor with recirculation mode and a batch photocatalytic reactor for the breakdown of methylene blue and phenol. The researchers suggest using the synthesized sol-gel film for water purification due to its excellent photocatalytic activity in decomposing organic molecules. In their work, a 180-minute photoreaction of phenanthrene resulted in 67.6% destruction and 40.1% conversion to CO₂.

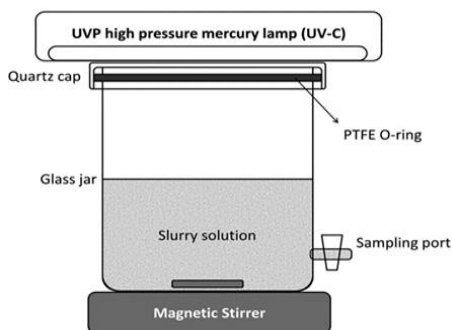


Figure 5. Laboratory slurry photocatalytic reactor (B. Liu et al. 2016).

The photocatalytic oxidation of a non-ionic surfactant was performed in a labyrinth flow reactor with an immobilized photocatalyst bed (Mozia et al. 2005). The study examined how flow rate affects the breakdown of non-ionic surfactants. The researchers found that photodegradation of the surfactant was most effective at a flow velocity of 11.98 dm³ h⁻¹. The researchers further, investigated the remediation of Acid Red 18, an azo dye (Mozia et al. 2007). An immobilized Aeroxide Degussa P25 catalyst was used to study the photodegradation of Acid Red over longer reaction durations. Mineralization timeframes ranged from 35 to 60 hours based on flow rate, indicating that slower flow rates reduced system efficiency.

Fluidized bed reactors, like fixed-bed reactors, employ a solid support for their photocatalysts. However, in this scenario, the movement of gas or liquid reactants suspends and fluidizes the catalyst particles. This increases mass transfer and the effectiveness of the photocatalytic process.

Nelson et al. compared a fluidized TiO₂ system for methanol oxidation to a packed bed reactor. The study

found that fluidization led to quicker photocatalytic breakdown rates compared to packed bed units. The fluidized reactor produced CO₂ at a rate of 2.0 × 10⁻⁷ mol cm⁻³ min⁻¹, while the packed bed reactor produced only 1.0 × 10⁻⁷ mol cm⁻³ min⁻¹. Static mixing and vibration were shown to diminish photocatalyst separation rates with Degussa P25, but not with TiO₂-Al₂O₃ (Nelson et al. 2007). Overall, TiO₂-Al₂O₃ was shown to be an effective photocatalyst, consistent with Paz's results (Paz 2010).

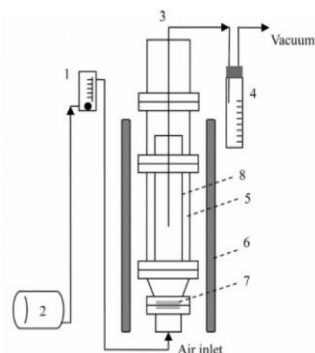


Figure 6. A small-scale, gas-liquid-solid, three-phase, fluidized-bed photoreactor: (1) flow controller, (2) compressor, (3) sampling tube, (4) sampling tank, (5) Pyrex® glass cylindrical vessel, (6) black light lamps, (7) gas distributor, and (8) draft tube (Matsumura et al. 2007).

A small-scale, gas-liquid-solid, three-phase, fluidized-bed photoreactor is shown in Figure 6 (Matsumura et al. 2007).

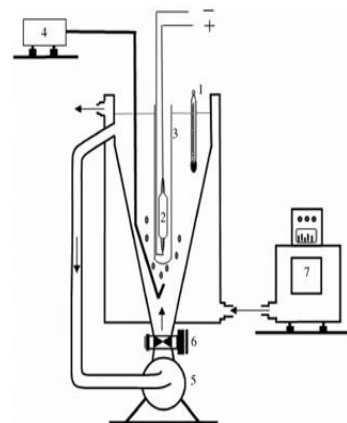


Figure 7. Conical-shaped circulating upflow reactor: (1) thermometer, (2) UV lamp, (3) quartz tube, (4) micro air compressor, (5) circulating pump, (6) valve, and (7) thermostat (Saïen and Nejadi 2007).

Tapered bubble columns (TBCs) are used for a range of processes, such as wastewater treatment, exothermic reactions, biofilm reactions, nuclear fuel particle coating, coal gasification, sulfide ores roasting, and food processing (Bandyopadhyay et al. 2011). TBCs are a specific type of bubble column reactor with a cross-sectional area that increases progressively down the vertical axis. The use of a higher superficial gas velocity ensures the suspension of heavier particles (with higher terminal particle settling velocities) at the bottom, while a lower superficial gas velocity prevents the entrainment of lighter particles (with lower terminal particle settling velocities) at the top. Therefore, tapered columns allow for extensive particle mixing and a wider range of particle size distributions

compared to traditional cylindrical columns (K. Zhang *et al.* 2003).

Saien and Soleymani (2007) used an annular and conic body shape circulating upflow reactor with a UV lamp at the center with no dead zone, as shown in Figure 7. About 50% removal of the chemical oxygen demand (COD) was obtained and 97% of dye degradation was achieved at the following operating conditions: 40 mg/l catalyst, 6.2 pH, 45°C, and 2 h irradiation.

5. Conclusions

This review shows how photocatalytic approaches have considerably improved the treatment of severely polluted industrial wastewater. There is evidence that TiO₂-based photocatalysts decompose organic contaminants more efficiently than other photocatalytic systems for wastewater treatment. The photocatalyst's physicochemical properties are influenced by the synthesis technique, chemical composition, and technological aspects.

Organic contaminants in wastewater can be considerably decreased by upgrading photoreactors, which convert pollutants to CO₂ and H₂O using photocatalysts. Although there are other types of catalysts, TiO₂ is one of the most commonly employed in the process. Pure TiO₂ absorbs relatively little sunlight, and photocatalysis needs UV radiation. Doping with metal ions such as Fe enhances electrochemical and photochemical activities, introducing new energy levels into the bandgap and decreasing the gap to the visible range.

Improved photocatalytic performance can be achieved by investigating the synergistic effects of various operating conditions. Despite major recent advances, decreasing efficiency and reutilization remain poor, making them unsuitable for use in practical applications.

The effectiveness of photocatalysis is heavily impacted by the operating parameters and reactor designs employed. In a photocatalytic reactor, elements such as degradation concentration, pH, temperature, charged nature of the pollutant, reactor, light source (lamp), and catalyst are all critical to achieve maximum efficiency. As a result, while developing and manufacturing photocatalysts for the treatment of organic pollutants, all critical parameters must be carefully examined.

The choice of a specific photocatalytic reactor type depends on the nature of the reaction, desired product, and other process parameters. Each type has its advantages and limitations, and researchers and engineers select the most suitable design based on the specific requirements of their application.

Immobilization for recycling, photocatalyst optimization, and reactor design to increase the separation efficiency are all crucial components needed to advance the development of innovative photocatalytic systems.

6. References

- Abdullah R.R., Shabeeb K.M., Alzubaydi A.B., Figoli A., Crisculi A., Drioli E. and Alsahy Q. (2022). Characterization of the Efficiency of Photo-Catalytic Ultrafiltration PES Membrane Modified with Tungsten Oxide in the Removal of Tinzaparin Sodium. *Eng. Technol. J.*, 40, 1–10.

- Ahmad R., Ahmad Z., Khan A.U., Mastoi N.R., Aslam M. and Kim J. (2016). Photocatalytic systems as an advanced environmental remediation: Recent developments, limitations and new avenues for applications. *Journal of Environmental Chemical Engineering*, 4(4), 4143–4164.
- Ahmed F. (2020). *Synthesis and characterization of Fe-doped TiO₂ on fiberglass cloth for the wastewater treatment reactor.*
- Al-Nuaim M.A., Alwasiti A.A. & Shnain Z.Y. (2023) The photocatalytic process in the treatment of polluted water. *Chem. Pap.* 77, 677–701. <https://doi.org/10.1007/s11696-022-02468-7>.
- Al-Nuaim M., Al-Wasiti A.A., Shnain Z.Y. and Al-Shalal A.K. (2022). The combined effect of bubble and photo catalysis technology in BTEX removal from produced water. *Bulletin of Chemical Reaction Engineering & Catalysis*, 17(3), 577–589.
- Ali T., Tripathi P., Azam A., Raza W., Ahmed A.S., Ahmed A. and Muneer M. (2017). Photocatalytic performance of Fe-doped TiO₂ nanoparticles under visible-light irradiation. *Materials Research Express*, 4(1), 15022.
- Aljouboury D., Palaniandy P., Abdul Aziz H.B. and Feroz S. (2017). Treatment of petroleum wastewater by conventional and new technologies-A review. *Glob. Nest J.*, 19(3), 439–452.
- Ani I.J., Akpan U.G., Olutoye M.A. and Hameed B.H. (2018). Photocatalytic degradation of pollutants in petroleum refinery wastewater by TiO₂-and ZnO-based photocatalysts: recent development. *Journal of Cleaner Production*, 205, 930–954.
- Ballari M. de los M., Satuf M.L. and Alfano O.M. (2020). Photocatalytic reactor modeling: application to advanced oxidation processes for chemical pollution abatement. *Heterogeneous Photocatalysis: Recent Advances*, 265–301.
- Bandyopadhyay A. and Biswas M.N. (2011). Hydrodynamics of a tapered bubble column. *Chemical Engineering & Technology*, 34(2), 186–200.
- Bansal P. and Verma A. (2018). In-situ dual effect studies using novel Fe-TiO₂ composite for the pilot-plant degradation of pentoxifylline. *Chemical Engineering Journal*, 332, 682–694.
- Barton I., Matejec V. and Matousek J. (2016). Photocatalytic activity of nanostructured TiO₂ coating on glass slides and optical fibers for methylene blue or methyl orange decomposition under different light excitation. *Journal of Photochemistry and Photobiology A: Chemistry*, 317, 72–80.
- Barzagan A. (2022). *Photocatalytic Water and Wastewater Treatment.* IWA Publishing.
- Bettini L.G., Diamanti M.V., Sansotera M., Pedferri M.P., Navarrini W. and Milani P. (2016). Immobilized TiO₂ nanoparticles produced by flame spray for photocatalytic water remediation. *Journal of Nanoparticle Research*, 18, 1–10.
- Boyjoo Y., Ang M. and Pareek V. (2014). CFD simulation of a pilot scale slurry photocatalytic reactor and design of multiple-lamp reactors. *Chemical Engineering Science*, 111, 266–277.
- Braham R.J. and Harris A.T. (2009). Review of major design and scale-up considerations for solar photocatalytic reactors. *Industrial & Engineering Chemistry Research*, 48(19), 8890–8905.
- Casado C., Garcia-Gil A., van Grieken R. and Marugan J. (2019). Critical role of the light spectrum on the simulation of solar

- photocatalytic reactors. *Applied Catalysis B: Environmental*, **252**, 1–9.
- Casado C., Marugán J., Timmers R., Muñoz M. and van Grieken R. (2017). Comprehensive multiphysics modeling of photocatalytic processes by computational fluid dynamics based on intrinsic kinetic parameters determined in a differential photoreactor. *Chemical Engineering Journal*, **310**, 368–380.
- Casado C., Timmers R., Sergejevs A., Clarke C.T., Allsopp D.W.E., Bowen C.R., Van Grieken R. and Marugán J. (2017). Design and validation of a LED-based high intensity photocatalytic reactor for quantifying activity measurements. *Chemical Engineering Journal*, **327**, 1043–1055.
- Cassano A.E. and Alfano O.M. (2000). Reaction engineering of suspended solid heterogeneous photocatalytic reactors. *Catalysis Today*, **58(2–3)**, 167–197.
- Cerrato G., Bianchi C.L., Galli F., Pirola C., Morandi S. and Capucci V. (2019). Micro-TiO₂ coated glass surfaces safely abate drugs in surface water. *Journal of Hazardous Materials*, **363**, 328–334.
- Chatnroor S., Taghadossi A.H., Alem S.A.A., Taati-Asil F., Raissi B., Riahifar R. and Yaghmaee M.S. (n.d.). Synthesizing Fe-Doped TiO₂ Nanoparticles by Anodic Dissolution Method and Preparing An Electrophoretic Deposited Layer. Available at SSRN 4369392.
- Chen D., Cheng Y., Zhou N., Chen P., Wang Y., Li K., Huo S., Cheng P., Peng P. and Zhang R. (2020). Photocatalytic degradation of organic pollutants using TiO₂-based photocatalysts: A review. *Journal of Cleaner Production*, **268**, 121725.
- Chen D.H., Ye X. and Li K. (2005). Oxidation of PCE with a UV LED photocatalytic reactor. *Chemical Engineering & Technology: Industrial Chemistry-Plant Equipment-Process Engineering-Biotechnology*, **28(1)**, 95–97.
- Chen X., Yang J. and Zhang J. (2004). Preparation and photocatalytic properties of Fe-doped TiO₂ nanoparticles. *Journal of Central South University of Technology*, **11(2)**, 161–165.
- Chen Y. and Dionysiou D.D. (2005). *High Performance TiO₂ Photocatalytic Coatings and Reactors for the Purification, Disinfection and Recycle of Water in Space Applications*. SAE Technical Paper.
- Chen Y. and Dionysiou D.D. (2007). A comparative study on physicochemical properties and photocatalytic behavior of macroporous TiO₂-P25 composite films and macroporous TiO₂ films coated on stainless steel substrate. *Applied Catalysis A: General*, **317(1)**, 129–137.
- Corradi A.B., Bondioli F., Focher B., Ferrari A.M., Grippo C., Mariani E. and Villa C. (2005). Conventional and microwave-hydrothermal synthesis of TiO₂ nanopowders. *Journal of the American Ceramic Society*, **88(9)**, 2639–2641.
- Cunha D.L., Kuznetsov A., Achete C.A., da Hora Machado A.E. and Marques M. (2018). Immobilized TiO₂ on glass spheres applied to heterogeneous photocatalysis: Photoactivity, leaching and regeneration process. *PeerJ*, **6**, e4464.
- Devi L.G., Nithya P.M., Abraham C. and Kavitha R. (2017). Influence of surface metallic silver deposit and surface fluorination on the photocatalytic activity of rutile TiO₂ for the degradation of crystal violet a cationic dye under UV light irradiation. *Materials Today Communications*, **10**, 1–13.
- Diya'uddeen B.H., Daud W.M.A.W. and Aziz A.R.A. (2011). Treatment technologies for petroleum refinery effluents: A review. *Process Safety and Environmental Protection*, **89(2)**, 95–105.
- Dominguez S., Ribao P., Rivero M.J. and Ortiz I. (2015). Influence of radiation and TiO₂ concentration on the hydroxyl radicals generation in a photocatalytic LED reactor. Application to dodecylbenzenesulfonate degradation. *Applied Catalysis B: Environmental*, **178**, 165–169.
- Drozd V.S., Zybina N.A., Abramova K.E., Parfenov M.Y., Kumar U., Valdés H., Smirniotis P.G. and Vorontsov A.V. (2019). Oxygen vacancies in nano-sized TiO₂ anatase nanoparticles. *Solid State Ionics*, **339**, 115009.
- Duran J.E., Mohseni M. and Taghipour F. (2011). Computational fluid dynamics modeling of immobilized photocatalytic reactors for water treatment. *AIChE Journal*, **57(7)**, 1860–1872.
- El Mragui A., Logvina Y., Pinto da Silva L., Zegaoui O. and Esteves da Silva J.C.G. (2019). Synthesis of Fe- and Co-doped TiO₂ with improved photocatalytic activity under visible irradiation toward carbamazepine degradation. *Materials*, **12(23)**, 3874.
- El Yadini A., Saufi H., Dunlop P.S.M., Byrne J.A., El Azzouzi M. and El Hajjaji S. (2014). Supported TiO₂ on borosilicate glass plates for efficient photocatalytic degradation of fenamiphos. *Journal of Catalysts*, **2014**.
- Ellouzi I., Regraguy B., El Hajjaji S., Harir M., Schmitt-Kopplin P., Lachheb H. and Laânab L. (2022). Synthesis of Fe-doped TiO₂ with improved photocatalytic properties under Vis-L irradiation. *Iranian Journal of Catalysis*, **12(3)**, 283–293.
- Elmobarak W.F., Hameed B.H., Almomani F. and Abdullah A.Z. (2021). A review on the treatment of petroleum refinery wastewater using advanced oxidation processes. *Catalysts*, **11(7)**, 782.
- Espindola J.C., Cristovao R.O., Mendes A., Boaventura R.A.R. and Vilar V.J.P. (2019). Photocatalytic membrane reactor performance towards oxytetracycline removal from synthetic and real matrices: Suspended vs immobilized TiO₂-P25. *Chemical Engineering Journal*, **378**, 122114.
- Feitz AJ, Boyden BH and Waite TD (2000), Evaluation of two solar pilot scale fixed-bed photocatalytic reactors. *Water Res* **34**:3927–3932.
- Foura G., Chouchou N., Soualah A., Kouachi K., Guidotti M. and Robert D. (2017). Fe-doped TiO₂ supported on HY zeolite for solar photocatalytic treatment of dye pollutants. *Catalysts*, **7(11)**, 344.
- Ganesh I., Kumar P.P., Gupta A.K., Sekhar P.S.C., Radha K., Padmanabham G. and Sundararajan G. (2012). Preparation and characterization of Fe-doped TiO₂ powders for solar light response and photocatalytic applications. *Processing and Application of Ceramics*, **6(1)**, 21–36.
- George S., Pokhrel S., Ji Z., Henderson B.L., Xia T., Li L., Zink J.I., Nel A.E. and Mädler L. (2011). Role of Fe doping in tuning the band gap of TiO₂ for the photo-oxidation-induced cytotoxicity paradigm. *Journal of the American Chemical Society*, **133(29)**, 11270–11278.
- Ghorbanpour M. and Feizi A. (2019). Iron-doped TiO₂ catalysts with photocatalytic activity. *Journal of Water and Environmental Nanotechnology*, **4(1)**, 60–66.
- Gogate P.R. and 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)**, 501–551.

- Gotic M., Ivanda M., Sekulić A., Musić S., Popović S., Turković A. and Furić K. (1996). Microstructure of nanosized TiO₂ obtained by sol-gel synthesis. *Materials Letters*, **28**(1–3), 225–229.
- Heda N.L., Kumar K., Sharma V., Ahuja U., Dalela S. and Ahuja B.L. (2023). Impact of Co doping on electronic response, momentum densities and localisation of d electrons of TiO₂: Compton profiles and first-principles calculations. *Materials Today Communications*, **34**, 105144.
- Ibhaddon A.O. and Fitzpatrick P. (2013). Heterogeneous photocatalysis: recent advances and applications. *Catalysts*, **3**(1), 189–218.
- Jamali A., Vanraes R., Hanselaer P. and Van Gerven T. (2013). A batch LED reactor for the photocatalytic degradation of phenol. *Chemical Engineering and Processing: Process Intensification*, **71**, 43–50.
- Jeon M.S., Yoon W.S., Joo H., Lee T.K. and Lee H. (2000). Preparation and characterization of a nano-sized Mo/Ti mixed photocatalyst. *Applied Surface Science*, **165**(2–3), 209–216.
- Jeon J., Kim S, Lim T and Lee D, (2005) Degradation of trichloroethylene by photocatalysis in an internally circulating slurry bubble column reactor. *Chemosphere* 60:1162–1168.
- Jo W.-K. and Tayade R.J. (2014). New generation energy-efficient light source for photocatalysis: LEDs for environmental applications. *Industrial & Engineering Chemistry Research*, **53**(6), 2073–2084.
- Kaur A., Umar A. and Kansal S.K. (2016). Heterogeneous photocatalytic studies of analgesic and non-steroidal anti-inflammatory drugs. *Applied Catalysis A: General*, **510**, 134–155.
- Kaur T., Sraw A., Wanchoo R.K. and Toor A.P. (2018). Solar assisted degradation of carbendazim in water using clay beads immobilized with TiO₂ & Fe doped TiO₂. *Solar Energy*, **162**, 45–56.
- Khan M.A.M., Siwach R., Kumar S. and Alhazaa A.N. (2019). Role of Fe doping in tuning photocatalytic and photoelectrochemical properties of TiO₂ for photodegradation of methylene blue. *Optics & Laser Technology*, **118**, 170–178.
- Kim Sang-don (2000). Gas Holdup and Bubble Characteristics in Tapered Bubble Columns. *Korean Chemical Engineering Research (Hwahak Konghak)*, **38**(6), 864–868.
- Kormann C, Bahnemann DW and Hoffmann MR (1991), Photolysis of chloroform and other organic molecules in aqueous titanium dioxide suspensions. *Environ Sci Technol* 25:494–500.
- Li Y., Chen J., Liu J., Ma M., Chen W. and Li L. (2010). Activated carbon supported TiO₂-photocatalysis doped with Fe ions for continuous treatment of dye wastewater in a dynamic reactor. *Journal of Environmental Sciences*, **22**(8), 1290–1296.
- Li Y., Ma Y., Li K., Chen S. and Yue D. (2022). Photocatalytic reactor as a bridge to Link the commercialization of photocatalyst in water and air purification. *Catalysts*, **12**(7), 724.
- Li Puma G and Yue PL (1999), Enhanced photocatalysis in a pilot laminar falling film slurry reactor. *Ind Eng Chem Res* 38:3246–3254.
- Liang D., Liu S., Wang Z., Guo Y., Jiang W., Liu C., Wang H., Wang N., Ding W. and He M. (2019). Coprecipitation synthesis of N, Fe doped anatase TiO₂ nanoparticles and photocatalytic mechanism. *Journal of Materials Science: Materials in Electronics*, **30**, 12619–12629.
- Lin HF and Valsaraj KT (2003) A titania thin film annular photocatalytic reactor for the degradation of polycyclic aromatic hydrocarbons in dilute water streams. *J Hazard Mater* 99:203–219.
- Liu B., Chen B., Zhang B.Y., Jing L., Zhang H. and Lee K. (2016). Photocatalytic degradation of polycyclic aromatic hydrocarbons in offshore produced water: effects of water matrix. *Journal of Environmental Engineering*, **142**(11), 4016054.
- Liu J., Dong M., Zuo S. and Yu Y. (2009). Solvothermal preparation of TiO₂/montmorillonite and photocatalytic activity. *Applied Clay Science*, **43**(2), 156–159.
- Maculan J.L., Luzza M., Pokrywiecki J.C., Dusmann E., Tonial I.B. and Pokrywiecki T.S. (2016). Aplicação de fotoirradiação solar para tratamento de efluentes de laticínios. *Tecnologia e Ambiente*, **22**.
- Manassero A., Satuf M.L. and Alfano O.M. (2017). Photocatalytic degradation of an emerging pollutant by TiO₂-coated glass rings: a kinetic study. *Environmental Science and Pollution Research*, **24**, 6031–6039.
- Mancuso A., Sacco O., Vaiano V., Bonelli B., Esposito S., Freyria F.S., Blangetti N. and Sannino D. (2021). Visible light-driven photocatalytic activity and kinetics of Fe-doped TiO₂ prepared by a three-block copolymer templating approach. *Materials*, **14**(11), 3105.
- Manzoor M., Rafiq A., Ikram M., Nafees M. and Ali S. (2018). Structural, optical, and magnetic study of Ni-doped TiO₂ nanoparticles synthesized by sol-gel method. *International Nano Letters*, **8**, 1–8.
- Marami M.B., Farahmandjou M. and Khoshnevisan B. (2018). Sol-gel synthesis of Fe-doped TiO₂ nanocrystals. *Journal of Electronic Materials*, **47**, 3741–3748.
- Matias M.L., Pimentel A., Reis-Machado A.S., Rodrigues J., Deuermeier J., Fortunato E., Martins R. and Nunes D. (2022). Enhanced Fe-TiO₂ solar photocatalysts on porous platforms for water purification. *Nanomaterials*, **12**(6), 1005.
- Matsumura T., Noshiroya D., Tokumura M., Znad H.T. and Kawase Y. (2007). Simplified Model for the Hydrodynamics and Reaction Kinetics in a Gas-Liquid-Solid Three-Phase Fluidized-Bed Photocatalytic Reactor: Degradation of o-Cresol with Immobilized TiO₂. *Industrial & Engineering Chemistry Research*, **46**(8), 2637–2647.
- Miranda-García N., Suárez S., Maldonado M.I., Malato S. and Sánchez B. (2014). Regeneration approaches for TiO₂ immobilized photocatalyst used in the elimination of emerging contaminants in water. *Catalysis Today*, **230**, 27–34.
- Moradi H., Eshaghi A., Hosseini S.R. and Ghani K. (2016). Fabrication of Fe-doped TiO₂ nanoparticles and investigation of photocatalytic decolorization of reactive red 198 under visible light irradiation. *Ultrasonics Sonochemistry*, **32**, 314–319.
- Mozia S, Tomaszewska M and Morawski AW (2005) Photocatalytic degradation of azo-dye Acid Red 18. *Desalination* 185:449–456.
- Mozia S, Tomaszewska M and Morawski AW (2007) Photodegradation of azo dye Acid Red 18 in a quartz labyrinth flow reactor with immobilized TiO₂ bed. *Dyes Pigments* 75:60–66.
- Muritala I.K., Guban D., Roeb M. and Sattler C. (2020). High temperature production of hydrogen: Assessment of non-renewable resources technologies and emerging trends.

- International Journal of Hydrogen Energy*, **45(49)**, 26022–26035.
- Mwangi I.W., Ngila J.C., Ndungu P., Msagati T.A.M. and Kamau J.N. (2013). Immobilized Fe (III)-doped titanium dioxide for photodegradation of dissolved organic compounds in water. *Environmental Science and Pollution Research*, **20**, 6028–6038.
- Nair P.B., Justinivictor V.B., Daniel G.P., Joy K., Ramakrishnan V., Kumar D.D. and Thomas P.V. (2014). Structural, optical, photoluminescence and photocatalytic investigations on Fe doped TiO₂ thin films. *Thin Solid Films*, **550**, 121–127.
- Natarajan T.S., Thomas M., Natarajan K., Bajaj H.C. and Tayade R.J. (2011). Study on UV-LED/TiO₂ process for degradation of Rhodamine B dye. *Chemical Engineering Journal*, **169(1–3)**, 126–134.
- Nelson RJ, Flakker CL and Muggli DS (2007). Photocatalytic oxidation of methanol using titania-based fluidized beds. *Appl Catal B: Environ* **69**:189–195.
- Nogueira RFP and Jardim WF (1996). TiO₂-fixed-bed reactor for water decontamination using solarlight. *Solar Energy* **56**:471–477.
- Oliveira T.P., Rodrigues S.F., Marques G.N., Viana Costa R.C., Garçone Lopes C.G., Aranas Jr C., Rojas A., Gomes Rangel J.H. and Oliveira M.M. (2022). Synthesis, characterization, and photocatalytic investigation of CuFe₂O₄ for the degradation of dyes under visible light. *Catalysts*, **12(6)**, 623.
- Paz Y. (2010) Application of TiO₂ photocatalysis for air treatment: patents' overview. *Appl Catal B: Environ* **99**:448–460.
- Peng Y.-H., Huang G.-F. and Huang W.-Q. (2012). Visible-light absorption and photocatalytic activity of Cr-doped TiO₂ nanocrystal films. *Advanced Powder Technology*, **23(1)**, 8–12.
- Persico F., Sansotera M., Bianchi C.L., Cavallotti C. and Navarrini W. (2015). Photocatalytic activity of TiO₂-embedded fluorinated transparent coating for oxidation of hydrosoluble pollutants in turbid suspensions. *Applied Catalysis B: Environmental*, **170**, 83–89.
- Pestana C.J., Hobson P., Robertson P.K.J., Lawton L.A. and Newcombe G. (2020). Removal of microcystins from a waste stabilisation lagoon: Evaluation of a packed-bed continuous flow TiO₂ reactor. *Chemosphere*, **245**, 125575.
- Pozzo R.L., Brandi R.J., Giombi J.L., Cassano A.E. and Baltanás M.A. (2006). Fluidized bed photoreactors using composites of titania CVD-coated onto quartz sand as photocatalyst: Assessment of photochemical efficiency. *Chemical Engineering Journal*, **118(3)**, 153–159.
- Qi N., Zhang H., Jin B. and Zhang K. (2011). CFD modelling of hydrodynamics and degradation kinetics in an annular slurry photocatalytic reactor for wastewater treatment. *Chemical Engineering Journal*, **172(1)**, 84–95.
- Ramasandaram S., Seid M.G., Choe J.W., Kim E.-J., Chung Y.C., Cho K., Lee C. and Hong S.W. (2016). Highly reusable TiO₂ nanoparticle photocatalyst by direct immobilization on steel mesh via PVDF coating, electrospraying, and thermal fixation. *Chemical Engineering Journal*, **306**, 344–351.
- Rokhmat M., Wibowo E., Murniati R. and Abdullah M. (2017). Novel solar photocatalytic reactor for wastewater treatment. *IOP Conference Series: Materials Science and Engineering*, **214(1)**, 12010.
- Sacco O., Sannino D., Matarangolo M. and Vaiano V. (2019). Room temperature synthesis of V-doped TiO₂ and its photocatalytic activity in the removal of caffeine under UV irradiation. *Materials*, **12(6)**, 911.
- Sacco O., Sannino D. and Vaiano V. (2019). Packed bed photoreactor for the removal of water pollutants using visible light emitting diodes. *Applied Sciences*, **9(3)**, 472.
- Sajda S. Alsaedi, Seba Saeed Mohammed, Alyaa Esam Mahdi, Zainab Y. Shnain, Hasan Sh. Majdi, Adnan A. AbdulRazak & Asawer A. Alwasiti (2024) Modeling spinel oxide based-photocatalytic degradation of organic pollutants from industrial wastewater, *Chemical Engineering Communications*, **211:4**, 603-613, DOI: 10.1080/00986445.2023.2269526
- Sampaio M.J., Silva C.G., Silva A.M.T., Vilar V.J.P., Boaventura R.A.R. and Faria J.L. (2013). Photocatalytic activity of TiO₂-coated glass raschig rings on the degradation of phenolic derivatives under simulated solar light irradiation. *Chemical Engineering Journal*, **224**, 32–38.
- Sarasidis V.C., Patsios S.I. and Karabelas A.J. (2011). A hybrid photocatalysis-ultrafiltration continuous process: The case of polysaccharide degradation. *Separation and Purification Technology*, **80(1)**, 73–80.
- Sarasidis V.C., Plakas K.V., Patsios S.I. and Karabelas A.J. (2014). Investigation of diclofenac degradation in a continuous photo-catalytic membrane reactor. Influence of operating parameters. *Chemical Engineering Journal*, **239**, 299–311.
- Satuf M.L., Macagno J., Manassero A., Bernal G., Kler P.A. and Berli C.L.A. (2019). Simple method for the assessment of intrinsic kinetic constants in photocatalytic microreactors. *Applied Catalysis B: Environmental*, **241**, 8–17.
- Sbouli M., Nsib M.F., Rayes A., Swaminathan M. and Houas A. (2017). TiO₂-PANI/Cork composite: A new floating photocatalyst for the treatment of organic pollutants under sunlight irradiation. *Journal of Environmental Sciences*, **60**, 3–13.
- Shi Z., Zhang Y., Duoerkun G., Cao W., Liu T., Zhang L., Liu J., Li M. and Chen Z. (2020). Fabrication of MoS₂/BiOBr heterojunctions on carbon fibers as a weaveable photocatalyst for tetracycline hydrochloride degradation and Cr (VI) reduction under visible light. *Environmental Science: Nano*, **7(9)**, 2708–2722.
- Si C., Zhou J., Gao H., Liu G. and Wu J. (2015). Typical Application of Sound Field in Wastewater Treatment with Fluidized Bed Photocatalytic Reactor. *Water Environment Research*, **87(4)**, 378–383.
- Silva P.C., Ferraz N.P., Perpetuo E.A. and 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 A.P., Kodan N., Mehta B.R., Held A., Mayrhofer L. and Moseler M. (2016). Band edge engineering in BiVO₄/TiO₂ heterostructure: enhanced photoelectrochemical performance through improved charge transfer. *ACS Catalysis*, **6(8)**, 5311–5318.
- Sood S., Umar A., Mehta S.K. and Kansal S.K. (2015). Highly effective Fe-doped TiO₂ nanoparticles photocatalysts for visible-light driven photocatalytic degradation of toxic organic compounds. *Journal of Colloid and Interface Science*, **450**, 213–223.
- Sraw A., Kaur T., Pandey Y., Sobti A., Wanchoo R.K. and Toor A.P. (2018). Fixed bed recirculation type photocatalytic reactor with TiO₂ immobilized clay beads for the degradation of

- pesticide polluted water. *Journal of Environmental Chemical Engineering*, **6(6)**, 7035–7043.
- Srikanth B., Goutham R., Narayan R.B., Ramprasath A., Gopinath K.P. and Sankaranarayanan A.R. (2017). Recent advancements in supporting materials for immobilised photocatalytic applications in waste water treatment. *Journal of Environmental Management*, **200**, 60–78.
- Tugaoen H.O., Garcia-Segura S., Hristovski K. and Westerhoff P. (2018). Compact light-emitting diode optical fiber immobilized TiO₂ reactor for photocatalytic water treatment. *Science of The Total Environment*, **613**, 1331–1338.
- Turolla A., Santoro D., de Bruyn J.R., Crapulli F. and Antonelli M. (2016). Nanoparticle scattering characterization and mechanistic modelling of UV–TiO₂ photocatalytic reactors using computational fluid dynamics. *Water Research*, **88**, 117–126.
- Urkasame K., Yoshida S., Takanohashi T., Iwamura S., Ogino I. and Mukai S.R. (2018). Development of TiO₂–SiO₂ photocatalysts having a microhoneycomb structure by the ice templating method. *ACS Omega*, **3(10)**, 14274–14279.
- Varjani S., Kumar G. and Rene E.R. (2019). Developments in biochar application for pesticide remediation: current knowledge and future research directions. *Journal of Environmental Management*, **232**, 505–513.
- Wang B., de Godoi F.C., Sun Z., Zeng Q., Zheng S. and Frost R.L. (2015). Synthesis, characterization and activity of an immobilized photocatalyst: natural porous diatomite supported titania nanoparticles. *Journal of Colloid and Interface Science*, **438**, 204–211.
- Wang J., Li X., Ren Y., Xia Z., Wang H., Jiang W., Liu C., Zhang S., Li Z. and Wu S. (2021). The effects of additive on properties of Fe doped TiO₂ nanoparticles by modified sol-gel method. *Journal of Alloys and Compounds*, **858**, 157726.
- Wang L., Wang X., Yin J., Zhu Y. and Wang C. (2016). Silica induced oxygen vacancies in supported mixed-phase TiO₂ for photocatalytic degradation of phenol under visible light irradiation. *Catalysis Communications*, **87**, 98–101.
- Wang X. and Lim T.-T. (2010). Solvothermal synthesis of C–N codoped TiO₂ and photocatalytic evaluation for bisphenol A degradation using a visible-light irradiated LED photoreactor. *Applied Catalysis B: Environmental*, **100(1–2)**, 355–364.
- Wetchakun N., Pirakitikulr P., Chiang K. and Phanichphant S. (2008). Visible light-active nano-sized Fe-doped TiO₂ photocatalysts and their characterization. *2008 2nd IEEE International Nanoelectronics Conference*, 836–841.
- Xu Z., Li C., Fu N., Li W. and Zhang G. (2018). Facile synthesis of Mn-doped TiO₂ nanotubes with enhanced visible light photocatalytic activity. *Journal of Applied Electrochemistry*, **48**, 1197–1203.
- Zhang H. and Zhu H. (2012). Preparation of Fe-doped TiO₂ nanoparticles immobilized on polyamide fabric. *Applied Surface Science*, **258(24)**, 10034–10041.
- Zhang K. (2002). Axial solid concentration distribution in tapered and cylindrical bubble columns. *Chemical Engineering Journal*, **86(3)**, 299–307.
- Zhang K., Zhao Y. and Zhang B. (2003). Gas holdup characteristics in a tapered bubble column. *International Journal of Chemical Reactor Engineering*, **1(1)**.
- Zhang K., Zhao Y. and Zhang B. (2004). Hydrodynamic behavior in a tapered bubble column. *Chemical Research in Chinese Universities*, **20(4)**, 478–482.
- Zhang S., Zhang J., Sun J. and Tang Z. (2020). Capillary microphotoreactor packed with TiO₂-coated glass beads: An efficient tool for photocatalytic reaction. *Chemical Engineering and Processing-Process Intensification*, **147**, 107746.
- Zhang Y., Shen Y., Gu F., Wu M., Xie Y. and Zhang J. (2009). Influence of Fe ions in characteristics and optical properties of mesoporous titanium oxide thin films. *Applied Surface Science*, **256(1)**, 85–89.
- Zhu J., Ren J., Huo Y., Bian Z. and Li H. (2007). Nanocrystalline Fe/TiO₂ visible photocatalyst with a mesoporous structure prepared via a nonhydrolytic sol-gel route. *The Journal of Physical Chemistry C*, **111(51)**, 18965–18969.