KOVALEN: Jurnal Riset Kimia

https://bestjournal.untad.ac.id/index.php/kovalen

Review:

Design and Optimization of Fe-Doped TiO_2 Photocatalytic Reactors for Pollutant Degradation: A Systematic Literature Review

Misriyani[1]✉, Emil Hardiansyah[2]

[1)] *Department of Biochemistry, Faculty of Medicine, Alkhairaat University, Jl. Diponegoro Palu 94221, Central Sulawesi, Indonesia*

[2)] *Department of Information Technology Education, Faculty of Teacher Training and Education, Alkhairaat University, Jl. Diponegoro Palu 94221, Central Sulawesi, Indonesia*

Abstract. Environmental pollution caused by industrial wastewater containing persistent organic compounds remains a major global concern. Although TiO_2 is widely used as a photocatalyst because of its stability and strong oxidation capability, its wide band gap limits activity mainly to ultraviolet light. Fe doping offers a promising approach to improve visible-light response and charge separation. This review provides an integrated analysis of Fe-doped TiO_2 synthesis parameters, reactor configurations, light sources, and operating conditions. Following the PRISMA guidelines, 166 articles were identified from Scopus, Web of Science, and ScienceDirect, of which 18 studies were included in the final analysis. The findings show that sol-gel and hydrothermal methods strongly influence catalyst properties, while packed-bed, fluidized-bed, and membrane reactors improve light utilization and mass transfer. Reported degradation efficiencies ranged from approximately 45% to more than 99%, depending on catalyst characteristics, reactor design, and operating conditions. Despite promising laboratory-scale performance, limited catalyst stability, energy efficiency, real-wastewater validation, and reactor scalability remain major barriers to industrial implementation.

Keywords: *Photocatalysis, Fe-doped TiO_2, photocatalytic reactor, pollutant degradation, wastewater treatment*

Abstrak. Pencemaran lingkungan akibat limbah industri yang mengandung senyawa organik persisten masih menjadi permasalahan global. TiO_2 banyak digunakan sebagai fotokatalis karena stabilitas dan kemampuan oksidasinya yang tinggi, tetapi celah pita energinya yang lebar membatasi aktivitas terutama pada cahaya ultraviolet. Doping Fe menjadi pendekatan yang menjanjikan untuk meningkatkan respons terhadap cahaya tampak dan pemisahan muatan. Tinjauan ini menyajikan analisis terpadu mengenai parameter sintesis Fe-doped TiO_2, konfigurasi reaktor, sumber cahaya, dan kondisi operasi. Berdasarkan pedoman PRISMA, sebanyak 166 artikel diidentifikasi dari Scopus, Web of Science, dan ScienceDirect, kemudian 18 studi dimasukkan dalam analisis akhir. Hasil kajian menunjukkan bahwa metode sol-gel dan hidrotermal memengaruhi karakteristik katalis, sedangkan reaktor packed-bed, fluidized-bed, dan membran meningkatkan pemanfaatan cahaya serta transfer massa. Efisiensi degradasi yang dilaporkan berkisar antara sekitar 45% hingga lebih dari 99%, bergantung pada karakteristik katalis, desain reaktor, dan kondisi operasi. Meskipun menunjukkan hasil yang menjanjikan pada skala laboratorium, stabilitas katalis, efisiensi energi, validasi pada limbah nyata, dan skalabilitas reaktor masih menjadi hambatan utama dalam implementasi industri.

Kata kunci: *Fotokatalisis, TiO_2 terdoping Fe, reaktor fotokatalitik, degradasi polutan, pengolahan air limbah*

Received: March 16, 2026; Accepted: August 27, 2026

Citation: Mistriyani and Hardiansyah, E. (2026). Design and Optimization of Fe-Doped TiO_2 Photocatalytic Reactors for Pollutant Degradation: A Systematic Literature Review. *KOVALEN: Jurnal Riset Kimia,* 12(2), 125-140

✉ Corresponding author
E-mail: misriyani85@gmail.com

https://doi.org/10.22487/kovalen.2026.v12.i2.18038

INTRODUCTION

Environmental pollution caused by industrial waste, harmful organic compounds, and inorganic contaminants has become a major global challenge in recent decades (C. Wang *et al*., 2023). Wastewater generated from industries such as textile, pharmaceutical, agricultural, and petrochemical sectors often contains persistent organic compounds that are difficult to degrade naturally and may pose serious risks to human health and aquatic ecosystems. Conventional wastewater treatment methods, including adsorption, coagulation, filtration, and chemical oxidation, still face several limitations in terms of treatment efficiency, operational costs, and the potential formation of harmful by-products (Navidpour *et al*., 2024). Therefore, the development of more efficient, environmentally friendly, and sustainable treatment technologies has become an important focus in modern environmental research (Navidpour *et al*., 2024; C. Wang *et al*., 2023).

One promising approach to address these challenges is semiconductor photocatalysis, which utilizes light energy to activate semiconductor materials and generate electron–hole pairs that initiate oxidation and reduction reactions on the catalyst surface. These reactions produce reactive oxygen species (ROS), such as hydroxyl radicals (•OH) and superoxide radicals ($O_2^{\bullet-}$), which possess strong oxidation capability to degrade organic pollutants into simpler and less harmful compounds. In addition to wastewater treatment, photocatalysis also shows significant potential for air purification, hydrogen production through water splitting, and degradation of pharmaceutical compounds and pesticides (Fouad *et al*., 2023).

Among various semiconductor materials, titanium dioxide (TiO_2) is one of the most widely studied photocatalysts due to its high chemical stability, corrosion resistance, non-toxicity, abundance, and relatively low production cost. TiO_2 also exhibits strong oxidative capability under ultraviolet (UV) irradiation, enabling effective degradation of various organic pollutants. Moreover, TiO_2 can be synthesized in various nanostructured forms such as nanoparticles, nanotubes, nanorods, and thin films, which increase the active surface area and improve photocatalytic performance (Sun *et al*., 2025).

Despite these advantages, pure TiO_2 has several limitations. Its relatively wide band gap (3.0–3.2 eV) restricts activation mainly to ultraviolet radiation, which represents only about 5% of the solar spectrum. Additionally, TiO_2 exhibits a high electron–hole recombination rate, which reduces the number of charge carriers available for photocatalytic reactions and decreases overall efficiency (Navidpour *et al*., 2024).

To overcome the intrinsic limitations of pure TiO_2, transition-metal doping has been widely investigated as a strategy to modify its electronic structure, extend light absorption into the visible region, and suppress electron–hole recombination. Dopants such as Ag, Cu, Ni, Mn, and Fe can introduce additional energy levels within the TiO_2 band structure, although their effects depend strongly on dopant concentration, oxidation state, synthesis route, and thermal treatment (Mahadadalkar *et al*., 2023; Tanguturi Venkata *et al*., 2026; Thomas *et al*., 2016). Ag can enhance visible-light absorption through localized surface plasmon resonance, but its high cost and possible instability may constrain large-scale application

(Zarzzeka *et al*., 2024). Cu can narrow the band gap and promote charge separation, although its performance depends strongly on oxidation state and dopant loading (Khan & Shah, 2023). Ni and Mn may improve visible-light activity, but excessive loading can create secondary phases or recombination centers (Markose *et al*., 2023; Tee *et al*., 2024). Fe^{3+} and Fe^{2+} species can act as temporary trapping sites, while excessive Fe may accelerate recombination (Hasanuzzaman *et al*., 2023; Markose *et al*., 2023).

Compared with other metal dopants, Fe offers several practical and physicochemical advantages. Ag can enhance visible-light absorption through localized surface plasmon resonance, but its high cost, tendency to agglomerate, and potential leaching limit large-scale application. Cu can narrow the band gap and promote charge separation, yet its variable oxidation states may lead to instability and photocorrosion. Ni and Mn may also improve visible-light activity, but excessive loading can generate secondary phases, block active sites, or create recombination centers. In contrast, Fe is relatively inexpensive, abundant, and environmentally compatible. The ionic radius of Fe^{3+} is also close to that of Ti^{4+}, which facilitates substitution within the TiO_2 lattice with limited structural distortion.

Fe^{3+} and Fe^{2+} species can act as temporary trapping sites for photogenerated electrons and holes, thereby prolonging charge-carrier lifetime and enhancing the formation of reactive oxygen species. Fe-containing systems may also benefit from photo-Fenton reactions under suitable conditions. Nevertheless, the advantage of Fe is highly concentration-dependent. Excessive Fe loading can introduce deep trap states that accelerate electron–hole recombination, reduce active surface area, and increase the risk of iron leaching. Therefore, Fe should not be regarded as universally superior to other dopants, but as a cost-effective and scalable option whose performance depends on careful optimization of dopant concentration, synthesis conditions, and reactor operation (Navidpour *et al*., 2024).

However, the efficiency of these modified catalysts is ultimately governed by the environment in which the reaction occurs: the photocatalytic reactor. Although photocatalyst modification is essential, photocatalytic reactor design also plays a crucial role in determining the overall efficiency of the process. Parameters such as reactor configuration, light distribution, catalyst surface area, fluid flow dynamics, and mass transfer mechanisms can significantly influence the performance of photocatalytic systems (Wang *et al*., 2023). Photocatalytic reactors are generally classified into several configurations, including slurry reactors, immobilized photocatalytic reactors, fixed-bed reactors, fluidized-bed reactors, and membrane-based photoreactors. Each reactor type offers specific advantages and limitations in terms of reaction efficiency, catalyst recovery, operational stability, and scalability for industrial applications (Wang *et al*., 2023).

Research on TiO_2-based photocatalysis has expanded considerably, resulting in several reviews on metal-doped TiO_2 materials, pollutant degradation mechanisms, and photocatalytic reactor development. Previous reviews have generally focused on one of three areas: the synthesis and physicochemical characteristics of metal-doped TiO_2, the degradation of pollutant groups, or the engineering principles of photocatalytic reactors. Reviews of metal-doped TiO_2 have mainly discussed dopant selection, band-gap modification, charge-carrier separation, and photocatalytic mechanisms. Meanwhile, reactor-oriented reviews have emphasized reactor geometry, irradiation systems, hydrodynamics, mass transfer, and scale-up considerations. These studies provide important foundations, but they often examine photocatalyst properties and reactor engineering as separate research domains (Visan *et al*., 2019; Basavarajappa *et al*., 2020; Enesca, 2021; Alalm *et al*., 2021; Binjhade *et al*., 2022; Sultana *et al*., 2023).

This separation limits understanding of how Fe-doped TiO_2 preparation parameters interact with reactor configuration and operating conditions to determine pollutant degradation performance. Differences in Fe concentration, synthesis route, catalyst morphology, immobilization method, light source, pH, catalyst loading, flow regime, and reaction time make direct comparison among studies difficult. High degradation efficiency reported in one system may result from favorable operating conditions rather than from Fe doping or reactor design alone. Moreover, many studies remain confined to controlled laboratory experiments and provide limited information on catalyst durability, iron leaching, energy consumption, treatment of real wastewater, and long-term reactor operation. These limitations create uncertainty regarding which combinations of catalyst and reactor characteristics offer the most consistent performance and the greatest potential for scale-up.

Therefore, a systematic review that integrates material synthesis and reactor engineering is needed. Unlike reviews that discuss photocatalyst modification or reactor design independently, the present study compares Fe-doped TiO_2 preparation methods, reactor configurations, light sources, operating parameters, and degradation performance within a single analytical framework. This integrated approach is intended to identify the factors responsible for variations among reported results, evaluate the advantages and limitations of the principal synthesis and reactor approaches, and clarify the technical barriers that must be addressed before Fe-doped TiO_2 photocatalytic systems can progress from laboratory studies to large-scale environmental applications.

Accordingly, this systematic literature review addresses the following research questions:

RQ1: How do synthesis methods and Fe-doping parameters influence the structural, optical, and photocatalytic properties of Fe-doped TiO_2?

RQ2: Which photocatalytic reactor configurations provide the most consistent pollutant degradation performance, and what are their main advantages and limitations?

RQ3: How do light sources and operating parameters influence degradation efficiency across different reactor systems?

RQ4: What methodological and technological gaps currently limit the scale-up and industrial implementation of Fe-doped TiO_2 photocatalytic reactors?

METHODS

Study Design

This systematic review was conducted following the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines (Page *et al*., 2021) to ensure transparency, reproducibility, and methodological rigor in synthesizing scientific evidence. The review focuses on studies related to the synthesis of Fe-doped TiO_2 photocatalysts, photocatalytic reactor configurations, operational parameters, and their performance in pollutant degradation processes. Through the systematic identification and evaluation of relevant studies, this review aims to provide an overview of recent research trends, technological developments, and key factors influencing the performance of Fe-doped TiO_2-based photocatalytic reactor systems.

Literature Search Strategy

The literature search was conducted on 20 February 2026 to identify relevant studies on the development and optimization of photocatalytic reactors based on Fe-doped TiO_2 for pollutant degradation. The search covered publications indexed from database inception to February 2026 and was performed using three major scientific databases: Scopus, Web of Science, and ScienceDirect, which are widely recognized for indexing high-quality peer-reviewed publications. The main search terms included “TiO_2 photocatalysis,” “Fe-doped TiO_2,” “photocatalytic reactor,” “photocatalytic reactor design,” and “pollutant degradation.”

Boolean operators such as AND and OR were used to refine the search results and combine relevant terms. Advanced search functions were applied in Scopus, Web of Science, and ScienceDirect to accommodate complex Boolean search strings. Full details of the search strategies used in each database are presented in Table 1.

In addition, the reference lists of the selected articles and relevant review papers were manually screened to identify additional publications that might not have been retrieved during the initial database search.

Table 1. Search strategy on online databases

Databases	Search strategy	Number of articles
Scopus	TITLE-ABS-KEY ("Fe doped TiO_2" OR "iron doped titanium dioxide" OR "Fe-TiO_2") AND ("photocatalytic reactor" OR "photocatalysis reactor" OR "photocatalytic degradation") AND ("reactor design" OR "reactor optimization" OR "photocatalytic system"))	68
Web of Science	TS=(("Fe doped TiO_2" OR "iron doped titanium dioxide" OR "Fe-TiO_2") AND ("photocatalytic reactor" OR "photocatalytic degradation") AND ("reactor design" OR "photocatalytic system" OR "reactor optimization"))	41
ScienceDirect	("Fe doped TiO_2" OR "iron doped titanium dioxide") AND ("photocatalytic reactor" OR "photocatalytic degradation") AND ("reactor design" OR "reactor optimization")	57

The literature search focused on articles published in peer-reviewed journals and written in English. Only studies that investigated photocatalytic systems involving modified TiO_2 catalysts and reported pollutant degradation performance were considered. The initial search resulted in 166 potentially relevant articles, which were then subjected to further screening and eligibility assessment following the PRISMA guidelines.

Eligibility Criteria

Studies were included if they reported the synthesis, characterization, or application of Fe-doped TiO_2 photocatalysts in photocatalytic reactor systems for pollutant degradation.

Eligible studies were limited to original experimental research conducted at laboratory or pilot scale and were required to provide sufficient information on catalyst preparation, reactor configuration, operating conditions, and pollutant degradation performance. Studies involving TiO_2 modified with metals other than Fe, such as Ag, Pt, Cu, Ni, Mn, or Bi-based composites, were excluded from the primary synthesis because they did not directly correspond to the specific scope of this review. However, selected non-Fe TiO_2 studies were used only as supporting references in the Introduction and Discussion to provide comparative context regarding photocatalyst modification and reactor design.

Screening Process

The study selection process followed the PRISMA 2020 framework and consisted of four sequential stages: identification, screening, eligibility assessment, and final inclusion. After removing duplicate records, all remaining articles were screened based on their titles and abstracts to determine their relevance to the review objective. Studies that clearly did not investigate photocatalytic reactors, did not involve Fe-doped TiO_2 or related photocatalytic systems, or lacked experimental pollutant degradation data were excluded at this stage.

The remaining articles underwent full-text assessment to determine compliance with the predefined inclusion and exclusion criteria. Articles were excluded if sufficient experimental information regarding catalyst synthesis, reactor configuration, or degradation performance was unavailable. Any uncertainty during the screening process was resolved through discussion among the reviewers until consensus was achieved.

Data Extraction

Data from each eligible study were extracted using a standardized data extraction form developed specifically for this review. The extracted information included:

- publication year;
- catalyst synthesis method;
- Fe doping concentration;
- catalyst morphology;
- reactor configuration;
- light source;
- operating conditions (pH, catalyst loading, reaction time, and pollutant concentration when available);
- pollutant type;
- degradation efficiency;
- major findings;
- reported limitations.

Data extraction was performed to enable systematic comparison among studies and to identify relationships between synthesis parameters, reactor design, and photocatalytic performance.

Quality Assessment

The methodological quality of the included studies was evaluated using a customized assessment checklist adapted for photocatalytic reactor research. Each study was assessed based on six criteria:

1. clarity of catalyst synthesis;
2. completeness of material characterization;
3. description of reactor configuration;
4. reporting of operating parameters;
5. presentation of degradation performance;
6. reproducibility of experimental procedures.

Each criteria was scored as:

- 2 = adequately reported
- 1 = partially reported
- 0 = not reported

The quality assessment was used to evaluate the overall strength of the available evidence and to support the qualitative synthesis rather than to exclude studies from the review.

Study Selection Rationale

Articles were selected because they provided experimental evidence directly relevant to Fe-doped TiO_2 photocatalytic reactor systems. Studies involving non-Fe-modified TiO_2 materials were excluded from the primary systematic synthesis to maintain consistency with the scope of the review. Nevertheless, selected studies on other TiO_2 modifications were retained only as contextual references for comparative discussion of catalyst modification mechanisms and reactor engineering approaches.

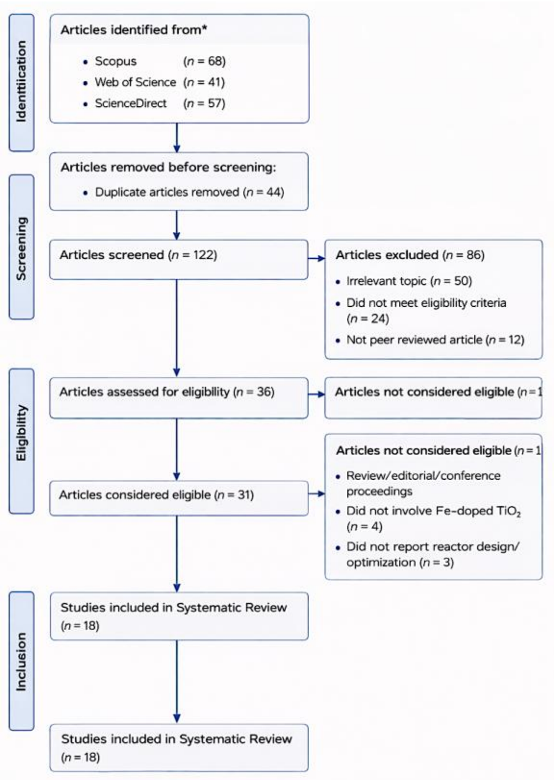

Figure 1. Summarizes the identification, screening, eligibility assessment, and inclusion process according to the PRISMA 2020 guideline.

The literature selection process followed the PRISMA guidelines, including identification, screening, eligibility assessment, and study inclusion. A total of 166 articles were initially identified from three scientific databases. After removing 44 duplicate records, 122 articles remained for title and abstract screening. During the initial screening, 86 articles were excluded due to irrelevance to the research topic or failure to meet the eligibility criteria. The remaining 36 articles were assessed through full-text evaluation, resulting in 18 studies that met all inclusion criteria and were included in the final systematic review analysis. The methodological quality of the selected studies was evaluated using a customized checklist focusing on catalyst synthesis clarity, reactor operational parameters, degradation performance reporting, and reproducibility of experimental procedures.

Data Synthesis

Due to the considerable heterogeneity in photocatalyst synthesis methods, reactor configurations, operational conditions, pollutant types, and performance indicators across the included studies, a quantitative meta-analysis was not considered appropriate. Therefore, the findings were synthesized using a qualitative comparative approach.

The qualitative synthesis focused on comparing Fe-doped TiO_2 synthesis methods, photocatalytic reactor configurations, light sources, operational parameters, and pollutant degradation performance. It emphasized identifying common research trends, explaining discrepancies among studies, evaluating the strengths and limitations of different synthesis methods and reactor configurations, and identifying the key factors influencing photocatalytic performance. The synthesis also examined the remaining methodological and technological gaps to formulate directions for future research and large-scale implementation.

RESULTS

Characteristics of the analyzed study

Table 2 presents a comparative summary of the experimental studies included in this systematic review. In addition to reporting the catalyst synthesis method, reactor configuration, light source, pollutant type, and degradation efficiency, the table incorporates key technical parameters, including Fe doping concentration, band-gap energy, photocatalyst loading, and major operating conditions (e.g., pH, reaction time, and irradiation intensity), whenever such information was available in the original studies.

The included studies demonstrated considerable variation in catalyst synthesis methods, reactor configurations, and operational conditions. Sol-gel and hydrothermal methods were the most frequently employed synthesis techniques, while packed-bed, fixed-bed, fluidized-bed, membrane, and continuous-flow reactors represented the principal reactor configurations. Such diversity reflects the wide range of strategies used to improve light utilization, mass transfer, catalyst stability, and pollutant degradation performance. The comparative presentation of these parameters facilitates systematic comparison among studies, enables the identification of factors contributing to variations in photocatalytic performance, and supports the critical synthesis of relationships among catalyst characteristics, reactor design, and operating conditions. Nevertheless, direct comparison remains challenging because several studies used different pollutant concentrations, irradiation conditions, catalyst dosages, and performance indicators, including degradation efficiency and apparent kinetic constants.

Effect of Synthesis Method on Photocatalytic Activity

The photocatalyst synthesis method plays an important role in determining the structural and optical properties of the modified TiO_2 material. Various studies show that different synthesis techniques can affect particle size, dopant distribution, specific surface area, as well as crystal structure, ultimately impacting the photocatalytic activity of materials. The sol-gel method is one of the most widely used synthesis techniques because it is able to produce nano-sized particles with a relatively homogeneous dopant distribution and a high specific surface area. These characteristics are very important in increasing the number of active sites on the catalyst surface, so that they can improve the efficiency of photocatalytic reactions.

For example, research by Sri Harsha *et al*. (2025) uses the sol-gel method to synthesize N-TiO_2 and Ag-TiO_2 materials, which are then applied in continuous flow photocatalytic reactor systems. The results showed that the system was able to degrade antibiotics such as ciprofloxacin and tetracycline with an efficiency of up to 96%, and showed the inactivation ability of E. coli bacteria up to 100% under visible light irradiation.

Table 2 presents only the experimental studies that directly investigated Fe-containing TiO_2 photocatalytic systems and met the predefined eligibility criteria. Studies involving Ag-TiO_2, Pt-TiO_2, TiO_2-Bi_2O_3, and other non-Fe modifications were excluded from the primary comparative analysis to ensure consistency between the review scope, research questions, and evidence synthesis.

Table 2. Characteristics of the studies analyzed in *the systematic literature review*

Authors and Year	Catalyst Synthesis Method (Fe–TiO_2 or Other)	Reactor Type	Light Source	Pollutant Type	Degradation Efficiency (%)
Yusuf *et al*., 2024	Combustion Solution (TiO_2/β-Bi_2O_3 Composite)	Fixed-bed reactor (recirculation mode)	UV LED	Diclofenac amide (DCFA)	Stable degradation performance with sustained kobs
Azghandi *et al*., 2025	Modified sol–gel (TiO_2 thin film)	Helical photocatalytic reactor (immobilized and suspended catalyst)	UV and UV/H_2O_2	Methyl orange (MO)	77.8% (immobilized), 97.3% (suspended)
Prowans *et al*., 2025	Microwave sputtering (Pt–TiO_2 on cenospheres)	Fluidized-bed reactor	UV LED	Acetaldehyde (gaseous pollutant)	99.6% (moderate flow rate)
Tryba, 2008	Mechanical mixing and Ar calcination (Fe–C–TiO_2)	Photocatalytic flow reactor	UV light	Phenol	>90% (with H_2O_2 addition)
Chang *et al*., 2024	Sol-gel (TiO_2 coated on iron-containing glass substrate)	Multi-chamber packed-bed reactor	UV lamp and UV-LED	BOD from aquaculture wastewater	45.8% (24 h) to 79.5% (48 h)
Wang *et al*., 2023	Hydrothermal (Fe–TiO_2 nanotubes)	Annular photocatalytic reactor	UV lamp	Tetracycline	91%
Tanguturi Venkata *et al*., 2026	Hydrothermal (Fe-doped TiO_2 nanorods)	Packed-bed photocatalytic reactor	Visible light	Rhodamine B	88%
Yilleng *et al*., 2023	Sol–gel (Fe–TiO_2 nanocomposite)	Continuous-flow reactor	UV light	Phenol	90%
Navidpour *et al*., 2024	Co-precipitation (Fe–TiO_2 nanoparticles)	Membrane photocatalytic reactor	Visible light	Pharmaceutical wastewater	90%
Harsha *et al*., 2025	Sol–gel (N–TiO_2 and Ag–TiO_2)	Stacked modular photocatalytic reactor (continuous flow)	Visible light (LED)	Ciprofloxacin, tetracycline, E. coli	87% (CPX), 96% (TTC), 100% (E. coli)
Mahadadalkar *et al*., 2023	Hydrothermal (Fe–TiO_2 nanofibers)	Fluidized-bed photocatalytic reactor	Visible light	Reactive Black 5	93%
Li *et al*., 2019	Hydrothermal (TiO_2–GO–Fe_3O_4)	Submerged magnetic separation membrane photocatalytic reactor (SMSMPR)	Visible/UV light	Amoxicillin (AMX)	88.5% (photo-Fenton synergy)
Sun *et al*., 2025	Co-precipitation (Fe–TiO_2 nanoparticles)	Batch slurry reactor	Visible light	Methyl orange	89%
Nayeri & Basiri Parsa, 2024	Hydrothermal synthesis (TiO_2–AgBr–Ag–NH_2–MIL-88B (Fe))	Crossflow photocatalytic membrane reactor (PMR)	Visible light (70 W)	Cefixime (antibiotic)	~90% (stable after 4 cycles)
Thomas *et al*., 2016	Sol–gel (Fe–TiO_2 coated glass beads)	Packed-bed reactor	UV light	Congo red	87%
R. Wang *et al*., 2009	Sol–gel (Fe–TiO_2 thin film)	Immobilized photocatalytic reactor	UV light	Bisphenol A	86%
Biao *et al*., 2025	Photo-assisted reduction (Ag–TiO_2 on ceramic substrate)	Immobilized photocatalytic membrane reactor (PMR)	UVC (254 nm)	Polyester microplastic fibers (PMPF)	23.2% degradation, 99.9% rejection
Fouad *et al*., 2023	Sol–gel (Fe–TiO_2 nanoparticles)	Slurry photocatalytic reactor	UV light	Methylene blue	92%

In addition to the sol-gel method, hydrothermal techniques are also widely used because they are able to produce TiO_2 crystals with a more orderly structure and better stability. Research by Nayeri & Basiri Parsa (2024) reports that TiO composites$_2$-AgBr-Ag-NH_2-MIL-88B(Fe) composites synthesized by the hydrothermal method exhibit high photocatalytic activity in the degradation of cefixime antibiotics, with an efficiency of about 90% under visible light irradiation.

In addition to these two methods, other synthesis techniques such as solution combustion and magnetron sputtering are also reported to be able to produce photocatalytic materials with different characteristics. For example, research by Prowans *et al.* (2025) using the magnetron sputtering technique to deposition TiO_2-Pt on the particles of the cenospheres, which are then applied in fluidized-bed reactors. The system exhibits an acetaldehyde degradation efficiency of up to 99.6%, indicating high potential for gaseous pollutant treatment applications. Fe^{3+} ions act as shallow trapping sites for electrons and holes, thereby suppressing electron–hole recombination and prolonging charge carrier lifetime. However, excessive Fe concentration may generate recombination centers, reducing photocatalytic efficiency. Therefore, optimization of Fe doping concentration is essential to achieve maximum photocatalytic performance. Overall, these synthesis methods show that control of material structure, dopant distribution, and catalyst morphology are key factors influencing the photocatalytic activity of TiO_2 in the pollutant degradation process.

Influence of Photocatalytic Reactor Design

In addition to the properties of the catalyst material, the design of photocatalytic reactors also has a very significant influence on the efficiency of the pollutant degradation process. The reactor configuration determines the distribution of light in the system, the area of contact between the catalyst and the pollutant, as well as the characteristics of the fluid flow, which directly affect the photocatalytic reaction rate and the degradation efficiency of pollutants.

One of the reactor configurations that has been widely developed is the photocatalytic membrane reactor (PMR). The system integrates the photocatalysis and membrane filtration processes, allowing the degradation process of pollutants as well as the simultaneous separation of catalysts or contaminant particles. Research by X. Wang et al. (2024) shows that the use of membrane reactors with Ag-TiO catalysts$_2$ It is able to achieve microplastic rejection efficiency of up to 99.9%, although its photocatalytic degradation rate is relatively lower than that of other reactor systems.

Other widely used configurations are packed-bed reactors and fixed-bed reactors, where catalysts are immobilized on a solid substrate. The main advantages of this system are the ease of separation of the catalyst, good operational stability, and the potential for application to continuous reactor systems. Research by Chang *et al*. (2024) used a packed-bed multi-chamber reactor for aquaculture waste treatment and reported a decrease in Biochemical Oxygen Demand (BOD) value of up to 79.5% after 48 hours of operation, demonstrating the effectiveness of this system in liquid waste treatment.

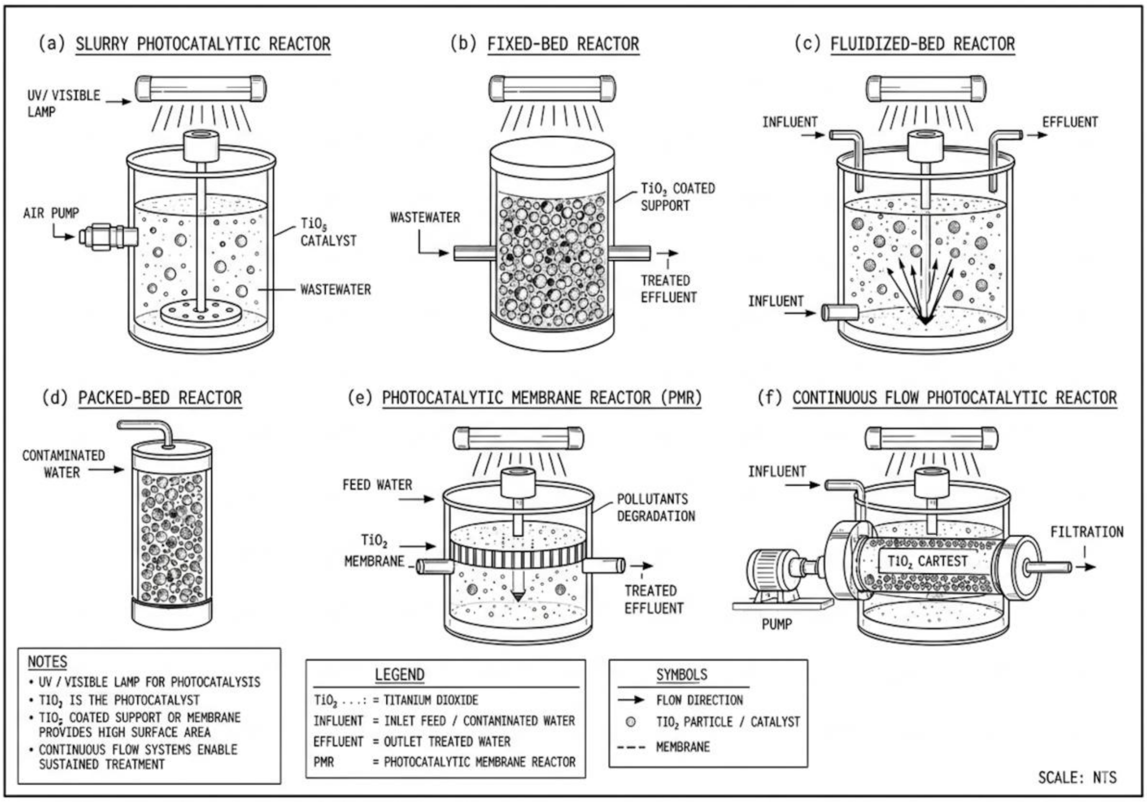

Figure 2. Schematic illustration of various photocatalytic reactor configurations: (a) slurry reactor, (b) fixed-bed reactor, (c) fluidized-bed reactor, (d) packed-bed reactor, and (e) photocatalytic membrane reactor.

On the other hand, fluidized-bed reactors offer advantages in terms of better mixing as well as increased mass transfer between catalysts and pollutants. In this system, the catalyst particles are in a state of fluidization by the flow of fluids, thus increasing the frequency of contact between the solid phase and the reactant phase. Study by Prowans et al. (2025) It shows that this configuration is particularly effective for the degradation of gaseous pollutants such as acetaldehyde, with very high degradation efficiency.

Overall, the various configurations of photocatalytic reactors suggest that optimization of reactor design is an important factor in improving the performance of photocatalytic systems. The selection of the type of reactor must consider the type of pollutant, the reaction phase (liquid or gas), the method of immobilizing the catalyst, and the operational needs of the system, so that it can achieve optimal degradation efficiency.

Influence of light sources on photocatalytic efficiency

The light source is one of the important parameters in the photocatalytic system because it plays a role in activating semiconductor materials through the process of electron excitation from the valence band to the conduction band, resulting in an electron-hole pair that plays a role in the oxidation and reduction reaction on the catalyst surface. Therefore, the characteristics of the light source, such as wavelength, radiation intensity, and energy efficiency, greatly affect the performance of photocatalytic systems.

The studies analyzed show that different types of light sources are used in photocatalysis experiments, including conventional ultraviolet (UV) lamps, UV light-emitting diodes (UV-LEDs), as well as visible light LEDs. In general, TiO_2 has a band gap of about 3.0–3.2 eV, so it is naturally more active under UV light irradiation. However, the use of metal dopants such as Fe can modify the electronic structure of TiO_2 and extend its spectral response to the region of visible light.

In recent years, the use of UV-LEDs has been increasingly reported because it offers a few advantages over conventional UV lamps, such as higher energy efficiency, longer operational life, more compact size, and lower heat production. These characteristics make UV-LED more suitable for the development of efficient and sustainable photocatalytic reactor systems.

In addition, the development of photocatalyst materials that are active under light appears to be also a major focus in modern photocatalysis research, especially to utilize solar energy as a renewable energy source. For example, research by Harsha et al. (2025) shows that light-LED-based photocatalytic reactor systems appear to be able to effectively degrade antibiotics such as ciprofloxacin and tetracycline without the need for high-intensity UV radiation. These results show the potential for the application of solar energy-based photocatalytic systems for waste treatment applications on a larger scale.

Overall, the selection of the right light source, as well as the development of photocatalysts that have a wider spectral response, are key factors in improving the efficiency and sustainability of photocatalytic systems for environmental treatment applications.

Pollutant Degradation Performance

In general, the results of the literature analysis show that modified TiO_2-based photocatalytic systems, including Fe-doped TiO_2, can achieve relatively high pollutant degradation efficiency. Various studies report degradation efficiency that ranges from 45% to more than 99%, depending on several key factors, such as the type of pollutant, the catalyst synthesis method, the photocatalytic reactor design, the light source, as well as the operating conditions of the system.

The types of pollutants most used in the study include synthetic dyes, antibiotics, pharmaceutical compounds, volatile organic compounds (VOCs), and microplastics. The variety of pollutant types shows that TiO_2-based photocatalytic technology has wide application potential in environmental treatment, both for liquid waste treatment and gaseous phase pollutants. Some studies have reported very high levels of degradation under certain experimental conditions, especially when using catalysts with a high surface area, optimal reactor design, and an adequate intensity light source. Modification of TiO_2 with metal dopants, including Fe, has also been reported to improve the spectral response of materials as well as reduce the rate of electron-hole pair recombination, thereby increasing photocatalytic activity.

Despite this, most of the analyzed studies are still conducted on a laboratory scale, with relatively controlled experimental conditions. Therefore, further research is still needed to develop a more efficient and stable photocatalytic reactor design on a larger scale, including evaluation of energy consumption, long-term catalyst stability, and system performance under real waste conditions.

Overall, the results of existing studies show that TiO_2-based photocatalytic technologies have very promising potential for environmental treatment applications, but further development is still needed to bridge the gap between laboratory-scale research and industrial-scale implementation. Although high degradation efficiencies were reported, energy consumption remains an important consideration for large-scale applications. UV-LED systems are increasingly preferred over conventional mercury lamps due to lower energy demand, longer operational lifetime, and environmental safety.

CONCLUSION

This systematic review synthesized current advancements in Fe-doped TiO_2 photocatalytic reactors, demonstrating that iron modification significantly narrows the band gap and suppresses charge carrier recombination. These factors collectively extend the photocatalytic response into the visible light region, a critical requirement for sustainable solar-driven wastewater treatment. The analysis highlights that while sol-gel and hydrothermal methods remain the preferred routes for tailoring catalyst morphology, the choice of reactor configuration specifically fluidized-bed and membrane-based systems is the primary driver for mass transfer efficiency and light utilization. Despite the high degradation efficiencies reported (up to >99% for certain pollutants), a clear gap remains between laboratory success and industrial feasibility.

Future research must move beyond controlled batch experiments to address long-term catalyst stability, energy consumption (EEO), and performance under complex, multi-pollutant real-waste matrices. Bridging this "lab-to-industry" gap is essential for the commercialization of Fe-doped TiO_2 technologies as a viable environmental solution.

REFERENCES

Alalm, M. G., Djellabi, R., Meroni, D., Pirola, C., Bianchi, C. L., & Boffito, D. C. (2021). Toward Scaling-Up Photocatalytic Process for Multiphase Environmental Applications. *Catalysts*, *11*(5), 562. https://doi.org/10.3390/catal11050562

Azghandi, A. V., Zakariapoornaeini, M., Rezazadeh, N., & Ghassemi, S. A. (2025). Evaluation and comparison of the performance of immobilized and suspended UV/TiO2 helical reactor in photocatalytic degradation of methyl orange. *Journal of Molecular Liquids*, *439*, 128940. https://doi.org/10.1016/j.molliq.2025.128940

Basavarajappa, P. S., Patil, S. B., Ganganagappa, N., Reddy, K. R., Raghu, A. V., & Reddy, Ch. V. (2020). Recent progress in metal-doped TiO2, non-metal doped/codoped TiO2 and TiO2 nanostructured hybrids for enhanced photocatalysis. *International Journal of Hydrogen Energy*, *45*(13), 7764–7778. https://doi.org/10.1016/j.ijhydene.2019.07.241

Biao, W., Awanis Hashim, N., Rabuni, M. F. B., Lide, O., & Ullah, A. (2025). An innovative strategy for polyester microplastic fiber elimination from laundry wastewater via coupled separation and degradation using TiO2-based photocatalytic membrane reactor. *Separation and Purification Technology*, *356*, 129929. https://doi.org/10.1016/j.seppur.2024.129929

Binjhade, R., Mondal, R., & Mondal, S. (2022). Continuous photocatalytic reactor: Critical review on the design and performance. *Journal of Environmental Chemical Engineering*, *10*(3), 107746. https://doi.org/10.1016/j.jece.2022.107746

Chang, C., Li, Z., Rad, S., Gan, L., Dai, J., & Shahab, A. (2024). Preparation and application of nano TiO2 filmcoated recycled low-iron crushed glass in a novel packed-bed photocatalytic reactor for efficient removal of biodegradable contaminants. *Environmental Technology & Innovation*, *33*, 103541. https://doi.org/10.1016/j.eti.2024.103541

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. https://doi.org/10.3390/ catal11050556

Fouad, S. M., El-Shazly, Y. M. S., Alyoubi, M. A., Nosier, S. A., & Abdel-Aziz, M. H. (2023). Enhanced photocatalytic degradation of cationic dyes using slurry of anatase titania in a falling film reactor. *Case Studies in Chemical and Environmental Engineering*, *8*, 100518. https://doi.org/10.1016/j.cscee.2023.100518

Harsha, N. V. M. S., Singh, S. P., & Shriwastav, A. (2025). A stacked photocatalytic reactor immobilized with visible light driven doped TiO2 nanoparticles for effective wastewater treatment with simultaneous removal of antibiotics and disinfection. *Chemical Engineering Journal*, *524*, 169122. https://doi.org/10.1016/j.cej.2025.169122

Hasanuzzaman, M., Mokammel, Mohammad., Islam, Md. Johirul., & Hashmi, Saleem. (2023). Co-doped (N and Fe) TiO_2 photosensitising nanoparticles and their applications: A review. *Advances in Materials and Processing Technologies*, 1–24. https://doi.org/10.1080/2374068X.2023.2189634

Khan, H., & Shah, M. U. H. (2023). Modification strategies of TiO2 based photocatalysts for enhanced visible light activity and energy storage ability: A review. *Journal of Environmental Chemical Engineering*, *11*(6), 111532. https://doi.org/10.1016/j.jece.2023.111532

Li, Q., Kong, H., Li, P., Shao, J., & He, Y. (2019). Photo-Fenton degradation of amoxicillin via magnetic TiO2-graphene oxide-Fe3O4 composite with a submerged magnetic separation membrane photocatalytic reactor (SMSMPR). *Journal of Hazardous Materials*, *373*, 437–446. https://doi.org/10.1016/j.jhazmat.2019.03.066

Mahadadalkar, M. A., Park, N., Yusuf, M., Nagappan, S., Nallal, M., & Park, K. H. (2023). Electrospun Fe doped TiO2 fiber photocatalyst for efficient wastewater treatment. *Chemosphere*, *330*, 138599. https://doi.org/10.1016/j.chemosphere.2023.138599

Markose, A., Das, D., & Ravindran, P. (2023). Quantitative framework development for understanding the relationship between doping and photoelectrochemical energy conversion of TiO_2. *Materials Advances*, *4*(16), 3399–3451. https://doi.org/10.1039/D3MA00059A

Navidpour, A. H., Ahmed, M. B., & Zhou, J. L. (2024). Photocatalytic Degradation of Pharmaceutical Residues from Water and Sewage Effluent Using Different TiO2 Nanomaterials. *Nanomaterials*, *14*(2), 135. https://doi.org/10.3390/ nano14020135

Nayeri, S., & Basiri Parsa, J. (2024). Cross-flow photocatalytic membrane reactor (PMR) based on TiO2–AgBr–Ag–NH2-MIL-88B (Fe) /poly (ethersulfone) for enhanced removal of cefixime, anti-fouling performance and permeability. *Polymer*, *307*, 127291. https://doi.org/10.1016/j.polymer.2024.127291

Page, M. J., McKenzie, J. E., Bossuyt, P. M., Boutron, I., Hoffmann, T. C., Mulrow, C. D., Shamseer, L., Tetzlaff, J. M., Akl, E. A., Brennan, S. E., Chou, R., Glanville, J., Grimshaw, J. M., Hróbjartsson, A., Lalu, M. M., Li, T., Loder, E. W., Mayo-Wilson, E., McDonald, S., … Moher, D. (2021). The PRISMA 2020 statement: An updated guideline for reporting systematic reviews. *BMJ*, *372*, n71. https://doi.org/10.1136/bmj.n71

Prowans, B., Rychtowski, P., & Tryba, B. (2025). TiO2-Pt coated cenospheres as efficient photocatalytic bed for acetaldehyde removal in the fluidized bed reactor. *Journal of Environmental Chemical Engineering*, *13*(6), 119499. https://doi.org/10.1016/j.jece.2025.119499

Sultana, M., Mondal, A., Islam, S., Khatun, Most. A., Rahaman, Md. H., Chakraborty, A. K., Rahman, Md. S., Rahman, M. M., & Nur, A. S. M. (2023). Strategic development of metal doped TiO2 photocatalysts for enhanced dye degradation activity under UV–Vis irradiation: A review. *Current Research in Green and Sustainable Chemistry*, *7*, 100383. https://doi.org/10.1016/j.crgsc.2023.100383

Sun, L., Li, Z., Yuan, Z., Liu, Y., Mei, S., Meng, F., Ouyang, X., Xiong, Y., Zhang, K., & Chen, Z. (2025). Preparation of Magnetic Photocatalyst Fe3O4@ SiO2@Fe-TiO2 and Photocatalytic Degradation Performance of Methyl Orange in Na2SO4 Solution. *Applied Sciences*, *15*(7), 3781. https://doi.org/ 10.3390/app15073781

Tanguturi Venkata, P., Police, A. K. R., Lee, J., Munnelli, N., Padma, L., Thummala, S., Nagappagari, L. R., Parthasarathy, R., Kanakkampalayam Krishnan, C., Mohan, S., Nallagondu, C. G. R., Murikinati, M. K., Bae, S., & Muthukonda Venkatakrishnan, S. (2026). Photocatalytic dye degradation under natural diurnal sunlight using anatase TiO2 nanorods: A structure-performance study. *Journal of Water Process Engineering*, *85*, 109793. https://doi.org/10.1016/j.jwpe.2026.109793

Tee, S. Y., Kong, J., Koh, J. J., Teng, C. P., Wang, X., Wang, X., Teo, S. L., Thitsartarn, W., Han, M.-Y., & Seh, Z. W. (2024). Structurally and surficially activated TiO_2 nanomaterials for photochemical reactions. *Nanoscale*, *16*(39), 18165–18212. https://doi.org/ 10.1039/D4NR02342K

Thomas, M., Naikoo, G. A., Sheikh, M. U. D., Bano, M., & Khan, F. (2016). Effective photocatalytic degradation of Congo red dye using alginate/carboxymethyl cellulose/TiO2 nanocomposite hydrogel under direct sunlight irradiation. *Journal of Photochemistry and Photobiology A: Chemistry*, *327*, 33–43. https://doi.org/10.1016/j.jphotochem.2016.05.005

Tryba, B. (2008). Immobilization of TiO2 and Fe–C–TiO2 photocatalysts on the cotton material for application in a flow photocatalytic reactor for decomposition of phenol in water. *Journal of Hazardous Materials*, *151*(2–3), 623–627. https://doi.org/ 10.1016/j.jhazmat.2007.06.034

Visan, A., Van Ommen, J. R., Kreutzer, M. T., & Lammertink, R. G. H. (2019). Photocatalytic Reactor Design: Guidelines for Kinetic Investigation. *Industrial & Engineering Chemistry Research*, *58*(14), 5349–5357. https://doi.org/10.1021/acs.iecr.9b00381

Wang, C., Liu, Y., Li, Y., Sun, X., Xu, L., & Huang, W. (2023). Facile defect construction of TiO2 nanotube for excellent photocatalytic degradation of tetracycline under visible light. *Journal of Photochemistry and Photobiology A: Chemistry*, *437*, 114475. https://doi.org/10.1016/j.jphotochem.2022.114475

Wang, R., Ren, D., Xia, S., Zhang, Y., & Zhao, J. (2009). Photocatalytic degradation of Bisphenol A (BPA) using immobilized TiO2 and UV illumination in a horizontal circulating bed photocatalytic reactor (HCBPR). *Journal of Hazardous Materials*, *169*(1–3), 926–932. https://doi.org/10.1016/j.jhazmat.2009.04.036

Wang, X., Teo, S. H., Shamsuddin, M., & Wid, N. (2024). Photocatalytic Degradation of Organic Pollutants and Microplastics Using Ag/TiO2: Recent Advances in Mechanism, Synthesis and Properties. *Water, Air, & Soil Pollution*, *236*. https://doi.org/10.1007/s11270-024-07669-2

Yilleng, M. T., Artioli, N., Rooney, D., & Manyar, H. (2023). Continuous Flow Photocatalytic Degradation of Phenol Using Palladium@Mesoporous TiO2 Core@Shell Nanoparticles. *Water*, *15*(16), 2975. https://doi.org/10.3390/ w15162975

Yusuf, A. O., Mohamed, G. H., Al-Sakkaf, R., Rodríguez, J., Žerjav, G., Pintar, A., & Palmisano, G. (2024). Photocatalytic degradation of diclofenac amide in a fixed-bed reactor using TiO2/β-Bi2O3: Process optimization and stability analysis. *Journal of Photochemistry and Photobiology A: Chemistry*, *450*, 115470. https://doi.org/10.1016/j.jphotochem.2024.115470

Zarzzeka, C., Goldoni, J., De Paula De Oliveira, J. D. R., Lenzi, G. G., Bagatini, M. D., & Colpini, L. M. S. (2024). Photocatalytic action of Ag/TiO2 nanoparticles to emerging pollutants degradation: A comprehensive review. *Sustainable Chemistry for the Environment*, *8*, 100177. https://doi.org/10.1016/j.scenv.2024.100177