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Review

Advanced Oxidation Processes and Treatment Strategies for Hospital Wastewater: A Comprehensive Review

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Abstract: Because Hospital Wastewater (HWW) is a complex mixture of chemicals, pharmaceutical residues, radioisotopes, and pathogens, it poses a serious environmental risk. Especially during epidemics, its unregulated discharge can contaminate water supplies and promote the spread of antibiotic-resistant microorganisms. Pharmaceuticals, endocrine disruptors, and persistent organic pollutants, which are present even at low concentrations but have high hazardous potential, are examples of these emerging contaminants, widespread in both developed and developing countries. Aquatic ecosystems are disrupted by the multitude of macro-pollutants (heavy metals, hormones, detergents) and micro-pollutants such as Chemical Oxygen Demand (COD), Total Suspended Solids (TSS), and nitrogen found in HWW. Advanced Oxidation Processes (AOPs) have become an increasingly popular technique for degrading harmful pollutants. Even though lab results are encouraging, further study is required before widespread application. This review discusses published research on AOPs for emerging pollutants in HWW, highlighting gaps in detection, optimization, and practical implementation, and emphasizing how future studies in these areas could help protect water resources and improve HWW management.

Keywords**:** hospital wastewater, emerging contaminants, Advanced Oxidation Processes (AOPs), pharmaceutical residues, pollutant removal

1. Introduction

The complex and potentially hazardous composition of Hospital Wastewater (HWW)-including pharmaceutical residues, antibiotic-resistant bacteria, and other emerging contaminants-poses a significant threat to the environment and public health [1]-[3]. Hospitals generate large volumes of wastewater, making on-site treatment essential to reduce risk before discharge into municipal sewage systems [4].

Advanced Oxidation Processes (AOPs) are recognized as a promising solution to degrade recalcitrant organic micropollutants and inactivate pathogens. In recent years, significant progress has been made in AOP technologies [5]-[8]. For instance, Alazaiza et al. [5] reviewed electrochemical-based AOPs tailored for HWW, highlighting their potential for high mineralization efficiency and detoxification. Umair et al. [6] analyzed the removal of various pharmaceutical molecules via AOPs, including Fenton, photocatalysis, and hybrid processes, demonstrating improved degradation efficiency and catalyst stability. Gonzaga et al. [7] critically reviewed photo-based AOPs, emphasizing advances in

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Ultraviolet (UV), visible-light, and combined systems for pharmaceutical degradation.

At the same time, Serna-Galvis et al. [8] assessed AOP sustainability, examining not only performance but also scalability, energy consumption, and integration with renewable energy. Zheng et al. [9] reported notable advances in catalytically driven AOPs, with novel catalysts increasing radical generation efficiency and reducing operational costs. Aziz et al. [10] discussed the formation of by-products, challenges in mineralization, and the development of green activators in AOP systems for pharmaceutical removal.

Additionally, persulfate-based AOPs have gained traction for antibiotic removal. Boczkaj et al. [11] reviewed persulfate and PeroxyMonoSulfate (PMS) activation for antibiotic degradation, highlighting challenges in real wastewater matrices and radical scavenging effects. These advances underscore emerging trends toward hybrid AOP systems, combining photocatalysis, electro-Fenton, or persulfate activation, as well as pilot-scale applications [12]-[15].

Despite these technological improvements, significant gaps remain: many studies still rely on synthetic wastewater, and there is a lack of comprehensive assessment under real hospital wastewater conditions [12], [14], [15].

2. Methodology

This review follows a systematic approach to analyze and synthesize current literature on Advanced Oxidation Processes (AOPs) for hospital wastewater treatment [16]. The methodology includes literature identification, data extraction, and critical evaluation of key findings.

2.1 *Literature search and selection*

A comprehensive search was conducted in Web of Science, Scopus, ScienceDirect, Google Scholar, and SpringerLink using keywords such as “advanced oxidation processes,” “antibiotics + wastewater treatment,” “emerging contaminants,” and “dyes + hospital wastewater” [16], [17]. Only peer-reviewed journal articles, high-quality conference papers, and authoritative reviews were included [18], [19].

Inclusion Criteria: Studies on AOPs applied to hospital wastewater, discussing treatment mechanisms, removal efficiency, or influencing factors [20], [21].

Exclusion Criteria: Studies on unrelated water treatment technologies, patents, non-peer-reviewed reports, or publications with insufficient data [16].

2.2 *Data extraction and synthesis*

Data were organized around key themes: AOP mechanisms, treatment efficiency for emerging contaminants, experimental conditions, comparisons with conventional treatments, and identified research gaps [22]-[26]. A comparative and thematic analysis was conducted to highlight patterns, common findings, and innovations [27], [28].

2.3 *Quality assessment*

The robustness and credibility of selected studies were evaluated based on journal impact factor (minimum 2) and citation frequency (≥ 10, unless highly relevant or recent), reproducibility of experiments, and alignment with established scientific knowledge [29]-[31].

3. Thematic discussion

3.1 *Emerging contaminants in wastewater*

Emerging Contaminants (ECs), have become a critical environmental and public health concern. Although often present at low concentrations, their persistence and bioaccumulation potential make them highly hazardous. Comparative analyses of multiple studies indicate that Pharmaceuticals, Personal Care Products (PPCPs), Endocrine Disruptors (EDCs), and Persistent Prganic Pollutants (POPs) are consistently resistant to conventional wastewater treatment, highlighting a persistent gap in current remediation strategies [32]-[36]. Figure 1 provides a visual summary of the main categories of emerging contaminants, their sources, and typical pathways into the aquatic environment, highlighting the challenges in their removal by conventional treatment methods.

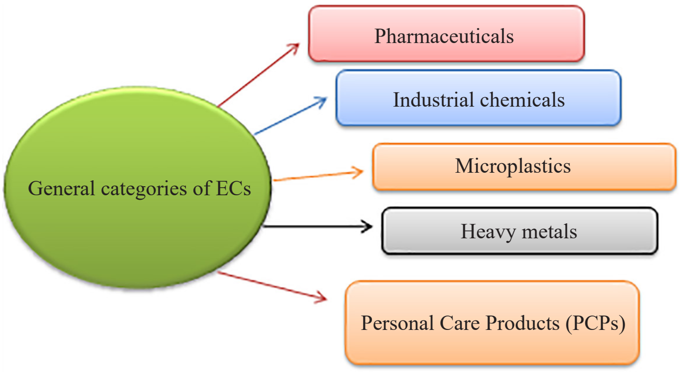

Figure 1. General categories of ECs

Detection methods have advanced, allowing for more precise quantification of ECs in surface water, municipal wastewater, and drinking water [37], [38]. Despite this, the fate of transformation products during treatment is often overlooked, representing a significant research gap [39], [40]. Certain novel psychoactive compounds damage neural pathways [41], while EDCs interfere with hormonal systems [42], underscoring the need for targeted treatment strategies [11]. Overall, the literature emphasizes not just the presence but the persistent ecological and human health risks of ECs, reinforcing the need for innovative removal methods like AOPs [7], [9].

3.2 *Emerging contaminants in HWW*

Urban Hospital Effluents (UHE) are major contributors to ECs, especially Pharmaceutically Active Compounds (PhACs), disinfectants, diagnostic agents, and PCCPs. Recent studies identify over 300 PhACs in hospital effluents, revealing considerable variability in removal efficiencies across conventional Wastewater Treatment Plants (WWTPs). For instance, sulfamethoxazole, ciprofloxacin, and trimethoprim exhibit clearance rates of 21-33%, 60-83%, and 48-85%, respectively, whereas other PhACs generally exceed 90% removal [43]. This variability highlights the limitations of standard treatment and underscores the need for targeted AOP-based interventions [44].

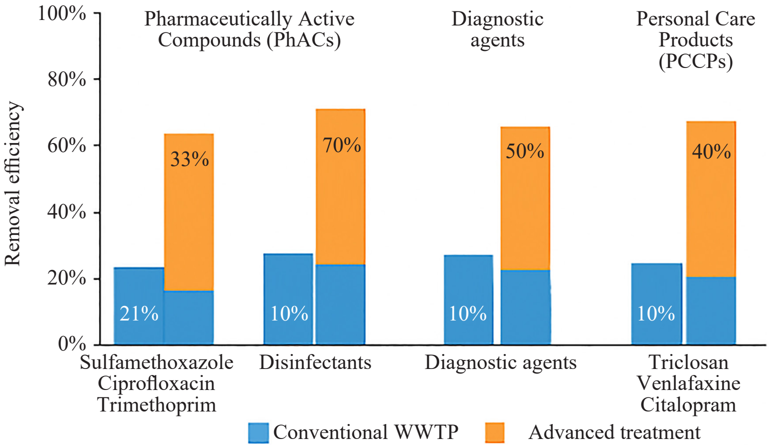

Figure 2. Pharmaceutical and emerging contaminants in hospital effluents and removal efficiency

Compounds like triclosan, venlafaxine, and citalopram further illustrate challenges. Their persistence or partial removal in WWTPs (e.g., only 10-12% for certain antidepressants) demonstrates the inadequacy of secondary treatment alone, emphasizing the potential of advanced treatment technologies [45], [46]. Comparative studies, such as those conducted in Bangkok, show estrogen removal ranging from 40-90% when advanced treatment is applied, indicating the critical role of technology selection in mitigating ECs [13], [47]. A summary of these removal efficiencies and the variability across different compounds is presented in Figure 2, providing a visual overview of the challenges and effectiveness of conventional versus advanced treatments for PhACs in hospital effluents.

3.3 *Characterization of hospital effluents*

3.3.1 *Physico-chemical characterization*

Hospital effluents show elevated levels of Chemical Oxygen Demand (COD), Biological Oxygen Demand (BOD_5), and Total Suspended Solids (TSS), often 2-3 times higher than municipal wastewater [48]. Heavy metals such as Hg, Cd, and Pt are frequently detected, posing long-term ecological risks [49]. Comparative analyses suggest that HWW requires customized treatment approaches due to its higher pollutant loads and chemical complexity [50].

3.3.2 *Microbiological characterization*

Hospital wastewater contains significant concentrations of fecal coliforms, streptococci, sulfite-reducing clostridia, and *E. coli*, often exceeding the World Health Organization (WHO) limits. These microbiological indicators, combined with residual antibiotics, contribute to antibiotic resistance proliferation, highlighting a dual challenge: chemical and biological contamination [51], [52]. To better illustrate the presence and significance of various microbiological indicators in hospital wastewater, the Table 1 presents their typical concentrations and their association with antibiotic resistance.

Table 1. Microbiological characterization of hospital effluents in selected countries

	Unit	(El-Ogri et al. [53]) Morocco (Marrakech)	(Alexandre et al. [54]) Bénin	(Touzani et al. [55]) Morocco (Taza)	(Bouzid et al. [56]) Morocco (Meknes)
Total coliforms	CFU/100 mL	8.3×10^7	11.7×10^5	2.94×10^4	4.5×10^6
Fecal coliforms	CFU/100 mL	7.7×10^7	7,565	5.93×10^3	10^5
Escherichia coli	CFU/100 mL	nd	7.15×10^5	nd	nd
Fecal Streptococci	CFU/100 mL	nd	8.3×10^4	4.8×10^3	1.35×10^8
Spores of anaerobie Sulfite reducers	CFU/100 mL	3.1×10^6	47.5×10^3	nd	nd
Staphylococcus Aureus	CFU/100 mL	7.5×10^5	nd	nd	nd
Pseudomonas Aeruginosa	CFU/100 mL	5.3×10^6	nd	nd	nd

nd: not detected; CFU: Colony-Forming Unit

3.4 *Pharmaceutical products in hospital wastewater*

HWW is rich in pharmaceuticals such as antibiotics, Non-Steroidal Anti-Inflammatory Drugs (NSAIDs), analgesics, and cytostatic agents. Comparative studies reveal that conventional treatment rarely achieves complete removal, with residual drugs contributing to Antibiotic Resistance Genes (ARGs) dissemination. For instance, ciprofloxacin, azithromycin, and metronidazole are frequently detected in effluent samples [57]. This underscores the importance of integrating advanced treatment technologies capable of degrading these persistent compounds [58].

3.5 *Added value of this review*

While previous reviews have focused mainly on the efficiency of AOPs in synthetic or isolated systems, this review extends the literature by critically analyzing reaction kinetics, real effluent conditions (pH, light penetration, turbidity, radical scavenging), and practical operational considerations including scalability, energy consumption, and cost. Additionally, potential degradation by-products and their toxicological implications are discussed [58]. This comprehensive approach provides a more realistic assessment of AOP applicability for hospital wastewater treatment and highlights research gaps for practical implementation.

To provide a clear summary of AOP performance under both lab and real wastewater conditions, a comparative overview is presented in Table 2. This table highlights differences in removal efficiency, operational challenges, and limitations for each AOP, offering a practical reference for future research and pilot-scale implementation [59].

Table 2. Comparative overview of AOP performance in hospital wastewater

AOP type	Pollutants	Lab conditions	Lab removal (%)	Real HWW conditions	Real HWW removal (%)	Limitations/Notes
Photo-fenton	Paracetamol, benzophenone, cytostatics	pH_3, H_2O_2, Fe^{2+}	90-100	Variable pH, high COD, turbidity	50-80	Fe stability, H_2O_2 dosing, energy, scale
TiO_2 photocatalysis	Ibuprofen, Carbamazepine	UV or solar, doped TiO_2	80-95	High turbidity, co-contaminants	45-70	Light penetration, photon availability, matrix effects
Ozonation/UV	Diclofenac, NSAIDs	O_3, UV	90-100	Organic matter, pH variations	60-85	By-product formation, ozone solubility, energy
Hybrid (AOP + adsorption/US)	Mixed pharmaceuticals	Lab-scale	95-100	Real HWW	70-90	Pilot optimization required, cost, energy, matrix effects

4. Removal of emerging pollutants in hospital effluent with AOPs

AOPs, which generate highly reactive hydroxyl radicals (•OH), offer a versatile solution for degrading recalcitrant compounds [60]. Comparative assessments reveal differential efficiencies across techniques.

- Photo-Fenton process: Efficient for benzophenone, paracetamol, and cytostatic drugs [5]. However, operational limitations include iron stability, pH control, and H_2O_2 dosing, which may constrain large-scale application [4]. Kinetic studies indicate that pollutant degradation often follows first-order or pseudo-first-order kinetics, but reaction rates in real HWW are slower than in synthetic solutions due to matrix effects such as high organic load and suspended solids. Moreover, variations in pH, light penetration, and radical quenching by natural organic matter in real effluents can further limit hydroxyl radical formation and reduce degradation efficiency. Pilot-scale studies are therefore essential to optimize conditions under realistic settings [61].
- Heterogeneous photocatalysis (TiO_2-based): Offers chemical stability, low cost, and reusability. Doping strategies (Ag, S, K/I) improve performance under solar light [62]. Despite high lab-scale efficiency, the presence of complex organic matter and co-contaminants in real HWW reduces reaction rates, emphasizing the need to consider kinetic constraints and possibly implement pre-treatment or hybrid approaches. Light scattering and absorption by suspended solids in real wastewater can significantly decrease photon availability for photocatalysis, necessitating optimization of reactor design and light intensity [63].
- Ozonation and UV-based AOPs: Achieve 90-100% removal of certain pharmaceuticals [5]. Limitations include ozone solubility, cost, and potential formation of toxic byproducts [45]. Kinetic evaluation in real effluents shows that while ozone is highly reactive, the degradation rate can be affected by scavenging reactions with natural organic matter, which must be considered when scaling up. Additionally, pH and matrix composition influence ozone decomposition and radical generation, affecting treatment efficiency in real HWW [46].
- Hybrid approaches (AOP + adsorption or ultrasonication): Show synergistic effects, increasing degradation rates and mineralization efficiency [65]. These combinations often outperform single AOPs, especially for complex effluents. Integration of kinetic data from pilot studies demonstrates improved reaction rates and more predictable performance in

real matrices. Accounting for real wastewater parameters (turbidity, pH, organic load) in hybrid systems enhances the applicability of lab-scale findings to practical conditions.

Overall analysis: While AOPs demonstrate impressive lab-scale performance, comparative studies reveal challenges in scaling up, energy consumption, and matrix complexity, highlighting research gaps in practical implementation [66]. Incorporating kinetic analysis and real effluent conditions (pH, light penetration, radical quenching) is essential for accurate process design and optimization. Refer to Table 3 for a comprehensive summary of recent AOP applications in hospital wastewater.

Table 3. Summary of recent AOP applications in hospital wastewater treatment

Polluants	Processus	Removal efficiency (%)	Reference
Ciprofloxacin	Heterogeneous photocatalysis	92.81%	Malakootian et al. [67].
Flutamide	Photo-fenton	58%	Della-Flora et al. [68].
Ciprofloxacin	Electro-oxidation-ozonation	90% of removal	Rahmani et al. [69].
Sulfadimethoxine (SDM), Sulfamonomethoxine (SMM) and Sulfachloropyridazine (SCP)	Persulfate oxidation process combined to adsorption	The adsorption capacity of MIL-101 (Cr) decreased with the increase of oxidation times. The maximum adsorption capacities to SDM, SMM, and SCP were 588, 196, and 196 mg/g, respectively, by Langmuir at 25 °C	Shad et al. [70]
AcetaminophenAmoxicillin	Ozone oxidation combined to adsorption	Total removal of two drugs	Mojiri et al. [71]
Sulfamethazine Caffeine Tamoxifen KetoprofenSulfamethoxazole Diclofenac Chlotianidin Amoxicillin Venlafaxine Fenofibric acid Carbamazepine Atenolo	Photo-Fenton combined to adsorption	87.47% of removal 93.64% of removal 37.91% of removal 100% of removal 99.98% of removal 100% of removal 96.67% of removal 100% of removal 100% of removal 100% of removal 100% of removal	Mansouri et al. [72]

5. Degradation of pharmaceutical compounds in hospital wastewater with AOPs

Pharmaceutical residues such as ciprofloxacin, acetaminophen, amoxicillin, and NSAIDs show variable susceptibility to AOPs:

- Photo-Fenton and combined adsorption: Up to 100% removal for venlafaxine, diclofenac, and amoxicillin (see Table 4).
- UV/TiO_2 photocatalysis: Effective for ibuprofen, carbamazepine, propranolol [73].
- Electro-Fenton: Over 95% removal of mefenamic acid in 12 min [74].

Critical analysis: Removal efficiency is highly compound-dependent [75]. For example, flutamide resists photo-Fenton ($\leq$ 58% removal), highlighting the need for multi-technical strategies [76]. Furthermore, most studies focus on lab-scale synthetic wastewater, while real hospital effluents are more complex. Kinetic investigations indicate that reaction rates are generally slower in real HWW due to matrix effects such as high COD, suspended solids, and competing radical scavengers [77]. Real wastewater conditions such as variable pH, turbidity, and light penetration can also limit radical generation, further impacting reaction kinetics and treatment efficiency [78]. Understanding these factors is crucial to accurately predict performance and design operational parameters.

Recommendations: Optimizing reaction parameters (time, pH, catalyst loading), combining AOPs with other treatments, and considering real effluent matrices will enhance treatment effectiveness and support sustainable implementation. Future research should systematically include kinetic studies in real HWW and evaluate the impact of realistic physicochemical conditions (pH, light penetration, radical quenching) to bridge the gap between laboratory results and practical applications [79].

Table 4. Removal of dyes from hospital wastewater using AOPs

AOP type	Dye	Initial concentration	Removal efficiency	Conditions	References
Photo-fenton	Methyl orange	10 mg/L	90-95%	pH_3, H_2O_2/Fe^{2+} ratio optimized	Mansouri et al [72]
TiO_2 photocatalysis	Methylene blue	20 mg/L	85-92%	UV light, 0.5 g/L catalyst	Paital et al. [80]
Electro-fenton	Rhodamine B	15 mg/L	88-94%	pH_3, 12 min, current 0.1 A	Dolatabadi et al. [81]
Hybrid (AOP + adsorption)	Mixed dyes	10-20 mg/L	90-98%	Pilot-scale, optimized conditions	Oturan et al. [82]

6. Conclusion

Hospital Wastewater (HWW) poses major environmental and public health risks due to its complex composition, which includes pharmaceutical residues, heavy metals, pathogens, and various emerging contaminants. Conventional treatment systems often fail to fully remove these pollutants, allowing ecological impacts to persist and contributing to the spread of antimicrobial resistance.

Advanced Oxidation Processes (AOPs) have emerged as a highly promising solution because of their ability to generate highly reactive radicals capable of degrading a wide range of recalcitrant compounds. Techniques such as photo-Fenton, heterogeneous photocatalysis, ozonation, UV-based processes, and hybrid approaches have demonstrated high removal efficiencies under controlled laboratory conditions. However, real HWW matrices-characterized by high organic load, significant turbidity, variable pH, and radical scavengers-tend to reduce degradation rates and highlight the need for optimized operational conditions. Hybrid processes often show superior performance when addressing highly complex effluents.

Several gaps remain: most studies rely on synthetic or simplified wastewater, kinetic data for real effluents are limited, and the toxicity of degradation by-products is insufficiently assessed. To address these limitations, pilot-scale and full-scale studies are essential to validate the real-world performance of AOPs under authentic wastewater conditions, and future work should systematically consider matrix effects when assessing degradation kinetics. Additionally, integrating AOPs with complementary treatment technologies (e.g., adsorption, membrane processes, or biological treatments) will be crucial for optimizing the removal of micropollutants and dyes and ensuring robust overall treatment performance. Finally, evaluating treatment cost, energy consumption, and the formation of potentially toxic by-products is critical to guarantee sustainable and economically viable implementation.

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Author contributions

The study conception and design were performed by Mahmoud Bali. Data collection was performed by Wiem Mbarki. The manuscript was written by Mahmoud Bali and Wiem Mbarki. All authors read and approved the final manuscript.

Conflicts of interest

The authors declare that there are no financial or non-financial interests that are directly or indirectly related to the work submitted for publication. There are no conflicts of interest to disclose.

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