

Application of Fenton-like systems for wastewater detoxification

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Abstract: Industrialization has led to severe environmental challenges, primarily the contamination of water bodies with persistent organic pollutants (POPs) such as pharmaceuticals, synthetic dyes, and toxic organic compounds. Conventional treatment methods, including biological processes and coagulation, often prove insufficient for the complete degradation of these chemically stable substances. This review systematically examines the application of Fenton-like systems as a promising advanced oxidation process (AOP) for industrial wastewater detoxification. Specifically, the review aims to compare degradation efficiencies across three priority pollutant classes – toxic organic compounds, synthetic dyes, and pharmaceutical residues – identify the catalytic and operational factors governing process performance, and evaluate techno-economic constraints relevant to industrial scaling. The operational principles and catalytic cycles involving reactive hydroxyl radicals ($\cdot\text{OH}$) are detailed, highlighting the transition from classical homogeneous reactions to more versatile heterogeneous systems. Recent advances demonstrate that utilizing transition metals (Cu, Mn, Ni) and novel materials like metal-organic frameworks (MOFs) and bimetallic oxides allows these processes to operate effectively at near-neutral pH, overcoming the strict acidic limitations of traditional Fenton chemistry. Furthermore, the integration of physical stimuli – such as ultraviolet radiation (photo-Fenton), electricity (electro-Fenton), and ultrasound (sono-Fenton) – is shown to significantly enhance radical generation and mineralization rates for complex molecules. The review provides a comparative analysis of treatment efficiencies, achieving removal rates often exceeding 95 % for various toxic groups. Finally, technical and economic constraints, including sludge formation and energy intensity, are discussed alongside prospects for scaling these technologies for sustainable industrial application.

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1. Introduction

1.1 Relevance of the problem of pollution and toxic substances in industrial wastewater

Industrialization has become a turning point in human history, providing a powerful impetus for economic growth and technological advancement. However, alongside these positive changes, it has triggered a series of severe environmental consequences. One of the most pressing issues is the environmental pollution caused by industrial effluents. Wastewater generated at industrial facilities, containing pharmaceuticals, toxic organic compounds, and synthetic dyes, poses a substantial threat to both natural ecosystems and human health. Despite the implementation of treatment technologies, toxic compounds frequently continue to enter water bodies, accumulating in the environment and intensifying the ecological burden.

According to a large-scale international study published in 2022 covering 258 rivers across 104 countries, the concentration of at least one active pharmaceutical ingredient (API) exceeded safe levels for aquatic organisms in 25.7 % of the samples (Wilkinson et al., 2022). The most contaminated sites were recorded in regions with low wastewater treatment efficiency and high concentrations of pharmaceutical manufacturing, including South Asia, South America, and parts of Africa (Waleng & Nomngongo, 2022).

As a result of intensive pharmaceutical production and consumption, substances such as antibiotics, hormones, and anti-inflammatory drugs are increasingly detected in modern industrial wastewater (Lykov et al., 2020). In Europe, according to the European Environment Agency, approximately 30 % of water bodies contain pharmaceutical pollutants, which have already led to serious disruptions in biodiversity and a deterioration of drinking water quality (Samal et al., 2022).

These compounds are detected in surface and drinking waters at concentrations ranging from nanograms to micrograms; however, they exhibit hormone-like, mutagenic, and toxic effects on aquatic organisms and humans (Samal et al., 2022). The consequences of such exposure include endocrine system disruptions and genetic defects.

In addition to pharmaceutical residues, effluents contain toxic organic compounds used in the chemical industry and solvent production, which volatilize easily and contaminate both the atmosphere and water sources (Wołowicz & Munir, 2025). For instance, China generates approximately 3.12×10^8 m³ of coking wastewater annually, containing 558 different organic compounds. This wastewater contributes to increasing concentrations of toxic organic matter in the environment, posing a significant risk to public health, particularly in countries with developing industries (Wołowicz & Munir, 2025; Andreeva, 2021). Of particular concern are recalcitrant and toxic pollutants that persist even after conventional wastewater treatment methods (Burkhardt-Holm, 2010).

Toxic organic substances accumulate in trophic chains, leading to bioaccumulation and biomagnification, thereby exacerbating the pressure on ecosystems (Titchou et al., 2021). VOCs, such as benzene, toluene, xylenes, chlorine-based compounds, hydrocarbons, and phenols, possess carcinogenic and mutagenic activity, exerting a negative impact on human health and ecosystems.

The problem of industrial wastewater pollution by dyes, alongside other toxic substances, remains one of the most acute environmental threats today (Kant, 2012). For example, the textile industry alone produces about 70 million tons of various dyes annually, of which more than 10,000 tons are utilized in fabric dyeing processes (Slama et al., 2021).

However, inefficient dyeing technologies result in 15 % to 50 % of these dyes failing to bind to fibers and being discharged into wastewater, subsequently contaminating water bodies (Ramamurthy et al., 2024). Textile effluents contain not only dyes but also a wide range of toxic substances, including heavy metals, phthalates, phenols, and other organic compounds (Kant, 2012). Thus, industrialization, along with economic development and scientific progress, has led to a series of inevitable environmental issues, such as the contamination of wastewater with pharmaceuticals and toxic compounds. The emerging challenges of wastewater pollution necessitate the development of advanced treatment methods tailored to chemically resistant pollutants (Y. Liu et al., 2024).

1.2. Limitations of conventional treatment and detoxification methods

Conventional treatment methods, including mechanical filtration, sedimentation, coagulation, and biological treatment, are effective in removing suspended solids, organic matter, and pathogens (Y. Liu et al., 2024). However, they demonstrate low efficiency in eliminating persistent organic pollutants (POPs), synthetic dyes, pharmaceutical compounds, hormones, and pesticides (Andreeva, 2021). Mechanical filtration, utilized during the primary treatment stage via screens, meshes, or sand filters, removes large suspended solids such as debris and grit. Nevertheless, dissolved organic compounds and microbes cannot be captured at this stage. Similarly, sedimentation only facilitates the removal of large particles that settle under gravity. While water is retained in settling tanks for a specific duration to allow particle precipitation, this method does not involve the cleavage of chemical bonds in toxic organic compounds, synthetic dyes, or pharmaceutical pollutants; thus, it cannot be employed for wastewater detoxification.

Coagulation and flocculation are widely used wastewater treatment techniques, the efficacy of which depends on the precise selection and dosage of reagents. Incorrect selection or improper dosing leads to incomplete pollutant removal or excessive sludge formation (Kyuregyan et al., 2022). These processes are highly sensitive to fluctuations in pH, temperature, and wastewater composition, including the presence of inhibitory substances, necessitating constant monitoring and adjustments. Even with optimal dosing, the chemistry of coagulation often fails to address specific contaminants such as POPs, synthetic dyes, or pharmaceuticals. Consequently, coagulation-based methods alone are insufficient for treating wastewater containing these persistent pollutants (Kachalova, 2019).

Biological treatment methods, such as activated sludge, perform poorly in removing both organic pollutants and stable pharmaceutical compounds. This inefficiency is attributed to the high stability and low biodegradability of these substances, rendering biological treatment generally ineffective (Tiwari et al., 2017). Furthermore, certain pharmaceuticals can inhibit microbial activity, further reducing treatment efficiency (Ostaschenko et al., 2023). Removal efficiency depends on the chemical properties of the substances – such as water solubility, stability, biodegradability, and molecular weight – as well as process conditions, including temperature, pH, contact time, dissolved oxygen levels, and the composition of the microbial community (Ignatenko, 2022). Readily biodegradable drugs (e.g., ibuprofen) are removed at rates of 60–100 %, whereas recalcitrant ones (e.g., carbamazepine) persist (Ostaschenko et al., 2023). Even when removal efficiency is high, residual concentrations of pharmaceutical substances in treated water pose significant ecological and sanitary risks. Thus, conventional treatment methods do not ensure sufficient efficacy in removing persistent and toxic pollutants, as these compounds often retain their toxicity and chemical stability even after standard treatment procedures.

This underscores the urgent need to develop and implement advanced treatment methods capable not only of separating pollutants from the medium but also of degrading them into harmless components, thereby minimizing environmental risks and ensuring a higher degree of purification.

1.3. Prospects for the application of Fenton-like processes for industrial wastewater treatment from toxic organic pollutants

The Fenton process, developed in the late 19th century by the British chemist Henry John Horstman Fenton, is an oxidation process in which hydrogen peroxide (H_2O_2) in the presence of ferrous ions (Fe^{2+}) generates highly reactive hydroxyl radicals. These radicals possess the capability to degrade a wide range of organic pollutants, including persistent and toxic compounds (Parmar, 2015). Although the method was initially applied in laboratory settings, its efficiency has, over time, been recognized across various industries, particularly in the field of wastewater treatment (Vasilieva et al., 2019).

Modern research demonstrates the high efficiency of the Fenton process in removing organic pollutants from wastewater. For instance, laboratory experiments have shown that implementing the Fenton method with aeration increases treatment efficiency from 72.2 % to 96.8 % (Vasilieva et al., 2019). Furthermore, the acetaldehyde content in treated samples decreased nearly 40-fold compared

to initial values (Trapido et al., 2009). These results confirm the potential of the Fenton method in ensuring a high level of wastewater purification from toxic organic compounds.

The Fenton-like oxidation method, a modification of the classical approach, expands the possibilities for oxidative degradation by utilizing various catalysts and reaction conditions. For example, patent RU2303572C2 describes the application of the Fenton reagent in combination with micellar sludge treatment methods, which allows for an average increase in organic matter decomposition by 5–30 % (Fleri, 2007). Such approaches demonstrate the promising nature of Fenton-like oxidation in various fields, including industrial wastewater treatment and sludge processing.

Figure 1 presents a chart showing the number of publications dedicated to the application of Fenton-like processes from 2010 to 2024. The data were retrieved from the Scopus scientific database. The chart clearly illustrates a growing trend in research interest regarding this subject.

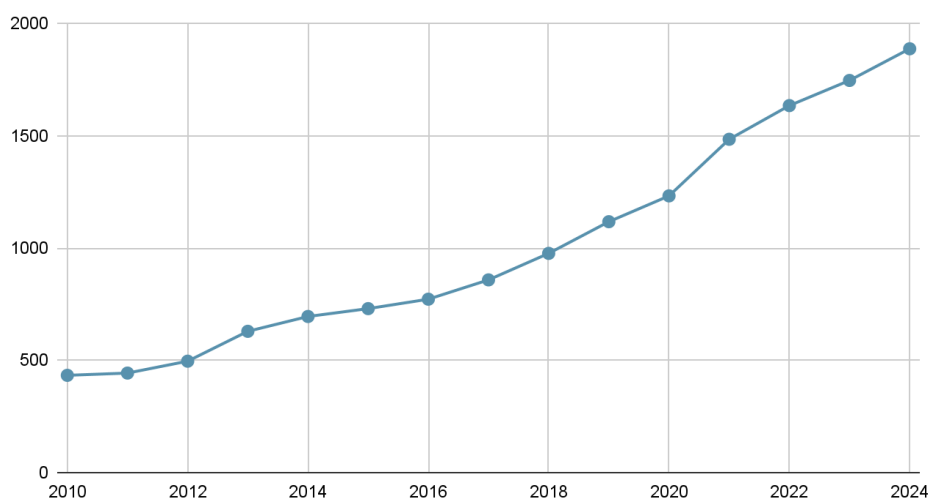


Figure 1. A chart showing the number of publications dedicated to the study of Fenton-like catalytic systems from 2010 to 2024, based on Scopus database data

Therefore, the objective of this article is to conduct a systematic review of contemporary scientific research dedicated to the application of Fenton-like systems for the detoxification of industrial wastewater containing toxic organic compounds, synthetic dyes, and pharmaceuticals. To achieve this objective, the following research tasks were established:

- To characterize the operational principle of Fenton-like processes;
- To examine the industrial application areas of Fenton-like processes;
- To evaluate their efficiency in removing toxic organic compounds, dyes, and pharmaceutical pollutants from wastewater;
- To identify the most promising approaches for implementing Fenton-like catalytic degradation of persistent organic pollutants based on the analysis of literature data.

Unlike previously published reviews that typically focus on either a single pollutant class or a specific catalyst type, the present work provides a cross-class comparative analysis spanning toxic organic compounds, synthetic dyes, and pharmaceutical residues within a unified analytical framework. Particular emphasis is placed on the evolution from classical homogeneous iron-based systems toward heterogeneous and bimetallic catalysts capable of operating at near-neutral pH – a transition that is critical for industrial applicability yet rarely discussed in terms of quantitative performance metrics across pollutant categories. Furthermore, this review systematically addresses hybrid activation strategies (photo-, electro-, and sono-Fenton) and evaluates their contribution to mineralization depth, alongside techno-economic constraints that condition the scalability of these processes.

2. Methods

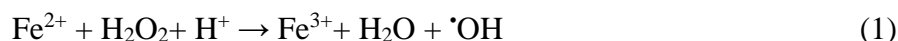
The present review is based on a comprehensive analysis of peer-reviewed literature indexed in major scientific databases, including Scopus, Web of Science, and Google Scholar. The search strategy was designed to identify relevant studies published between 2010 and 2026, focusing on the development and application of advanced oxidation processes and Fenton-like systems. The primary search queries involved combinations of terms such as "Fenton-like systems," "heterogeneous catalysis," "industrial wastewater treatment," and specific pollutant categories including pharmaceuticals and synthetic dyes.

The selection of sources was conducted based on several fundamental scientific criteria. Priority was given to research introducing novel catalytic materials, such as metal-organic frameworks, bimetallic oxides, and nanostructured composites, as well as studies demonstrating significant advancements in expanding the operational pH range. Furthermore, the analysis included only those articles that provided comprehensive experimental data, including precise reaction conditions and quantitative metrics for pollutant removal and mineralization rates.

3. Current advances in the application of Fenton-like systems for wastewater treatment processes

3.1. The operational principle of Fenton-like systems

The Fenton process is a prominent type of Advanced Oxidation Processes (AOPs) that is currently under intensive research and is likely to be implemented in industrial applications in the near future. This process is fundamentally based on the reaction (1):



The hydroxyl radical formed in the reaction promotes the degradation of organic pollutants into simpler components. A simplified scheme of the oxidation mechanism in the Fenton process is shown in Figure 2.

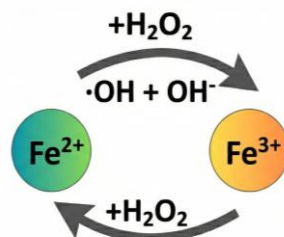
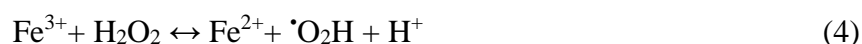
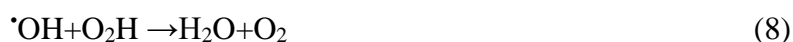


Figure 2. Schematic representation of the catalytic cycle and the generation of reactive oxygen species (ROS) in Fenton systems

According to published studies, more than 20 different reactions occur during the process (Moorjani & Gohil, 2021), of which the following are key to Fenton chemistry:





The chain reaction of hydrogen peroxide decomposition involving iron ions consists of several key stages. In reaction (2), the chain initiation occurs: Fe^{2+} interacts with H_2O_2 to form hydroxyl radicals ($\cdot\text{OH}$), which are highly reactive species capable of oxidizing a wide range of organic compounds. Reaction (3) represents a chain termination step due to the interaction of $\cdot\text{OH}$ with Fe^{2+} . In reaction (4), Fenton-like processes are realized – the reduction of Fe^{3+} to Fe^{2+} in the presence of H_2O_2 , accompanied by the formation of hydroperoxyl radicals ($\cdot\text{OOH}$). Reactions (5) and (6) describe the subsequent transformations of Fe^{3+} and radical species, thereby maintaining the catalytic cycle.

It is specifically reactions (3)–(6) that constitute the rate-limiting steps, as these stages involve relatively slow electron transfer processes between iron ions and radicals. These steps determine the overall rate of hydrogen peroxide decomposition and the efficiency of active oxidant generation within the Fenton system (Moorjani & Gohil, 2021).

3.2. Classification of Fenton-like processes

The classification of the diverse range of Fenton-like processes is presented in Figure 3.

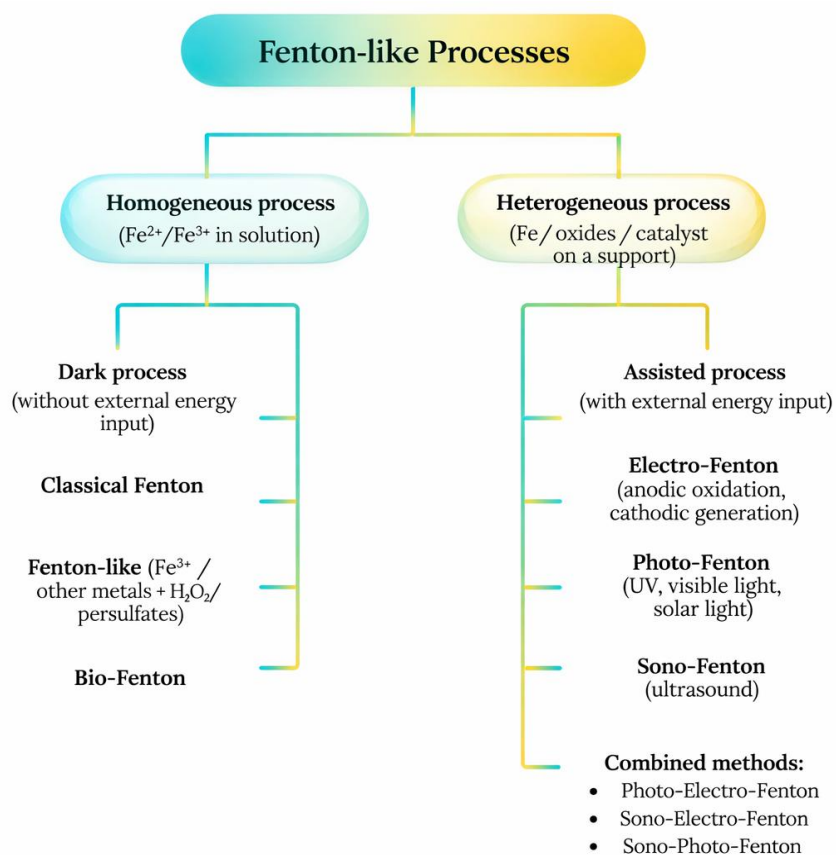


Figure 3. Classification of Fenton-like systems based on the catalyst phase state and process activation methods

The efficiency of Fenton-like processes is determined by numerous factors, primarily the nature of the catalyst used. Depending on the phase state, a distinction is made between homogeneous and heterogeneous systems: in the former, the catalyst (most commonly Fe^{2+}) is dissolved in the aqueous phase, while in the latter, it exists in the solid phase, for instance, on the surface of iron oxides.

In addition to traditional iron, ions of other transition metals—such as Mn^{2+} , Cu^{2+} , or Ni^{2+} — can be used as catalysts, as they possess the ability to activate hydrogen peroxide (H_2O_2) to form hydroxyl radicals ($\cdot\text{OH}$). For instance, manganese-based systems, especially in the form of MnO_2 or Mn_3O_4 , demonstrate high activity at neutral and slightly acidic pH. Furthermore, in electrochemically activated variants, such as Electro-Fenton with Mn^{2+} , a high degree of organic pollutant removal is observed (Omarov et al., 2022).

Copper-based catalysts deserve special attention, where the cycling between $\text{Cu}^{2+}/\text{Cu}^+$ states promotes effective H_2O_2 activation even at neutral pH. Although nickel is less active compared to iron or copper, it is also employed in certain systems, particularly under conditions of precisely controlled electric current (Hussain et al., 2021).

Alongside the choice of catalyst, external physical influences play a crucial role. The development of modifications, such as processes utilizing additional energy, has significantly expanded the application range of Fenton-like methods. Physical stimuli—light radiation, electricity, and ultrasound—facilitate enhanced radical generation and increase the degree of pollutant mineralization (Arefieva et al., 2020). For example, in systems implementing a mechanism analogous to Photo-Fenton, irradiation with ultraviolet or visible light reduces Fe^{3+} to Fe^{2+} , thereby accelerating the oxidation reaction. In practice, this is achieved using UV radiation sources ($\lambda < 390 \text{ nm}$), such as xenon lamps or LED lights, as well as through the utilization of visible light, which is particularly effective in treatment systems with minimal energy consumption.

Ultrasonic technologies implemented within Sono-Fenton processes promote cavitation, improve the dispersion of reagents, and ensure the intensive formation of reactive oxygen species. When combined with electrochemical action, as seen in Sono-Electro-Fenton systems, a synergistic effect occurs, allowing for a high degree of degradation even for persistent compounds. Similarly, the simultaneous application of light and electricity in the Photo-Electro-Fenton configuration results in accelerated metal ion reduction and intensification of $\cdot\text{OH}$ radical formation. In hybrid systems that combine ultrasound and photochemistry, such as Sono-Photo-Fenton, maximum destruction of organic pollutants is achieved through multi-stage H_2O_2 activation.

The most important parameters determining the performance of such processes also include temperature and electrical voltage. For instance, an optimal temperature of around $60 \text{ }^\circ\text{C}$ promotes maximum H_2O_2 decomposition to form $\cdot\text{OH}$ radicals; however, an excessive increase may lead to premature peroxide decomposition without radical formation, reducing process efficiency. Voltage, in turn, determines the rate of H_2O_2 generation and catalyst recovery, especially under Electro-Fenton conditions or its analogs, where iron is replaced by Cu^{2+} or Ni^{2+} . With a properly selected voltage, a high degradation rate for substances such as 2-phenylphenol is ensured.

Additional efficiency is provided by integration with biological systems. In the microbially-activated Fenton process, microorganisms either participate in the regeneration of active iron ions or perform the preliminary breakdown of complex organic compounds, facilitating the subsequent oxidative attack by radicals. The diversity of approaches, from the classical Fenton process to hybrid schemes including Sono-Photo-Fenton or Photo-Electro-Fenton, allows for the adaptation of technologies to specific conditions, pollutant types, and desired treatment rates. Advanced and combined methods are particularly promising for the elimination of persistent and hard-to-oxidize compounds, providing more complete and rapid destruction compared to conventional approaches. Optimization of parameters—the nature of the catalyst, type of physical action, temperature, and voltage—opens wide possibilities for creating efficient and environmentally sustainable wastewater treatment systems.

3.3. Application of Fenton-like processes for the degradation of various pollutant groups

3.3.1. Detoxification of toxic organic compounds using Fenton-like processes

The scientific literature presents numerous studies dedicated to the removal of toxic organic compounds and persistent pollutants, such as pharmaceuticals and synthetic dyes, from aqueous systems. Fenton-like oxidation processes are considered among the most effective and versatile methods for addressing this challenge. Results from various studies confirm the successful application of these processes for treating wastewater, industrial effluents, and other contaminated media, highlighting their significance in the modern development of environmental technologies.

In a study conducted by Gaoyuan Liu et al. (2017), the treatment of wastewater contaminated with benzene was investigated. Iron sulfate was used as the catalyst, and hydrogen peroxide served as the oxidant. A key feature of the method was the step-by-step introduction of H_2O_2 into an aerated reactor, which achieved 85 % benzene removal, whereas a single addition of the same volume of hydrogen peroxide did not lead to significant purification. Furthermore, a nearly three-fold increase in CO_2 formation was observed with an absence of harmful by-products in the gas phase, indicating the complete decomposition of benzene and emphasizing the environmental safety and efficiency of this approach.

Durai et al. (2020) investigated the treatment of stabilized landfill leachate, which represents a recalcitrant pollutant with a low BOD/COD ratio (0.045). For the detoxification of toxic organic compounds in this pollutant, Fenton-like oxidation was applied using iron sulfate ($FeSO_4$) as the catalyst and hydrogen peroxide (H_2O_2) as the oxidant. Optimization of the process parameters using the central composite design (CCD) method allowed for maximum organic matter removal at a $FeSO_4$ concentration of 14.44 mM, pH 3.0, and an H_2O_2 dose of 29.12 mM.

The research results showed a significant reduction in chemical oxygen demand (COD) and total organic carbon (TOC), which was confirmed by gas chromatography-mass spectrometry (GC-MS) analysis. Thus, the proposed approach demonstrated high efficiency and environmental safety in the treatment of stabilized landfill leachate—a serious pollutant that poses a significant environmental problem.

In researches (Shokri & Fard, 2022; Tian et al., 2024), the treatment of persistent organic pollutants, such as 1,4-dioxane, was studied, which poses a severe threat to aquatic ecosystems and human health. The heterogeneous Fenton-like oxidation method was used for the detoxification of these toxic organic compounds.

The catalyst used was Fe-ZSM-5 zeolite with various Si/Al ratios, which activated hydrogen peroxide (H_2O_2), leading to the generation of reactive oxygen species—hydroxyl radicals ($\cdot OH$) and singlet oxygen (1O_2). The results showed the high efficiency of Fe-ZSM-5 in removing 1,4-dioxane from aqueous solutions, ensuring significant mineralization of the pollutants. Consequently, the proposed method represents a promising and environmentally safe way to combat the problem of persistent organic matter pollution in aquatic environments.

In a study by Tokumura et al. (2012), an effective methodology for the detoxification of toxic organic compounds using photo-Fenton-like oxidation was developed. Volatile organic compounds (VOCs), such as toluene, were used as the substrate. The iron ion (Fe^{2+}) served as the catalyst, and hydrogen peroxide (H_2O_2) was used as the oxidant. The method involved a wet scrubber combined with a photo-Fenton-like reaction, in which UV irradiation activated H_2O_2 in the presence of Fe^{2+} to generate hydroxyl radicals ($\cdot OH$). The results showed high efficiency in VOC removal without the formation of gas-phase by-products. Thus, the proposed approach demonstrates high efficiency and environmental friendliness in the oxidative detoxification of TOCs.

The article by Vasilieva et al. (2019) examined the treatment of wastewater containing toxic organic compounds that pose a serious threat to aquatic ecosystems and human health. The organic compounds present in the wastewater were successfully removed using the Fenton reaction. The ferrous ion (Fe^{2+}) served as the catalyst, and hydrogen peroxide (H_2O_2) was used as the oxidant. The Fenton reaction effectively degraded the organic pollutants, leading to a significant reduction in TOC concentration in the wastewater. The authors demonstrated the high efficiency of the Fenton reaction for wastewater treatment.

In conclusion, Fenton-like oxidation is an effective, versatile, and environmentally safe method for removing toxic organic compounds from various aqueous and gaseous media. The reviewed studies demonstrate the broad possibilities of this approach for solving urgent environmental problems, such as the removal of benzene, persistent organic pollutants (e.g., 1,4-dioxane), and volatile organic compounds. These results confirm that Fenton-like oxidation has high potential for practical application in treatment systems for wastewater, industrial discharges, and other contaminated environments, making a significant contribution to the development of sustainable environmental technologies.

3.3.2. Degradation of synthetic dyes using Fenton-like processes

The degradation of synthetic dyes is one of the key tasks of modern chemical technology in wastewater treatment, as these compounds account for a significant portion of organic pollutants in industrial effluents. Synthetic dyes are widely used in the textile, leather, paper, and plastic industries; however, their high chemical stability, resistance to photolysis, and biological degradation make them some of the most difficult pollutants to remove from the aquatic environment. Conventional treatment methods, such as sedimentation, coagulation, or biological treatment, often prove insufficient for their complete removal. Consequently, particular attention is paid to Fenton-like and Advanced Oxidation Processes (AOPs) based on the generation of highly reactive hydroxyl radicals ($\cdot\text{OH}$), which are capable of deeply oxidizing organic compounds into safe products such as CO_2 and H_2O .

In a study by Aneghi et al. (2024), the degradation of synthetic organic dyes—methylene blue (MB), rhodamine B (RhB), and malachite green (MG), which belong to the class of cationic and azo dyes—was investigated. Mono- and bimetallic oxide systems based on transition metals (Mn–Fe, Co–Fe, Cu–Mn, etc.), synthesized via the hydrothermal method, were used as catalysts. The process was conducted according to the mechanism of heterogeneous Fenton-like oxidation using hydrogen peroxide (H_2O_2) as an oxidant at $\text{pH} \approx 3\text{--}5$ and a temperature of $25\text{ }^\circ\text{C}$. Optimal conditions ensured almost complete degradation of the pollutants: 99 % removal of MB and MG within 5 minutes and 95 % of RhB within 30 minutes. The catalysts demonstrated high catalytic activity and stability, maintaining over 95 % efficiency after several application cycles, indicating their potential for industrial use in wastewater treatment systems.

Moving from oxide systems to magnetic catalysts, the study by Ribeiro et al. (2024) is of interest, where the degradation of azo dyes—Acid Red 18 (AR18), Acid Red 66 (AR66), and Orange II (OR2) – was carried out via the photo-Fenton-like oxidation mechanism using magnetite nanoparticles (Fe_3O_4). These compounds are anionic dyes with high resistance to biological degradation. The Fe_3O_4 catalyst was obtained by the hydrothermal method, and hydrogen peroxide (H_2O_2) at a concentration of 60 mg/L served as the oxidant. The reaction was performed at $\text{pH} \approx 3$ and a temperature of $25\text{ }^\circ\text{C}$ under UV irradiation. As a result, removal efficiencies reached 62.3 % for AR18, 79.6 % for AR66, and 83.8 % for OR2 within 180 minutes. The catalyst maintained high activity after six application cycles, demonstrating its stability and practical suitability for the advanced treatment of textile effluents.

Hameed & Salman (2024) investigated the efficiency of methyl orange (MO) removal from aqueous solutions using three-dimensional electro-Fenton (3D EF) in a batch reactor with a porous graphite anode and a copper foam cathode in the presence of granular activated carbon (GAC) as a third electrode. To optimize the process conditions, response surface methodology (RSM) in conjunction with the Box-Behnken design (BBD) was applied, studying the effects of current density ($3\text{--}8\text{ mA/cm}^2$), electrolysis time (10–20 min), and GAC mass (1–3 g) on removal efficiency, as well as their interactions. The model showed high reliability ($R^2 > 0.98$), with current density having the greatest influence. The highest MO removal efficiency (95.62%) at $\text{pH} = 3$ was achieved at a current density of 5.12 mA/cm^2 , a GAC mass of 3 g, and a time of 20 min, with low concentrations of Fe^{2+} (0.124 mM) and Na_2SO_4 (0.02 M); the average energy consumption was 6.22 kWh/kg MO. The effect of ultrasonic exposure in Sono-Electro-Fenton (SEF) was also examined, showing a slight improvement compared to minimum EF conditions (50.51% vs. 49.24%). The use of copper foam as

a cathode and granular carbon provided high catalytic activity, simplicity, speed, and environmental friendliness, making the method promising for the industrial removal of dyes from wastewater.

In the study by Ismail & Sakai (2025), the efficiency of Fenton-like processes for the removal of textile dyes Direct Red 28 (DR28), Reactive Blue 19 (RB19), and Reactive Black 5 (RBk 5) from wastewater was investigated using various combinations of catalysts and active radicals. Copper ions (Cu^{2+}) and peroxydisulfate ($\text{S}_2\text{O}_8^{2-}$) were used as catalysts, activating the formation of hydroxyl ($\cdot\text{OH}$) and sulfate ($\text{SO}_4\cdot^-$) radicals, which provided a high oxidative capacity for the system. Optimization of reaction conditions took into account catalyst concentration, pH, and treatment time, allowing for complete decolorization and a 98.5% reduction in total organic carbon (TOC) for RBk5. Mechanistic analysis showed that the synergistic interaction between copper and peroxydisulfate enhances radical formation and accelerates dye degradation. The results confirm that the proper selection of catalysts and radicals in Fenton-like systems ensures high efficiency in synthetic dye removal and can be applied for the industrial treatment of textile wastewater.

Meurs et al. (2024) considered the use of a Fenton-like process for the decolorization of reactive-dyed cotton waste as a pretreatment before textile recycling. Pre-moistened dark (black and blue) knitted samples with an area of 300 cm² were treated in 1200 ml of Fenton solution containing 14 mM Fe^{2+} and 280 mM H_2O_2 at 40 °C. Characterization of the fabrics before and after treatment was performed using UV-visible spectroscopy to measure color strength, as well as microscopy, IR spectroscopy, thermal analysis, and tensile testing to measure strength and elongation. Subsequently, the cotton was mechanically shredded for a qualitative analysis of recyclability. Color strength measurements for black and blue cotton showed decolorization efficiencies of 61.5 % and 72.9 %, respectively. The results provide proof-of-concept for an alternative color removal method using a Fenton-like process as a pretreatment before textile recycling.

Papadopoulou et al. (2025) examined homogeneous and heterogeneous photocatalytic methods based on the photo-Fenton reaction for the degradation of Nile Blue dye. Within the scope of homogeneous photocatalysis, the classical photo-Fenton ($\text{UV}/\text{Fe}^{2+}/\text{H}_2\text{O}_2$) and a modified photo-Fenton-like system ($\text{UV}/\text{Fe}^{2+}/\text{S}_2\text{O}_8^{2-}$) were studied. For heterogeneous photocatalysis, a commercial MOF catalyst (Basolite F300) and the natural iron-containing mineral goethite were used. The results showed that modification with peroxydisulfate ($\text{S}_2\text{O}_8^{2-}$) increases degradation efficiency compared to the traditional H_2O_2 system, especially in the homogeneous phase. Heterogeneous systems based on goethite ($\alpha\text{-FeO}(\text{OH})$) and Basolite F300 also demonstrated high efficiency, with goethite showing better stability across a wide pH range (3–7). This study highlights the promise of using modified photo-Fenton-like systems for the effective removal of synthetic dyes from wastewater.

Fenton-like processes have demonstrated high efficiency in the degradation of specific synthetic dyes from wastewater, including methylene blue (MB), rhodamine B (RhB), malachite green (MG), Acid Red 18 (AR18), Acid Red 66 (AR66), Orange II (OR2), Direct Red 28 (DR28), Reactive Blue 19 (RB19), Reactive Black 5 (RBk5), and Nile Blue. The use of various catalysts—transition metal oxide systems, magnetic Fe_3O_4 nanoparticles, goethite, and MOF catalysts—ensured a high degree of degradation, stability, and recyclability. Modern methods, including three-dimensional electro-Fenton, Sono-Electro-Fenton, and photo-Fenton with peroxydisulfate, increase degradation rates and reduce total organic carbon (TOC). These results confirm the potential of Fenton-like processes as an effective and environmentally safe method for industrial wastewater treatment.

3.3.3. Degradation of pharmaceutical compounds

Currently, increasing attention is being paid to the development of effective methods for the degradation of pharmaceutical compounds (PCs), which are among the priority and most persistent pollutants in the aquatic environment. The application of photocatalysis, advanced oxidation processes (AOPs), and bioremediation is considered one of the most promising directions for treating wastewater containing such substances. These technologies ensure the deep destruction of hard-to-

decompose compounds, including antibiotics, analgesics, cytostatics, hormones, and other pharmaceutical drugs characterized by high chemical stability and biological activity.

Special research focus is directed toward studying the degradation mechanisms of these compounds and optimizing conditions to ensure their complete decomposition and toxicity reduction. According to Höler et al. (2023), the main substrates in such studies are antibiotics, analgesics, and hormonal drugs that are resistant to conventional wastewater treatment methods. For their destruction, photocatalysts based on TiO₂ and its modifications, activated by ultraviolet or visible radiation, are most widely used. Such systems implement advanced oxidation processes (AOPs), where hydroxyl radicals ([•]OH) and reactive oxygen species serve as the key oxidants. Consequently, partial or complete mineralization of the initial compounds and a significant reduction in their toxicity are achieved, making this approach highly effective and environmentally justified.

In a study by Zhuo et al. (2025) on water treatment from pharmaceutical pollutants, the decomposition of the antibiotic ciprofloxacin with an initial concentration of 10.0 mg/L was investigated using a heterogeneous Fenton-like process with peroxymonosulfate activation. A Co/GO heterostructure with a cobalt content of 12.3 wt.% and a specific surface area of 385 m²/g was used as the catalyst. Under optimal conditions—catalyst dose of 0.20 g/L, PMS concentration of 0.50 g/L, temperature of 25.0 °C, and initial pH of 5.5—the system demonstrated exceptional efficiency: 98.7 % decomposition of ciprofloxacin within 20.0 minutes with a rate constant of 1.456 min⁻¹ and an activation energy of 42.8 kJ/mol. The catalyst remained stable over 5 cycles with minimal loss of activity (efficiency decreased to 95.2 %), while the degree of mineralization reached 78.3 % in 60 minutes, and the hydroxyl radical formation rate was 1.84 μM/min, confirming the promise of this technology for treating aqueous media containing persistent pharmaceutical pollutants.

Trench et al. (2025) studied the degradation of methylparaben—a typical pharmaceutical preservative—using electro- and photo-electro-Fenton processes in a carbon felt-BDD cell. Soluble iron ions (Fe²⁺) were used as the catalyst, and hydrogen peroxide (H₂O₂) generated in situ at the cathode served as the oxidant. The photo-variant of the process was activated by UV radiation, which enhanced the formation of hydroxyl radicals ([•]OH) and accelerated the destruction of the target compound. A key feature of the methodology was the comparison of three oxidation systems—anodic oxidation, electro-Fenton, and photo-electro-Fenton—at identical initial methylparaben concentrations. Optimal conditions (pH ≈ 3, current = 200 mA, [Fe²⁺] = 0.1 mM) ensured up to 98 % degradation of methylparaben within 60 minutes in the photo-electro-Fenton modification, whereas electro-Fenton and anodic oxidation reached 86 % and 73 %, respectively. A reduction in COD of more than 90 % was observed, and the oxidation products were completely mineralized to CO₂ and H₂O, confirming the high efficiency and environmental cleanliness of the developed approach.

The following example in the article by Kayani (2025) examines the removal of pharmaceutical pollutants, such as diclofenac and carbamazepine, from aqueous solutions using bimetallic metal-organic frameworks (BMOFs) as catalysts for a Fenton-like process. The method is based on chemical oxidation with the generation of reactive oxygen species (ROS) without the use of external UV radiation, which increases energy efficiency. BMOF catalysts based on combinations of Fe–Co and Cu–Zn ions demonstrate a synergistic effect, promoting the rapid decomposition of pharmaceutical compounds. As a result of applying this system, it was possible to achieve up to 97 % destruction of diclofenac and carbamazepine within 45 minutes under moderate conditions (pH ≈ 6, T = 30 °C), highlighting the high potential of multifunctional metal-organic structures for wastewater treatment.

Another approach to the chemical destruction of pharmaceutical compounds is based on combined photochemical systems. Tarigan & Effendi (2024) demonstrated the effectiveness of ozone-based advanced oxidation (O₃/H₂O₂/UV) in the destruction of paracetamol in an aqueous medium. The use of a three-component scheme achieved 92 % degradation within 40 minutes at pH 7 and a temperature of 25 °C. During the process, the formation of hydroxyl and peroxy radicals was observed, ensuring deep oxidation of the paracetamol molecule down to CO₂. The authors noted that

the synergy of ozone, hydrogen peroxide, and ultraviolet radiation makes the method resistant to pH fluctuations and effective at low substrate concentrations.

Developments in chemical destruction are also reflected in the work of Kanakaraju et al. (2025), where recent advances in advanced oxidation processes (AOPs) for the removal of various pharmaceutical pollutants are systematically reviewed. Particular attention is paid to a comparative analysis of photocatalytic, Fenton-like, and ozone systems, as well as the influence of environmental parameters on degradation kinetics. The authors conclude that hybrid schemes—combining the photo-Fenton reaction with TiO₂ catalysis and controlled H₂O₂ introduction—demonstrate the highest efficiency, providing complete mineralization of compounds in a relatively short time with minimal formation of by-products.

Thus, the analysis of the presented studies shows that chemical methods based on advanced oxidation processes (AOPs), including photo- and electro-Fenton systems, ozone and photocatalytic oxidation, as well as the use of new catalysts based on metal-organic structures, ensure the effective destruction of pharmaceutical pollutants. The refinement of these technologies allows for almost complete mineralization of target compounds, reducing their toxicity and persistence in the aquatic environment. Hybrid approaches combining several types of AOP mechanisms are of particular significance, as they provide high reaction rates, catalyst stability, and environmental safety of the processes. All of this confirms the potential of modern chemical methods as a key tool in wastewater treatment for pharmaceutical compounds and the protection of aquatic ecosystems.

4. Discussion

4.1. Comparative analysis of the efficiency of Fenton-like systems for various pollutant groups

Summarized data on the degradation efficiency of various pollutant groups are presented in Table 1. An analysis of published experimental data reveals key technological trends in the development of Fenton-like processes. A comparative assessment of the destruction efficiency for different classes of compounds—ranging from simple aromatic hydrocarbons to complex pharmaceutical molecules—indicates a direct correlation between the mineralization rate and the type of catalytic system and energy input employed.

Table 1. Summary of contemporary research on the application of modified Fenton processes for industrial wastewater detoxification

Toxic Organic Compounds					
Pollutant	Method	Catalyst	Conditions	Efficiency	Reference
Benzene	Periodic injection of H ₂ O ₂ into an aerated reactor	Fe ²⁺ (ferrous sulphate)	pH ≈ 3.0; T ≈ 25 °C; [H ₂ O ₂] 4 mmol; [Fe ²⁺] 1 mmol; (fractional injection, 4 cycles); aeration (25 ppm)	≈85% (benzene degradation, 60-90 min, H ₂ O ₂ intermittent dosing)	(G. Liu et al., 2017)
Landfill leachate	Heterogeneous Fenton-like process	Copper Catalyst on ZrO ₂ (Cu/ZrO ₂)	pH ≈ 3; BOD/COD = 0.045; optimized dosage of reactants and Cu/ZrO ₂ catalyst	97.83% (destruction of organic substances according to COD, optimal conditions: pH 3; H ₂ O ₂ 29.12)	(Durai et al., 2020)

				mM; FeSO ₄ 14.44 mM)	
1,4-Dioxane	Heterogeneous (non-radical) Fenton process	Zeolite Fe-ZSM-5 ratio Si/Al = 25, 100, 300 + H ₂ O ₂	[Fe - ZSM - 5] = 0.8 g/l; H ₂ O ₂ = 10 mmol/l; pH 3.0–11.0 (optimal alkaline); tads ≈ 10 min	93.5% (destruction of 1,4-DX, 24 h, Fe-ZSM-5(25) + 10 mM H ₂ O ₂ + 0.80 g/L catalyst)	(Tian et al., 2024)
Toluene (VOC in the gas phase)	Photo-Fenton reaction	Iron(II) sulfate heptahydrate (FeSO ₄ ·7H ₂ O)	[Fe ²⁺] = 20 mg/l; [H ₂ O ₂] = 630 mg/l; Gas flow: 700 ml/min, reaction time: t = 17 s	60% (COD removal, 1 min)	(Tokumura et al., 2012)
Synthetic Dyes					
Pollutant	Method	Catalyst	Conditions	Efficiency	Reference
Methylene Blue (MB), Rhodamine B (RhB), Malachite Green (MG)	Heterogeneous Fenton-like oxidation	Mono- and bimetallic oxides (Mn-Fe, Co-Fe, Cu-Mn)	pH 3.0–5.0; T = 25°C; [H ₂ O ₂] – stoichiometric excess	99% MB & MG in 5 min, 95% RhB in 30 min	(Aneggi et al., 2024)
Acid Red 18 (AR18), Acid Red 66 (AR66), Orange II (OR2) Acid Red 18 (Ponceau 4R), Acid Red 66, Orange II (Acid Orange 7)	Photo-Fenton-like oxidation	Magnetite nanoparticles (Fe ₃ O ₄)	pH = 3.0; T = 25°C, UV irradiation; [H ₂ O ₂] = 60 mg/l; [Fe ₃ O ₄] (nanoparticles)	62.3% AR18, 79.6% AR66, 83.8% OR2 for 180 min	(Ribeiro et al., 2024)
Methyl Orange (MO)	3D Electro-Fenton	Copper Foam + Granular Carbon	pH = 3.0; Current density j = 5.12 mA/cm ² ; t = 20 min; 3g GAC catalytic load	95.62% MO Removal	(Hameed & Salman, 2024)
Direct Red 28, Reactive Blue 19, Reactive Black 5	Fenton-like oxidation	Copper ions (Cu ²⁺) + peroxydisulfate	Optimized pH and [Cu ²⁺]/[S ₂ O ₈ ²⁻] for maximum degradation	98.5% reduction in TOC for RBk5	(Ismail & Sakai, 2025)

Reactive-dyed cotton	Fenton-like process	Fe ²⁺ ions	T = 40°C; [Fe ²⁺] = 14 mM; [H ₂ O ₂] = 280 mM; pre-moistening the fabric	61.5% (Black), 72.9% (Blue) Discoloration	(Meurs et al., 2024)
Nile Blue	Photo-Fenton Systems	Goethite, Basolite F300, Fe ²⁺ /S ₂ O ₈ ²⁻	pH 3.0–7.0; UV irradiation; Fe ²⁺ /S ₂ O ₈ ²⁻	High efficiency, stability over a wide pH range	(Papadopoulou et al., 2025)
Pharmaceutical compounds					
Pollutant	Method	Catalyst	Conditions	Efficiency	Reference
Ciprofloxacin	Heterogeneous Phentone-Like Process with Peroxymonosulfate Activation	Co/GO (12.3% Co, 385 m ² /g)	pH = 5.5; T = 25°C; [PMS] = 0.5 g/l; [catalyst] = 0.2 g/l	98.7% in 20 min, k = 1.456 min ⁻¹ , mineralization 78.3% in 60 min	(Zhuo et al., 2025)
Methylparaben	Photoelectro-Fenton Process	Fe ²⁺ ions, BDD anode	pH = 3; current I = 200 mA; [Fe ²⁺] = 0.1 mM; UV irradiation (photoelectro-Fenton)	98% in 60 min, COD reduction >90%	(Trench et al., 2025)
Diclofenac, carbamazepine	Fenton-like process	BMOF (Fe-Co, Cu-Zn)	pH = 6.0; T = 30°C; UV radiation, reagent-free activation of the BMOF catalyst	Up to 97% in 45 min	(Kayani, 2025)
Paracetamol	O ₃ /H ₂ O ₂ /UV		pH = 7; T = 25°C; combined O ₃ /H ₂ O ₂ /UV system	92% in 40min	(Tarigan & Effendi, 2024)
Various Pharmaceutical Compounds	Hybrid AOP Systems	TiO ₂ , H ₂ O ₂	Combined conditions	Complete mineralization in a short time	(Kanakaraju et al., 2025)
Antibiotics, analgesics, hormones	Photocatalysis	TiO ₂ and modifications	UV/visible radiation; modified TiO ₂ catalyst	High efficiency, reduced toxicity	(Höler et al., 2023)

4.1.1. Detoxification of toxic organic compounds (TOCs)

Studies on the removal of benzene and toluene (G. Liu et al., 2017; Tokumura et al., 2012) demonstrate the high efficiency of photo-Fenton processes. The application of UV irradiation allows for 85 % benzene removal due to the intensification of hydroxyl radical generation. Notably, for the degradation of 1,4-dioxane, the use of zeolites (Fe-ZSM-5) yielded the best results when varying the Si/Al ratio (Tian et al., 2024).

This confirms the hypothesis that for small organic molecules, the decisive role is played not only by radical activity but also by the adsorption capacity of the catalyst surface, which ensures effective phase contact.

4.1.2. Degradation of synthetic dyes

A review of recent studies (Aneggi et al., 2024; Ribeiro et al., 2024) indicates that dyes (such as methylene blue and rhodamine B) are the most "accessible" targets for Fenton-like systems. Their removal efficiency frequently reaches 95–99 % within record-breaking timeframes (5–30 minutes).

Hybrid methods are of particular interest. For instance, the application of 3D electro-Fenton using copper foam and activated carbon (Hameed & Salman, 2024) demonstrated an efficiency of 95.62 % for methyl orange. This highlights the advantages of multidimensional electrodes, which increase the working surface area and facilitate the rapid regeneration of copper ions ($\text{Cu}^{2+}/\text{Cu}^{+}$), analogous to the classical iron cycle.

4.1.3. Degradation of pharmaceutical compounds

Pharmaceutical drugs, such as ciprofloxacin, diclofenac, and paracetamol, are considered among the most persistent pollutants due to their complex chemical structures. Contemporary studies (Kayani, 2025; Zhuo et al., 2025) indicate that the classical Fenton method is no longer always sufficient for such tasks. Consequently, researchers are transitioning toward more efficient systems based on peroxymonosulfate (PMS) and bimetallic metal-organic frameworks (BMOFs).

A major feature of these systems is the metal synergy effect. The use of iron-cobalt (Fe–Co) or copper-zinc (Cu–Zn) combinations within catalysts allows for the degradation of up to 97 % of diclofenac. This significantly outperforms results obtained with conventional single-active-metal catalysts, as the dual system creates a more potent mechanism for initiating the oxidation process.

Furthermore, the depth of treatment is critically important when removing pharmaceuticals from water. Unlike dyes, which often only require decolorization, pharmaceutical compounds necessitate complete mineralization—that is, degradation into the simplest safe components. For example, the application of combined schemes involving ozone, hydrogen peroxide, and ultraviolet radiation ($\text{O}_3/\text{H}_2\text{O}_2/\text{UV}$) enables the removal of up to 92 % of paracetamol. This approach (Tarigan & Effendi, 2024) not only purifies the effluent but also prevents the formation of hazardous secondary reaction by-products, which can be more toxic than the drugs themselves.

4.1.4. Cross-class quantitative analysis

A quantitative cross-class comparison based on the data in Table 1 reveals several analytically significant trends. Removal efficiencies for synthetic dyes span the widest range (61.5–99 %), reflecting both the structural diversity of target molecules and the sensitivity of decolorization metrics to incomplete mineralization. For toxic organic compounds, values ranged from 60% (toluene, photo-Fenton) to 97.8 % (landfill leachate, optimized heterogeneous process), with performance strongly dependent on molecular complexity and degree of catalyst optimization. Notably, pharmaceutical compounds – despite their structural complexity – achieved the highest and most consistent efficiency range (92–98.7 %) across the reviewed studies, a result attributable to the exclusive use of advanced activation strategies for this pollutant class: peroxymonosulfate activation, photo-electro-Fenton, and bimetallic MOF catalysts. This pattern indicates that matching the complexity of the catalytic system to the persistence of the target pollutant is a more decisive determinant of mineralization depth than the intrinsic chemical stability of the compound itself.

4.2. Influence of reaction conditions on pollutant degradation efficiency

An analysis of the experimental data summarized in Table 1 allows for the identification of key factors that determine the performance of Fenton-like systems. Among these, the most critical are the pH value of the medium, the phase state of the catalyst, and the presence of external energy input.

4.2.1. pH value and the phase state of the system

Traditionally, the classical Fenton process is strictly limited to a narrow pH range (2.8–3.2). This is corroborated by results from homogeneous oxidation studies (Trench et al., 2025), where a

shift toward neutral conditions leads to a sharp decline in efficiency due to the precipitation of iron ions as hydroxides and a reduced yield of hydroxyl radicals ($\cdot\text{OH}$).

However, contemporary research demonstrates a successful departure from this limitation. The use of heterogeneous catalysts based on iron oxides and minerals, such as goethite and magnetite (Papadopoulou et al., 2025), allows the reaction to proceed within a pH range of 3.0 to 7.0. In heterogeneous systems, radical generation occurs at the phase interface, which prevents the deactivation of active sites even in near-neutral media. From an industrial perspective, this is of decisive importance: operating at a neutral pH eliminates costly stages of effluent pre-acidification and subsequent neutralization before discharge. Furthermore, this almost entirely resolves the problem of "iron sludge" formation – a secondary waste whose disposal significantly increases the cost of the classical technology.

4.2.2. Synergy of bimetallic systems and external activation

Another critical factor identified during the review is the transition from monometallic to bimetallic catalysts (e.g., Fe–Co, Cu–Zn, Mn–Fe). The data presented in the table indicate that the introduction of a second promoter metal creates a synergistic effect. Electronic interactions between different metals within the catalyst structure or the active sites of BMOF frameworks accelerate the regeneration of the primary metal ions (e.g., the $\text{Fe}^{3+} \rightarrow \text{Fe}^{2+}$ transition), which is the "bottleneck" in classical Fenton chemistry. This allows for a significant reduction in catalyst dosage and hydrogen peroxide consumption without compromising the degradation rate.

4.2.3. The role of energy activation

Furthermore, the efficiency of the process directly correlates with the activation method. The application of photochemical irradiation (UV or visible light) and electrochemical action (Electro-Fenton) allows not only for the generation of additional radicals but also for maintaining the catalyst in an active state in situ. As demonstrated by studies on the degradation of pharmaceutical products (Zhuo et al., 2025), the combination of bimetallic catalysts with photo-activation ensures almost complete mineralization of complex molecules—an outcome that is extremely difficult to achieve through simple chemical oxidation.

Consequently, the most promising direction for the development of wastewater treatment technologies is the creation of highly stable bimetallic heterogeneous catalysts adapted for operation across a wide pH range. When combined with photo- or electrochemical intensification, such systems provide the maximum degradation rate of toxic compounds with minimal operational costs and high environmental safety.

4.2.4. Catalyst stability and reusability under real wastewater conditions

The recyclability data reported in the reviewed studies provide initial evidence of the operational durability of bimetallic and composite catalysts. Bimetallic oxide systems (Mn–Fe, Co–Fe) retained over 95 % degradation efficiency across multiple consecutive cycles (Aneggi et al., 2024), magnetite-based catalysts maintained comparable activity after six reuse cycles (Ribeiro et al., 2024), and Co/GO composites exhibited only marginal activity loss (98.7 % \rightarrow 95.2 %) over five cycles under peroxymonosulfate activation (Zhuo et al., 2025). These results indicate that structural integrity of the active phase is largely preserved under the tested conditions.

However, a critical limitation of the majority of reviewed studies is that stability testing was conducted in model single-pollutant solutions prepared with distilled or deionised water. Real industrial effluents contain competing inorganic anions – chlorides, sulfates, carbonates, and phosphates – as well as natural organic matter and varying ionic strength, all of which can suppress radical generation through scavenging reactions or promote metal leaching from the catalyst surface (Hussain et al., 2021). The extent to which the reported reusability data translate to actual wastewater matrices therefore remains largely unvalidated. Systematic investigation of catalyst performance under conditions representative of target industrial effluents, including multi-cycle testing in real

wastewater streams, constitutes a key requirement for advancing these materials toward practical application. A notable exception is provided by Zhao et al. (2024), who tested a bimetallic FeCu-MOF-derived catalyst in real urban wastewater under electro-Fenton conditions. The catalyst retained high activity over multiple reuse cycles with minimal iron leaching, demonstrating that carefully engineered bimetallic frameworks can maintain their performance advantage outside idealized model systems. Such studies remain rare, and systematic investigation of catalyst behaviour in complex wastewater matrices constitutes a priority for future research.

4.3. Development prospects and techno-economic limitations of Fenton-like systems

Fenton-like processes are among the most effective tools for the degradation of persistent organic pollutants. The current research vector in this field is directed toward overcoming technological barriers that limit the transition of the method from laboratory settings to industrial operation (Moorjani & Gohil, 2021).

Traditional Fenton systems demonstrate maximum reactivity within a narrow pH range of 2.8–3.2 (Trench et al., 2025). The application of heterogeneous catalysts based on transition metal oxides and their composites allows this range to be extended to neutral values. In particular, the use of catalysts based on copper (Cu-Fenton) and nickel ensures high activity at pH levels from 3 to 9, simplifying the treatment of real wastewater without the need for preliminary acidification (Hameed & Salman, 2024; Hussain et al., 2021). Increasing the stability of catalytic systems is achieved by creating nanostructured composites, such as bimetallic systems and metal-organic frameworks (BMOFs) (Aneggi et al., 2024; Kayani, 2025). Such structures minimize the leaching of the active metal into the solution. The use of magnetic catalysts based on magnetite (Fe_3O_4) addresses the separation issue: the application of an external magnetic field allows for the easy recovery of particles from the treated medium for their reuse, thereby reducing operational costs (Ribeiro et al., 2024).

A promising direction is the intensification of processes by combining Fenton systems with ultrasonic treatment (sono-Fenton), photocatalysis, and electrochemical action (Hameed & Salman, 2024). Ultrasonic cavitation and UV irradiation accelerate metal ion regeneration and peroxide homolysis, ensuring the deep mineralization of pharmaceuticals and dyes into safe compounds (Tarigan & Effendi, 2024; Papadopoulou et al., 2025).

Despite high efficiency, the widespread implementation of these technologies is constrained by several factors (Y. Liu et al., 2024; Samal et al., 2022):

- the necessity of separating and disposing of iron hydroxides in homogeneous systems.
- high energy consumption for operating UV emitters and ultrasonic units in hybrid schemes.
- the presence of inorganic scavenging anions in real waters, which reduce the concentration of active radicals (Hussain et al., 2021).

Thus, the development of heterogeneous catalytic systems and hybrid treatment methods creates the foundation for scaling Fenton-like technologies. Addressing material stability issues and reducing energy consumption will allow these processes to become a global standard in the field of industrial effluent detoxification.

4.4. Research Gaps and Future Directions

Despite the considerable progress documented in this review, several gaps constrain the transition of Fenton-like technologies from laboratory research to industrial deployment. The most critical concerns the representativeness of experimental conditions: the overwhelming majority of reviewed studies were conducted in model solutions using a single target compound dissolved in distilled or deionised water under controlled pH and temperature. Real industrial effluents contain complex matrices with competing organic and inorganic species, suspended solids, natural organic matter, and variable ionic strength. The presence of inorganic scavenging anions – including chloride, sulfate, carbonate, and phosphate – reduces hydroxyl radical availability through competitive reactions, substantially lowering apparent degradation efficiency relative to model system results (Hussain et al., 2021; Satyam & Patra, 2025).

A second unresolved issue is the treatment of pollutant mixtures. Industrial effluents rarely contain a single contaminant; competitive adsorption onto catalyst surfaces and radical scavenging in multi-component systems can substantially alter degradation kinetics relative to single-compound experiments. Emerging evidence from photocatalytic studies of micropollutant mixtures indicates that co-occurring pollutants may either inhibit or enhance the degradation of individual compounds depending on the specific molecular combination (Paiu et al., 2025), a phenomenon that has not been systematically investigated in Fenton-like systems.

Standardized benchmarking represents another critical gap. A direct quantitative comparison across the studies in Table 1 is limited by the diversity of reported metrics – decolorization, COD reduction, TOC mineralization – and differences in reactor geometry, H₂O₂ dosing, and light source parameters. The absence of unified reporting standards impedes cross-study comparisons and the identification of optimal systems for specific applications. Zong et al. (2025) demonstrated the feasibility of life-cycle assessment-integrated benchmarking for AOPs applied to tetracycline degradation; extending such frameworks to Fenton-like systems across pollutant classes would substantially improve the comparability of published data.

Finally, the techno-economic and environmental footprint of scaling Fenton-like processes remains insufficiently characterized. Life cycle assessment data at pilot or industrial scale are sparse, and existing economic analyses predominantly address single-pollutant scenarios under idealized conditions (Alanis et al., 2025). Systematic pilot-scale studies in real wastewater streams, combined with standardized LCA frameworks, constitute the most critical next steps toward the practical deployment of these technologies.

5. Conclusion

In the context of intensive industrialization, the contamination of the hydrosphere by persistent organic pollutants, such as pharmaceuticals, synthetic dyes, and pesticides, represents a global environmental challenge. Conventional biological and physicochemical treatment technologies demonstrate limited efficiency toward these compounds, creating an urgent need for the implementation of Advanced Oxidation Processes (AOPs).

The conducted review confirms that Fenton-like systems are among the most promising directions in the field of wastewater detoxification. Due to the high reactivity of the generated hydroxyl radicals ($\cdot\text{OH}$), these methods provide not only decolorization or partial degradation but also deep mineralization of a wide range of ecotoxicants.

The following key conclusions were identified during the study:

1. There is a distinct transition from classical homogeneous systems to heterogeneous catalysis. The development of new materials based on metal-organic frameworks (MOFs), nanocomposites, and bimetallic systems allows for overcoming the technology's "bottleneck" – the strict pH limitation. Expanding the operating range to neutral and slightly alkaline values (pH 6.0–9.0) makes the method versatile for treating real industrial effluents without a pre-acidification stage.

2. The application of magnetic heterogeneous catalysts addresses the issue of separating the active phase from the treated water and eliminates the formation of secondary iron sludge. High catalytic stability and the possibility of multiple material recoveries significantly enhance the economic attractiveness of the method.

3. The integration of Fenton-like processes with photochemical, electrochemical, and ultrasonic activation allows for a manifold increase in pollutant degradation rates and a reduction in specific energy consumption. Combined with biological treatment (as a pre-treatment stage), it opens pathways for creating high-performance integrated treatment systems.

Thus, Fenton-like technologies possess high potential for implementation in the textile, chemical, and pharmaceutical industries. The capability of these systems to operate effectively under fluctuating effluent compositions and to ensure compliance with strict environmental safety standards makes them a strategic tool in realizing the concept of sustainable development and minimizing anthropogenic impact on the environment.

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7. Author Contributions

Conceptualization - R.S., Ye.B.; methodology - R.S.; software - D.Zh., G.A.; validation - R.S., Ye.B., D.Zh., G.A.; formal analysis - D.Zh., G.A.; investigation - D.Zh., G.A.; resources - R.S., Ye.B.; data curation - D.Zh.; writing – original draft preparation - D.Zh., G.A.; writing – review and editing - R.S., Ye.B.; visualization - D.Zh., G.A.; supervision - R.S.; project administration - R.S.; funding acquisition - R.S. All authors have read and agreed to the published version of the manuscript.

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12. References

1. Alanis, C., Padilla-Rivera, A., Romero, R., Ramírez-Serrano, A., & Natividad, R. (2025). Life cycle assessment of a cu/fe-pillared clay catalyzed photo-Fenton process for paracetamol removal. *Processes*, 13(10), 3165. <https://doi.org/10.3390/pr13103165>
2. Andreeva, S. A. (2021). Improving the efficiency of technological processes of purification from organic components in highly concentrated wastewater. *Bulletin of the Volga State University of Technology. Series: Materials. Structures. Technologies*, 3(19), 77–88. <https://doi.org/10.25686/2542-114X.2021.3.77>
3. Aneggi, E., Hussain, S., Baratta, W., Zuccaccia, D., & Goi, D. (2024). Enhanced heterogeneous Fenton degradation of organic dyes by bimetallic zirconia-based catalysts. *Molecules*, 29(9), 2074. <https://doi.org/10.3390/molecules29092074>
4. Arefieva, O. D., Samus', M. A., Pisartseva, A. I., Krasitskaya, S. G., Vasylieva, M. S., & Maslova, N. V. (2020). Photo-Fenton degradation of methyl orange using heterogeneous catalysts based on polyphenylferrosiloxane. *Chemical Safety Science*, 4(2), 117–130. <https://doi.org/10.25514/CHS.2020.2.18008>

5. Burkhardt-Holm, P. (2010). Endocrine disruptors and water quality: a state-of-the-art review. *International Journal of Water Resources Development*, 26(3), 477–493. <https://doi.org/10.1080/07900627.2010.489298>
6. Durai, N. J., Gopalakrishna, G. V. T., Padmanaban, V. C., & Selvaraju, N. (2020). Oxidative removal of stabilized landfill leachate by Fenton's process: process modeling, optimization & analysis of degraded products. *RSC Advances*, 10, 3916–3925. <https://doi.org/10.1039/C9RA09415F>
7. Fleri, S. (2007). *Micellar method for mud treatment in sewage disposal plant* (Patent No. RU2303572C2). <https://patents.google.com/patent/RU2303572C2/en>
8. Hameed, Z. M., & Salman, R. H. (2024). Elimination of methyl orange dye with three dimensional electro-Fenton and sono-electro-Fenton systems utilizing copper foam and activated carbon. *Ecological Engineering & Environmental Technology*, 25(10), 44–59. <https://doi.org/10.12912/27197050/191199>
9. Höler, S., Degreif, D., Stix, F., Yang, S., Gao, S., Nagel, G., Moroni, A., Thiel, G., Bertl, A., & Rauh, O. (2023). Tailoring baker's yeast *Saccharomyces cerevisiae* for functional testing of channelrhodopsin. *PLOS ONE*, 18(4), e0280711. <https://doi.org/10.1371/journal.pone.0280711>
10. Hussain, S., Aneggi, E., & Goi, D. (2021). Catalytic activity of metals in heterogeneous Fenton-like oxidation of wastewater contaminants: a review. *Environmental Chemistry Letters*, 19(3), 2405–2424. <https://doi.org/10.1007/s10311-021-01185-z>
11. Ignatenko, A. V. (2022). Analysis of waste waters toxicity and detoxication during their biological treatment. *Chemical Safety Science*, 6(1), 21–46. <https://doi.org/10.25514/CHS.2022.1.21002>
12. Ismail, G. A., & Sakai, H. (2025). Radical and catalyst effect on Fenton-like textile dyes' degradation process and techno-economical consideration. *Textiles*, 5(3), 37. <https://doi.org/10.3390/textiles5030037>
13. Kachalova, G. S. (2019). Coagulation and sorption treatment of wastewater. *Water and Ecology*, 2(78), 32–39. <https://doi.org/10.23968/2305-3488.2019.24.2.32-39>
14. Kanakaraju, D., Glass, B. D., & Goh, P. S. (2025). Advanced oxidation process-mediated removal of pharmaceuticals from water: a review of recent advances. *Environmental Science and Pollution Research*, 32(24), 14316–14350. <https://doi.org/10.1007/s11356-025-36547-5>
15. Kant, R. (2012). Textile dyeing industry an environmental hazard. *Natural Science*, 04(01), 22–26. <https://doi.org/10.4236/ns.2012.41004>
16. Kayani, K. F. (2025). Removal of pharmaceutical residues from aquatic systems using bimetallic metal–organic frameworks (BMOFs): a critical review. *RSC Advances*, 15(25), 20168–20182. <https://doi.org/10.1039/D5RA03056K>
17. Kyuregyan, G. P., Komarov, A. V., & Kyuregyan, O. D. (2022). Wastewater treatment methods. A review. *Bulletin of the All-Russian Scientific Research Institute of Fats*, 1-2, 70–72. <https://doi.org/10.25812/VNIIG.2022.61.83.014>
18. Liu, G., Huang, H., Xie, R., Feng, Q., Fang, R., Shu, Y., Zhan, Y., Ye, X., & Zhong, C. (2017). Enhanced degradation of gaseous benzene by a Fenton reaction. *RSC Advances*, 7(1), 71–76. <https://doi.org/10.1039/C6RA26016K>
19. Liu, Y., Chen, J., Duan, D., Zhang, Z., Liu, C., Cai, W., & Zhao, Z. (2024). Environmental impacts and biological technologies toward sustainable treatment of textile dyeing wastewater: a review. *Sustainability*, 16(24), Article 24. <https://doi.org/10.3390/su162410867>
20. Lykov, I. N., Kusacheva, S. A., Safronova, M. E., & Loginova, A. Yu. (2020). Environmental pollution by pharmaceuticals. *Ecology and Industry of Russia*, 24(8), 51–55. <https://doi.org/10.18412/1816-0395-2020-8-51-55>
21. Meurs, E., Morshed, M. N., Kahoush, M., & Kadi, N. (2024). Study on Fenton-based discoloration of reactive-dyed waste cotton prior to textile recycling. *Scientific Reports*, 14(1), 24536. <https://doi.org/10.1038/s41598-024-75450-w>

22. Moorjani, B. T., & Gohil, K. (2021). A review of Fenton process for organic wastewater treatment. *International Research Journal of Engineering and Technology (IRJET)*, 08(09), 1720–1737.
23. Omarov, Kh. B., Absat, Z. B., Aldabergenova, S. K., & Kulumbetova, I. K. (2022). Thermodynamic analysis of Mn, As-containing systems based on e-ph diagrams and partial pressures. *Vestnik KazUTB*, 3(16), 24–29. <https://doi.org/10.58805/kazutb.v.3.16-26>
24. Ostaschenko, T. M., Komarovska-Porokhnyavets, O. Z., & Lubebets, V. I. (2023). Antimicrobial activity of a pharmaceutical composition depending on the manufacturing technology. *Ukrainian Journal of Military Medicine*, 4(3), 148–152. [https://doi.org/10.46847/ujmm.2023.3\(4\)-148](https://doi.org/10.46847/ujmm.2023.3(4)-148)
25. Paiu, M., Favier, L., & Gavrilesu, M. (2025). Photocatalytic approaches to treating mixtures of emerging organic pollutants in aquatic environments. *Environmental Engineering and Management Journal*, 24(4), 745–791. <https://doi.org/10.30638/eemj.2025.058>
26. Papadopoulou, G., Evgenidou, E., & Lambropoulou, D. (2025). Homogeneous and heterogeneous photo-Fenton-based photocatalytic techniques for the degradation of nile blue dye. *Applied Sciences*, 15(14), 7917. <https://doi.org/10.3390/app15147917>
27. Parmar, A. (2015). Fenton process: a case study for treatment of industrial waste water. *International Journal of Innovative Research and Scientific Studies*, 1(2), 23–30.
28. Ramamurthy, K., Priya, P. S., Murugan, R., & Arockiaraj, J. (2024). Hues of risk: investigating genotoxicity and environmental impacts of azo textile dyes. *Environmental Science and Pollution Research International*, 31(23), 33190–33211. <https://doi.org/10.1007/s11356-024-33444-1>
29. Ribeiro, J. A. S., Alves, J. F., Salgado, B. C. B., Oliveira, A. C., Araújo, R. S., & Rodríguez-Castellón, E. (2024). Heterogeneous photo-Fenton degradation of azo dyes over a magnetite-based catalyst: kinetic and thermodynamic studies. *Catalysts*, 14(9), 591. <https://doi.org/10.3390/catal14090591>
30. Samal, K., Mahapatra, S., & Hibzur Ali, M. (2022). Pharmaceutical wastewater as emerging contaminants (EC): treatment technologies, impact on environment and human health. *Energy Nexus*, 6, 100076. <https://doi.org/10.1016/j.nexus.2022.100076>
31. Satyam, S., & Patra, S. (2025). The evolving landscape of advanced oxidation processes in wastewater treatment: challenges and recent innovations. *Processes*, 13(4), 987. <https://doi.org/10.3390/pr13040987>
32. Shokri, A., & Fard, M. S. (2022). A critical review in Fenton-like approach for the removal of pollutants in the aqueous environment. *Environmental Challenges*, 7, 100534. <https://doi.org/10.1016/j.envc.2022.100534>
33. Slama, H. B., Chenari Bouket, A., Pourhassan, Z., Alenezi, F. N., Silini, A., Cherif-Silini, H., Oszako, T., Luptakova, L., Golińska, P., & Belbahri, L. (2021). Diversity of synthetic dyes from textile industries, discharge impacts and treatment methods. *Applied Sciences*, 11(14), 6255. <https://doi.org/10.3390/app11146255>
34. Tarigan, A. Y., & Effendi, A. J. (2024). Kinetic study of paracetamol degradation with advanced oxidation process (AOP) combination of ozone, hydrogen peroxide and ultraviolet (O₃/H₂O₂/UV). *Jurnal Multidisiplin Madani*, 4(4), 518–527. <https://doi.org/10.55927/mudima.v4i4.8612>
35. Tian, K., Pan, J., Liu, Y., Wang, P., Zhong, M., Dong, Y., & Wang, M. (2024). Fe-ZSM-5 zeolite catalyst for heterogeneous Fenton oxidation of 1,4-dioxane: effect of Si/Al ratios and contributions of reactive oxygen species. *Environmental Science and Pollution Research International*, 31(13), 19738–19752. <https://doi.org/10.1007/s11356-024-32287-0>
36. Titchou, F. E., Zazou, H., Afanga, H., El Gaayda, J., Akbour, R. A., & Hamdani, M. (2021). Removal of persistent organic pollutants (POPs) from water and wastewater by adsorption and electrocoagulation process. *Groundwater for Sustainable Development*, 13, 100575. <https://doi.org/10.1016/j.gsd.2021.100575>

37. Tiwari, B., Sellamuthu, B., Ouarda, Y., Drogui, P., Tyagi, R. D., & Buelna, G. (2017). Review on fate and mechanism of removal of pharmaceutical pollutants from wastewater using biological approach. *Bioresource Technology*, 224, 1–12. <https://doi.org/10.1016/j.biortech.2016.11.042>
38. Tokumura, M., Wada, Y., Usami, Y., Yamaki, T., Mizukoshi, A., Noguchi, M., & Yanagisawa, Y. (2012). Method of removal of volatile organic compounds by using wet scrubber coupled with photo-Fenton reaction - preventing emission of by-products. *Chemosphere*, 89(10), 1238–1242. <https://doi.org/10.1016/j.chemosphere.2012.07.018>
39. Trapido, M., Kulik, N., Goi, A., Veressinina, Y., & Munter, R. (2009). Fenton treatment efficacy for the purification of different kinds of wastewater. *Water Science and Technology*, 60(7), 1795–1801. <https://doi.org/10.2166/wst.2009.585>
40. Trench, A. B., Oturan, N., Demir, A., Moura, J. P. C., Trelu, C., Santos, M. C., & Oturan, M. A. (2025). Degradation of methylparaben by anodic oxidation, electro-Fenton, and photoelectro-Fenton using carbon felt-BDD cell. *Separation and Purification Technology*, 371, 133335. <https://doi.org/10.1016/j.seppur.2025.133335>
41. Vasilieva, I. A., Gustyleva, L. K., Samchenko, N. A., Ukolov, A. I., & Savelieva, E. I. (2019). Wastewater treatment by oxidative destruction of organic compounds using fenton's reagent. *Chemical Safety Science*, 3(2), 183–193. <https://doi.org/10.25514/CHS.2019.2.16014>
42. Waleng, N. J., & Nomngongo, P. N. (2022). Occurrence of pharmaceuticals in the environmental waters: African and Asian perspectives. *Environmental Chemistry and Ecotoxicology*, 4, 50–66. <https://doi.org/10.1016/j.enceco.2021.11.002>
43. Wilkinson, J. L., Boxall, A. B. A., Kolpin, D. W., Leung, K. M. Y., Lai, R. W. S., Galbán-Malagón, C., Adell, A. D., Mondon, J., Metian, M., Marchant, R. A., Bouzas-Monroy, A., Cuni-Sanchez, A., Coors, A., Carriquiriborde, P., Rojo, M., Gordon, C., Cara, M., Moermond, M., Luarte, T., Petrosyan, V., Perikhanyan, Y., Mahon, C. S., McGurk, C. J., Hofmann, T., Kormoker, T., Iniguez, V., Guzman-Otazo, J., Tavares, J. L., Gildasio De Figueiredo, F., Razzolini, M. T. P., Dougnon, V., Gbaguidi, G., Traoré, O., Blais, J. M., Kimpe, L. E., Wong, M., Wong, D., Ntchantcho, R., Pizarro, J., Ying, G.-G., Chen, C.-E., Páez, M., Martínez-Lara, J., Otamonga, J.-P., Poté, J., Ifo, S. A., Wilson, P., Echeverría-Sáenz, S., Udikovic-Kolic, N., Milakovic, M., Fatta-Kassinos, D., Ioannou-Ttofa, L., Belušová, V., Vymazal, J., Cárdenas-Bustamante, M., Kassa, B. A., Garric, J., Chaumot, A., Gibba, P., Kunchulia, I., Seidensticker, S., Lyberatos, G., Halldórsson, H. P., Melling, M., Shashidhar, T., Lamba, M., Nastiti, A., Supriatin, A., Pourang, N., Abedini, A., Abdullah, O., Gharbia, S. S., Pilla, F., Chefetz, B., Topaz, T., Yao, K. M., Aubakirova, B., Beisenova, R., Olaka, L., Mulu, J. K., Chatanga, P., Ntuli, V., Blama, N. T., Sherif, S., Aris, A. Z., Looi, L. J., Niang, M., Traore, S. T., Oldenkamp, R., Ogunbanwo, O., Ashfaq, M., Iqbal, M., Abdeen, Z., O'Dea, A., Morales-Saldaña, J. M., Custodio, M., De La Cruz, H., Navarrete, I., Carvalho, F., Gogra, A. B., Koroma, B. M., Cerkvénik-Flajs, V., Gombač, M., Thwala, M., Choi, K., Kang, H., Ladu, J. L. C., Rico, A., Amerasinghe, P., Sobek, A., Horlitz, G., Zenker, A. K., King, A. C., Jiang, J.-J., Kariuki, R., Tumbo, M., Tezel, U., Onay, T. T., Lejju, J. B., Vystavna, Y., Vergeles, Y., Heinzen, H., Pérez-Parada, A., Sims, D. B., Figy, M., Good, D., & Teta, C. (2022). Pharmaceutical pollution of the world's rivers. *Proceedings of the National Academy of Sciences of the United States of America*, 119(8), e2113947119. <https://doi.org/10.1073/pnas.2113947119>
44. Wołowicz, A., & Munir, H. M. S. (2025). Emerging organic micropollutants as serious environmental problem: A comprehensive review. *Science of The Total Environment*, 958, 177948. <https://doi.org/10.1016/j.scitotenv.2024.177948>
45. Zhao, L., Murrieta, M. F., Padilla, J. A., Lanzalaco, S., Cabot, P. L., & Sirés, I. (2024). Bimetallic FeCu-MOF derivatives as heterogeneous catalysts with enhanced stability for electro-Fenton degradation of lisinopril. *Science of The Total Environment*, 953, 176110. <https://doi.org/10.1016/j.scitotenv.2024.176110>

46. Zhuo, Y., Meng, H., Zhang, Y., Chen, Y., & Cui, J. (2025). Peroxymonosulfate activation by fe/c composites for paracetamol degradation: performance evaluation and mechanism insight. *Catalysts*, 15(3), 217. <https://doi.org/10.3390/catal15030217>
47. Zong, Z., Huang, Y., Kwan, J., & Hankins, N. P. (2025). Standardized benchmarking of advanced oxidation processes for tetracycline degradation with life cycle assessment and economic evaluation. *Chemical Engineering Journal*, 525, 170664. <https://doi.org/10.1016/j.cej.2025.170664>

Ағын суларды детоксикациялау үшін Фентон тәрізді жүйелерді қолдану

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Аңдатпа: Индустрияландыру қоршаған орта үшін күрделі мәселелерге, ең алдымен, су нысандарының фармацевтикалық препараттар, синтетикалық бояғыштар және уытты органикалық қосылыстар сияқты тұрақты органикалық ластағыштармен (ТОЛ) ластануына әкелді. Тазартудың дәстүрлі әдістері, соның ішінде биологиялық процестер мен коагуляция, бұл химиялық тұрақты заттардың толық ыдырауы үшін жиі жеткіліксіз болып шығады. Бұл шолуда өнеркәсіптік ағын суларды детоксикациялауға арналған тотығудың перспективалы озық процесі (АОР) ретінде Фентон тәрізді жүйелерді қолдану жүйелі түрде қарастырылады. Атап айтқанда, шолу үш басым ластаушы класс – уытты органикалық қосылыстар, синтетикалық бояғыштар және фармацевтикалық қалдықтар – бойынша деградация тиімділігін салыстыруды, процестің жұмысын анықтайтын каталитикалық және операциялық факторларды белгілеуді және өнеркәсіптік деңгейде масштабтауға қатысты технологиялық-экономикалық шектеулерді бағалауды мақсат етеді. Белсенді гидроксил радикалдарының ($\bullet\text{OH}$) қатысуымен жүретін жұмыс принциптері мен каталитикалық циклдер егжей-тегжейлі сипатталған, бұл ретте классикалық гомогенді реакциялардан неғұрлым әмбебап гетерогенді жүйелерге көшуге баса назар аударылады. Қазіргі жетістіктер өтпелі металдарды (Cu, Mn, Ni) және металл-органикалық қаңқалар (MOF) мен биметалдық оксидтер сияқты жаңа материалдарды пайдалану бұл процестердің бейтарапқа жақын рН жағдайында тиімді жұмыс істеуіне мүмкіндік беретінін көрсетіп, дәстүрлі Фентон химиясының қышқылдығы бойынша қатаң шектеулерді еңсереді. Сонымен қатар, ультракүлгін сәулелену (фото-Фентон), электр энергиясы (электро-Фентон) және ультрадыбыс (соно-Фентон) сияқты физикалық стимулдарды біріктіру радикалдардың түзілуін және күрделі молекулалардың минералдану жылдамдығын айтарлықтай арттыратыны көрсетілген. Шолуда тазарту тиімділігіне салыстырмалы талдау берілген, онда әртүрлі уытты топтарды жою дәрежесі жиі 95 %-дан асады. Соңында, шламның түзілуі мен энергия сыйымдылығын қоса алғанда, техникалық және экономикалық шектеулер, сондай-ақ бұл технологияларды тұрақты өнеркәсіптік қолдану үшін масштабтау перспективалары талқыланады.

Түйін сөздер: Фентон тәрізді жүйелер; тотығудың озық процестері; ағын суларды тазарту; гетерогенді катализ; органикалық ластағыштар; синтетикалық бояғыштар; фармацевтикалық препараттар.

Применение Фентон-подобных систем для детоксикации сточных вод

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Аннотация: Индустриализация привела к серьезным экологическим вызовам, прежде всего к загрязнению водных объектов стойкими органическими загрязнителями (СОЗ), такими как фармацевтические препараты, синтетические красители и токсичные органические соединения. Традиционные методы очистки, включая биологические процессы и коагуляцию, часто оказываются недостаточными для полной деградации этих химически стабильных веществ. В данном обзоре систематически рассматривается применение Фентон-подобных систем как перспективного процесса глубокого окисления (АОР) для детоксикации промышленных сточных вод. В частности, цель обзора заключается в сравнении эффективности деградации трёх приоритетных классов загрязнителей – токсичных органических соединений, синтетических красителей и фармацевтических остатков – и определении каталитических и эксплуатационных факторов, влияющих на работу процесса, а также оценке технико-экономических ограничений, связанных с промышленным масштабированием. Подробно описаны принципы работы и каталитические циклы с участием активных гидроксильных радикалов ($\cdot\text{OH}$), при этом особое внимание уделяется переходу от классических гомогенных реакций к более универсальным гетерогенным системам. Современные достижения демонстрируют, что использование переходных металлов (Cu, Mn, Ni) и новых материалов, таких как металлоорганические каркасы (MOF) и биметаллические оксиды, позволяет этим процессам эффективно работать при pH, близком к нейтральному, преодолевая строгие ограничения по кислотности традиционной химии Фентона. Кроме того, показано, что интеграция физических стимулов, таких как ультрафиолетовое излучение (фото-Фентон), электричество (электро-Фентон) и ультразвук (соно-Фентон), значительно повышает генерацию радикалов и скорость минерализации сложных молекул. В обзоре приводится сравнительный анализ эффективности очистки, при которой степень удаления различных групп токсичных веществ часто превышает 95 %. Наконец, обсуждаются технические и экономические ограничения, включая шламообразование и энергоёмкость, наряду с перспективами масштабирования этих технологий для устойчивого промышленного применения.

Ключевые слова: Фентон-подобные системы; процессы глубокого окисления; очистка сточных вод; гетерогенный катализ; органические загрязнители; синтетические красители; фармацевтические препараты.