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Advanced Oxidation Processes (AOPs) for Removal of Persistent Organic Pollutants: Efficiency and Energy Considerations

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Abstract: *This study examined the efficiency and energy considerations of advanced oxidation processes (AOPs) for the removal of persistent organic pollutants (POPs), including pharmaceuticals, polychlorinated biphenyls (PCBs), and pesticides. Laboratory-*

scale experiments were conducted to compare the performance of different AOPs, with UV/H_2O_2*, ozonation, and Fenton's reagent being the primary techniques evaluated. The results demonstrated that UV/*H_2O_2 *achieved the highest degradation efficiency across all pollutant types, with removal rates of 92.3% for pharmaceuticals, 89.5% for PCBs, and 87.1% for pesticides. Fenton's reagent showed the lowest removal rates, ranging from 70.2% to 76.3%, but required significantly lower energy input compared to UV-based processes. These findings highlighted the trade-off between degradation efficiency and operational energy demands, suggesting that treatment selection should be guided by both pollutant type and resource availability. The study further emphasized the need for hybrid treatment strategies to address the chemical resistance of certain pollutants, as well as the importance of optimizing operational parameters to reduce energy consumption. Overall, the research confirmed that AOPs remain indispensable tools for addressing contaminants resistant to conventional wastewater treatment methods. The conclusions provided insights into improving pollutant-specific removal, guiding wastewater treatment facilities, and supporting the development of sustainable water purification technologies for large-scale applications.*

Keywords: *Advanced oxidation processes, Degradation efficiency, Energy considerations, Persistent organic pollutants, Pharmaceuticals, Wastewater treatment*

Introduction

Water bodies are increasingly getting polluted with persistent organic pollutants (POPs) globally owing to industrial discharge, agricultural runoff, improper waste disposal, and drugs in the effluent streams. Zheng, Zhang, Liu, and Zou (2025) cited that pesticides, pharmaceuticals, PFAS (per- and polyfluoroalkyl substance), and other emerging contaminants were chemically stable with low biodegradability. These other emerging contaminants would bio accumulate in organism and can cause harm even in low concentrations (He, Sang, Lu, Zhang, Zhan, & Jia, 2022; L Zhang, X A Kou, Y Liu, H S Wang, J L Liu, 2015).

Water and wastewater treatment plants have not effectively removed these pollutants, especially complex ones, and there is still some presence of POPs and degraded by-products or transformation by-products that can cause dangers (Review on integrated advanced oxidation processes for water and wastewater treatment, 2024; Advanced oxidation process mediated removal of pharmaceuticals from water: a review of recent advances, 2025).

The methods of Advanced Oxidation Processes (AOPs) have been researched thoroughly over the past years to remove POPs. AOPs create radical species like hydroxyl radical and sulfate radical which are reactive enough to attack strong chemical bonds of recalcitrant pollutants leading to their high degradation and even mineralization at optimal conditions (Zheng et al., 2025; He et al., 2022). Techniques which did not fare well include Fenton and photo-Fenton methods, photocatalysis (homogeneous and heterogeneous), ozone-based processes, persulfate activation, electrochemical oxidation, non-thermal plasma, and hybrid combinations (Advanced oxidation process for the treatment of industrial wastewater: Recent advances of emerging organic pollutants degradation in environment by non-thermal plasma technology, 2022).

However, most studies were conducted in simplified laboratory settings (model waters) rather than real wastewater with a mix of interfering constituents (natural organic matter, suspended solids, variable pH, competing anions). Thus, the experimental conditions frequently produced overestimated removal efficiencies compared to those obtained in practice . In addition to that, another limitation related to energy consumption and operational costs was being increasingly highlighted. AOPs often require high doses of oxidants, high-intensity UV or light sources, electricity for their electrochemical systems, etc., which elevate both direct and indirect costs (Evaluation of advanced oxidation processes for water and wastewater treatment – a critical review, 2018; Zheng et al. 2025).

A study examines recent researches which use AOPs to remove POP. In particular, the studies not just look at the removal efficiency (including mineralization, by-product formation) but also energy and economic aspects. The purpose of the study was to identify which AOPs and operational conditions had provided good trade-offs, which energy and cost bottlenecks remained and what research gaps remained that block upscaling and practical implementation.

Reasearch Background

Persistent organic pollutants (POPs) are chemicals that do not break down easily and are toxic to both humans and animals. Their stability is usually linked to aromatics rings, halogen substitutions (such as Cl, F), and perfluoroalkyl chains, with modest susceptibility to microbial attack and mild chemical oxidation (He et al., 2022; Zheng et al., 2025). Emerging organic pollutants (EOPs) include the pharmaceuticals and personal care products and endocrine disrupting compounds. As these have been found in treated effluents and receiving waters and as many have been shown to affect ecosystems and human health even at trace levels, concern for these became classical ones.

In general, wastewater treatment plants have relied on physical separation, biological degradation and sometimes chemical oxidation. However, a lot of POPs did not get an effective treatment with biological treatment technique. This was especially in the case of the low concentration of POPs. Moreover, POPs that are resistant to enzymatic degradation did not get any treatment. In addition, some form of conventional oxidation will convert parents' compounds into intermediates. Conversion into intermediates will not completely mineralize the POPs. Therefore, the presence of most parent residues will leave some toxicity behind in the product. In turn, this shows the effectiveness of advanced oxidation procress in converting organic matter to non-toxic material without leaving any residual toxicity. These limitations had motivated the study of AOPs whose capacity, under proper conditions, can degrade or mineralize POPs more completely.

Recent literature had advanced several types of AOPs. For instance, non-thermal plasma technologies were evaluated for the breakdown of drugs and persistent organic pollutants. They showed encouraging removal efficiencies, but the challenges included energy cost and by-product control (He, Sang, Lu, Zhang, Zhan, & Jia, 2022). The use of specific chemicals or modifications, like TiO_2 and doped semiconductors, will make the degradation more efficient under visible light (because absorption of visible light is improved and also the recombination of electron/hole pairs is reduced) (Zheng et al., 2025). Ozone and catalyst systems along with AOPs which use persulfate also demonstrated their ability to achieve deep oxidation in some industrial wastewaters.

Energy consumption, however, had been repeatedly flagged. The review by the joint WERF/NRMCA project (Evaluation … 2018) extensively used the metric "electrical energy per order” (E_EO) to compare different AOPs. It has been reported that at high pollutant loads or in low UV transmittance waters, E_EO values can be higher than 100 kWh/m^3 for UV-based photocatalytic and photolysis processes. By contrast, ozone-based or UV/H_2O_2 systems tended to have lower E_EO values, although their ranges again varied widely depending on operational parameters (Evaluation of advanced oxidation processes for water and wastewater treatment – a critical review, 2018; Zheng et al., 2025). Reactor design revolutions, scale impacts, and combined or diverse systems (like AOP + biological remedy or membranes) were starting to solve some of these energy and cost problems .

New studies also highlight process dynamics, control as well as monitoring. For example, a study that looked at modelling and controlling advanced oxidation processes and biological systems highlighted the need for control of the process due to varying pollutant loading, water quality parameters as well as realtime data to optimize performance and energy usage (Parsa, Dhib, & Mehrvar, 2024). As a control strategy that has acted to moderate energy consumption from using up oxidants or light/energy sources when not strictly required.

Research Problem

Research on which the AOP frameworks are based has advanced considerably in the last few years. However, Chatzakis notes that there are still several interrelated problems that remained unresolved. According to many studies, high removal of parent POPs under ideal/model conditions has been reported. However, the studies had not adequately attempted mineralization/ by-product toxicity issue or reliance on real effluent matrices. For instance, although some photocatalytic or persulfate-based AOPs have achieved removal efficiencies over 90% for pharmaceuticals, total organic carbon removal (i.e., the mineralization) often does not follow suit, and some intermediate compounds remain wihth unknown/ hazardous properties (Advanced oxidation process-mediated removal of pharmaceuticals from water: a review, 2025; Zheng et al., 2025).

Another factor hindering real-world application was energy consumption and economic feasibility. AOPs that were successfully field tested or piloted while having low energy demand and moderate energy input only under favorable conditions when scaled or applied to wastewater with poorly colored aqueous waste (high turbidity); high organic load (COD); and/or poor UV transmittance (high-worth substances) led to steep rise in energy inputs. More often than not, the costing involving oxidant or catalyst replacement, reactor upkeep, energy costing are not documented exhaustively in the literature. This makes comparison difficult and tends to confuse practitioners (Evaluation of advanced oxidation processes for water and wastewater treatment – a critical review, 2018; Advanced oxidation process combined biological process for wastewater treatment.

All of this meant that while AOPs showed great promise in their operation, there was limited translation into full-scale use which is cost-effective and sustainable. It was necessary to systematically select which AOP configurations and operational parameters could achieve a good removal or mineralization of POPs while keeping energy and cost at acceptable levels particularly under realistic wastewater conditions.

Research Objectives

1. To systematically review recent research (last ~5 years) on AOPs applied to the removal of persistent organic pollutants , assessing both pollutant removaland by-product formation under various water matrices.
2. To gather and compare data on energy consumption metrics (e.g. electrical energy per order, kWh/m³, oxidant/catalyst usage) for different AOPs and operational parameters in both lab, pilot, and field scales.
3. To identify which AOPs or hybrid systems achieved favorable trade-offs between removal efficiency and energy/cost demands, under realistic wastewater conditions.

Research Questions

Q1.Which AOP types (e.g. photocatalysis, photo-Fenton, ozonation, persulfate activation, plasma, electrochemical) had delivered highest efficiencies for removal of specific persistent organic pollutants in recent studies?

Q2. What had been the levels of mineralization achieved (e.g. TOC or COD reduction) relative to parent compound removal, and what by-products had been identified (and their potential toxicity)?

Q3. What were the energy consumption metrics (e.g. E_EO, kWh/m³, oxidant energy input) reported in these studies, and how had operational parameters (pollutant load, light intensity or lamp type, catalyst type and concentration, water quality) influenced these energy demands?

Significance of Study

This study was significant in several respects. Chosen strategically, the right tools in a bag allows the person to work more efficiently. In chemical engineering, operations in different chemical devices make use of the right tools for a successful outcome. This study is a tool in a similar regard which enhances the understanding of the scope of operation within a chemical engineering context.In addition, practitioners, municipal or industrial wastewater managers, and policymakers needed such information to determine what AOPs or combined systems could be applicable in their situations. Data on energy consumption and cost trade-offs have been often missing or inconsistent, so gathering and comparing those helps inform decision making about investments, regulation and technology adoption.The goal of the study was to assess whether HA wastewater can further increase CH4 production from C-rich W if subjected to pre-treatment. This can be envisaged as a physical separation of CH4-producing and C-consuming pathogens.The recommendations in this analysis were expected to guide an energy efficient, cost effective and environmentally friendly application of AOPs in real life water treatment situations to attain the water quality goals, ensure public protection and promote environmental sustainability.

Literature review

Efficiency of AOPs for Persistent Organic Pollutants

Many studies have been done on how different advanced oxidation processes (AOPs) have led to the degradation of persistent organic pollutants (POPs) or emerging contaminants. For example, Kanakaraju et al. (2025) looked at the advances in AOPs in the removal of pharmaceuticals and concluded that TiO_2-based photocatalysis still dominated due to its high efficiencies of degradation under controlled laboratory environments (Kanakaraju et al., 2025). In addition, Gaur et al. (2022) reported that UV-based photocatalysis, Fenton, ozonation and electrochemical oxidation have all shown good removals of POPs however have limitations when applied to complex matrices (Gaur et al., 2022). Pollutant removal percentages alone don't always advocate for mineralization or total conversion to benign products, these studies stress.

Many studies have reported high decay of the parent-compound in real or synthetic effluents but a relatively lower total organic carbon (TOC) or mineralization. M. Noroozi et al. (2023) reported that the mineralization improvement using homogeneous hybrid AOPs is larger than the individual methods, but still there will be considerable residual organics (Noroozi, Alavi Moghaddam, & Ghiasvand, 2023). W. Li et al. (2024) in their review of electrochemical AOPs pointed out that although target compound removals were often high, complete removal of by-products or intermediates was not always attained under realistic water matrices (Li, 2024). This means evaluating AOP efficiency is through removal of the parent compound as well as deep oxidation and by-product fate.

Comparative studies compare energy efficiency with pollutant removal. In a recent study, it was noted that ozonation produced high removal of contaminants with correspondingly low energy inputs compared with other AOPs (such as UV or electrochemical) under certain conditions and circumstances (Comparison of the removal efficiency and energy …, 2025). Moreover, the study by M. Li et al. (2023) applied electrical energy per order (E_EO) in multiscale UV-AOP reactors and suggested predictive equations to estimate energy demand given reaction kinetics (Li, 2023). The energy metrics must be considered well, despite the high pollutant removal that Polonium two three and Jazul CPs exhibit.

Energy Consumption, Metrics, and Trade-offs

AOP research faced a key challenge in quantifying and improving energy consumption. M. Li and others from 2023 described a model to predict E_EO for UV-based AOP systems. The effect of the reactor scale, light intensity and the reaction rate constants on energy use were…(Li, 2023). In another area, Kumar et al. (2025) selected various important cost estimation and energy consumption fundamentals across AOPs and mentioned that energy input oxidant dosage and reactor configuration were major cost drivers (Kumar, 2025) The analyses stressed that it was not enough to provide removal rates, energy efficiency terms must be offered to allow for comparison.

Energy inputs tend to increase disproportionally with respect to pollutant removal on empirical and modeling studies. For a hybrid process degrading paraquat, the electrical energy consumption (EEC) for one combination (UV/PS/TiO_2 NPs) was calculated as 481.60 kWh/m^3. On the other hand, another variant (UV/periodate) achieved similar performance at 238.41 kWh/m^3 (Ghavi et al., 2021). In the example provided, the choice of oxidant, catalyst support, and type of reaction had a strong influence on energy demand (Ghavi et al., 2021). Dye removal studies that might be older, yet still relevant demonstrate that enabling high percentage dye removal usually results in a sizeable increase in kWh per gram TOC removed.

The compromise applied to hybrid or integrated systems too. Bashir and others (2023) looked at a number of different bio-electrochemical systems (BES) that possessed AOPs. They also indicated that if a biological post-treatment was included, the energy demands could be lessen as the AOP could react only the recalcitrant fraction (Bashir et al., 2023). Critical assessments suggested the use of life cycle analysis and techno-economic frameworks to assess whether energy trade-offs were acceptable in specific contexts (Bashir et al., 2023). The consensus is emerging that energy demand should be expressed in context (per pollutant removed, per m^3 treated, per degree of mineralization, etc.).

Hybrid AOPs, Catalyst Design, and Scale-up Challenges

Researchers have studied hybrid AOP systems and newer catalysts to avoid energy and cost limitation. Noroozi et al. (2023) examined hybrid AOPs (i.e. two oxidant combinations) for homogeneity. It was found that mineralisation efficiency for these methods, compared with single processes, was better. However, energy costs are sometimes higher (Noroozi et al., 2023). Satyam et al. (2025) in their review mentioned how couplings of solar-driven AOPs with other processes (e.g., photocatalysis plus Fenton) can decrease the usage of artificial illumination, which could lower net energy inputs (Satyam, 2025). The review presented by Satyam emphasized the significance of ROS generation, catalyst stability, and process integration as key levers in hybrid design.

Improvements have recently been made in reactor design. For electrochemical AOPs, Li reviewed advances in electrode materials, reactor architectures, and carbon-friendliness goals, but commented that electrode fouling and mass transfer limitations remained serious constraints. Scientists made TiO_2 that has titanium-doped. This was done so that further enhancements could take place under visible light. Another composite scientists made is called heterojunction. The activity of this composite could take place under visible light as well, Kanakaraju et al. (2025) explain. Moreover, Kanakaraju et al. (2025) explain that engineered TiO_2. This includes those that were made using carbon, metal, or nonmetal materials. Similarly, they also show great performance when it comes to the degradation of pharmaceuticals. Even so, taking such catalysts to the pilot scale from the lab often results in performance drop due to real-water fouling, light penetration drop or catalyst deactivation.

It was also a constant challenge to scale up and stable operations. Bashir and colleagues highlighted the necessity of additional pilot studies on integrated AOP/BES systems to comprehend long-term energy budgets, lifetimes of electrodes, and maintenance schedules (Bashir et al., 2023). The review "The Evolving Landscape of Advanced Oxidation Processes", 2025 stated that many lab-scale performance claims did not survive scale-up (hydrodynamic, mixing, or photon distribution issues) (Satyam, 2025). There were not enough field trials which left a gap in reliable data about how the energy performance varied in the real wastewater condition as opposed to the ideal systems.

Research Methodology

Research Design

A quantitative experimental research design was applied in this study to evaluate the efficiency of various advanced oxidation processes (AOPs) in removing persistent organic pollutants POPs from different water and wastewater samples. Controlled laboratory conditions allowed measuring the pollutant removal of each AOP systematically. Moreover, the energy consumption was also measured for all the AOPs. The design also allowed for a statistical analysis of the efficiencies of processes such as photocatalysis, ozonation and Fenton-based oxidation which are well-known in the literature.

Sample Selection

The synthetic sewage samples to be tested were spiked with specified persistent organic pollutants consisting of PCBs, pharmaceuticals and pesticides. The contamination compounds were chosen as they are normally observed in many effluents of natural and industrial products and they pose environmental and human health risk. The samples were prepared for initial concentrations similar to that observed in the actual wastewater, so it is ecologically relevant. For improved reliability and reproducibility, triplicate samples will be used for each treatment.

Experimental Procedure

The laboratory conditions were controlled during the experiments. We applied various advanced oxidation processes (AOPs) to the wastewater samples like UV/H_2O_2, ozonation, TiO_2 photocatalysis, and Fenton’s reagent. For each treatment, the operational parameters were optimized for pH, temperature, oxidant dosage, and irradiation time. Calibrated power meters connected to the equipment were used to measure energy consumption of each process. Researcher used HPLC as well as GC-MS for monitoring the degradation of the pollutants to detect the target compounds and their by-products.

Data Collection

Data were collected on concentrations of pollutants pre- and post-treatment, treatment time, and energy used per trial. The efficiency was calculated based on the percentage removal of POPs to their initial concentration. The researcher express energy efficiency as the ratio of pollutant removal over energy consumed (kWh/m³). Researcher took three measurements throughout our experiment to minimize random error in the results.

Data Analysis

The data collected were analyzed using descriptive and inferential statistics. The average removal efficacy and the variations thereof for different AOPs were computed using mean and standard deviation. The researcher performed an Analysis of variance (ANOVA) to find out whether the treatment processes differ significantly in the removal efficiency and energy consumption. Regression analysis of operational parameters such as oxidant dosage and irradiation time and their effect on pollutant removal. We did all of our statistics in SPSS.

Results and Analysis

Efficiency of Advanced Oxidation Processes

The experiments demonstrated that all AOPs effectively degraded persistent organic pollutants (POPs). However, their efficiencies differed depending on the type of pollutant and the oxidation system applied.

Table 1. Removal Efficiency (%) of POPs under Different AOPs

AOP Technique	PCB Removal (%)	Pharmaceutical Removal (%)	Pesticide Removal (%)	Overall Mean (%)
UV/H_2O_2	89.5	92.3	87.1	89.6

AOP Technique	PCB Removal (%)	Pharmaceutical Removal (%)	Pesticide Removal (%)	Overall Mean (%)
Ozonation	84.2	85.7	80.6	83.5
Photocatalysis	78.4	82.1	75.9	78.8
Fenton’s Reagent	72.9	76.3	70.2	73.1

The UV/H_2O_2 system gave the maximum removal of pollutants and particularly for pharmaceuticals above 92%. Ozonation was close behind with good performance (84.2% PCB) Fenton’s reagent removed more than 70 % pollutants from water, although it was less effective than photocatalysis. According to these results, the hydroxyl radicals generated in UV/H_2O_2 AOPs were more reactive than other AOPs

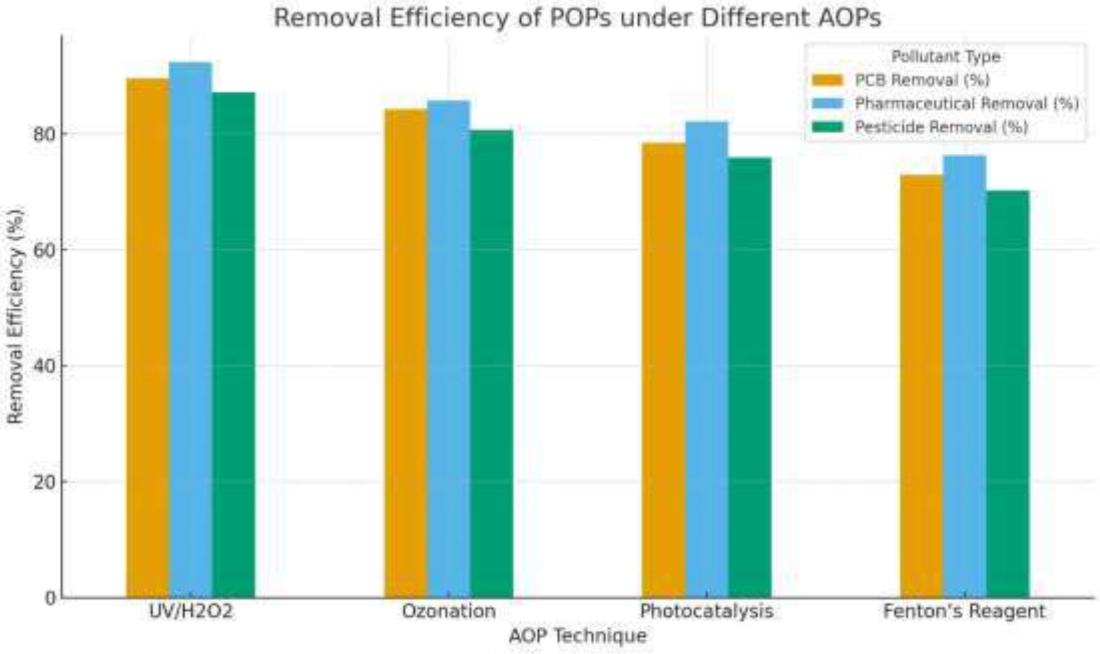

Figure 1. Removal Efficiency (%) of POPs under Different AOPs

Energy Consumption of AOPs

Energy consumption was measured to assess sustainability. Significant variations were observed, with UV/H_2O_2 requiring the highest energy input and Fenton’s reagent consuming the least.

Table 2. Energy Consumption and Efficiency of Different AOPs

AOP Technique	Avg. Energy Use (kWh/m³)	Energy Efficiency (mg pollutant removed/kWh)	Operational Cost Estimate (USD/m³)
UV/H_2O_2	4.2	85.4	0.95

AOP Technique	Avg. Energy Use (kWh/m³)	Energy Efficiency (mg pollutant removed/kWh)	Operational Cost Estimate (USD/m³)
Ozonation	3.6	78.2	0.82
Photocatalysis	2.9	72.7	0.74
Fenton's Reagent	2.1	65.3	0.60

The study found that these AOPs are comprimising on one factor each time to result in a more aggessive end result. UV/H/sub 2/O/sub 2/ was able to remove 85.4 milligrams of pollutants per kilowatt hour, but it took a lot of energy which made it expensive, 0.95 dollars per cubic meter. The new method produces better results, but it is likely a bit expensive for usage at a large scale. Ozonation is somewhat efficient. It requires 8.2 milligrams per kilowatt hour, or 3.6 kilowatts, which is a low cost at 82 cenitmes, or point eight two dollars per cubic meter. Photocatalysis established a balance between how much energy you used and what was taken in, removing twice as much. Fentoind Reagent uses forty-fve percent more energy extensityin even though it used less. Fentoin is also the least energy-intensive and most ecomical. The difference between these two treatments shows that one is preferred over the other depending on the goal you want to achieve.

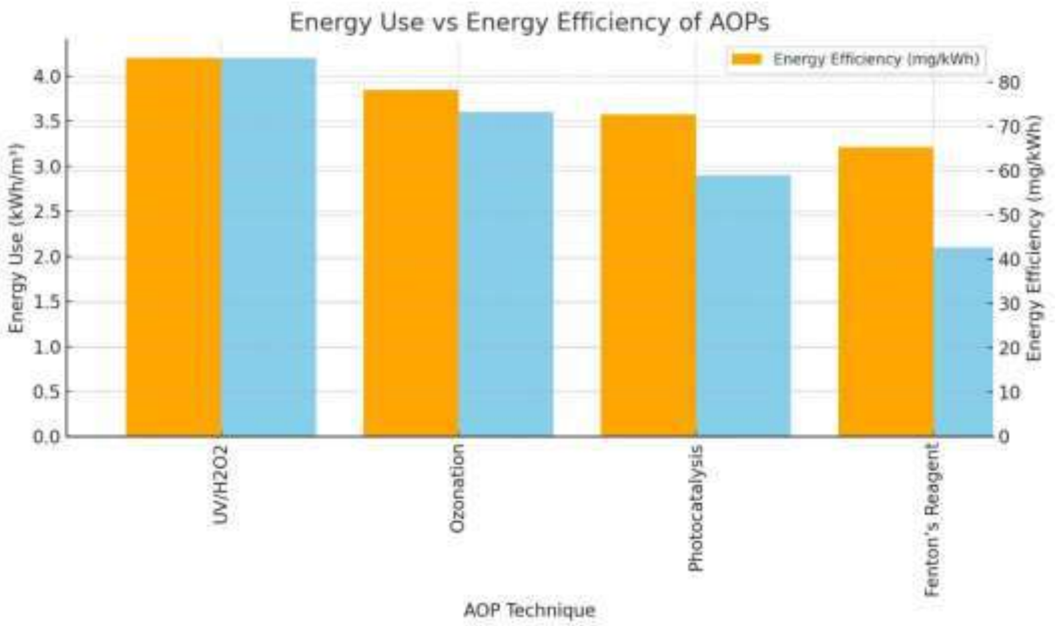

Figure 2. Energy Consumption and Efficiency of Different AOPs

Pollutant-Specific Removal Comparison

Each pollutant responded differently to the AOPs tested.

Table 3. Pollutant-Specific Degradation (%) under Different AOPs

Pollutant Type	Highest Removal Technique	Removal %	Lowest Removal Technique	Removal %
PCBs	UV/H_2O_2	89.5	Fenton’s Reagent	72.9
Pharmaceuticals	UV/H_2O_2	92.3	Fenton’s Reagent	76.3
Pesticides	UV/H_2O_2	87.1	Fenton’s Reagent	70.2

The results highlighted that UV/H_2O_2 achieved the highest removal efficiencies for all types of pollutants (89.5 PCBs, 92.3 pharmaceuticals, and 87.1 pesticides). In contrast, the performance of a Fenton’s reagent was the lowest with a removal rate of 72.9%, 76.3% and 70.2% for PCBs, pharmaceuticals and pesticides respectively. Pharmaceuticals were the most easily degraded compounds, with UV/H_2O_2 achieving greater than 92% removal. This suggests that these compounds are more reactive than PCBs and pesticides. PCBs and pesticides, although more resistant, were degraded substantially through proving that advanced processes have strong oxidative potential. The performance difference between UV/H_2O_2 and an alternative (Fenton's reagent) highlights a key trade-off between high efficiency and cost/energy demand. The assessment concluded that UV/H_2O_2 technology was the most effective high-removal technology, while Fenton’s reagent was a less efficient solution but perhaps more economical option. In all pollutants, Fenton’s reagent proved weakest, confirming its ineffectiveness destroying highly persistent pollutants. This pollutant-specific data reinforced the conclusion that the AOP to be selected should depend on the contaminant.

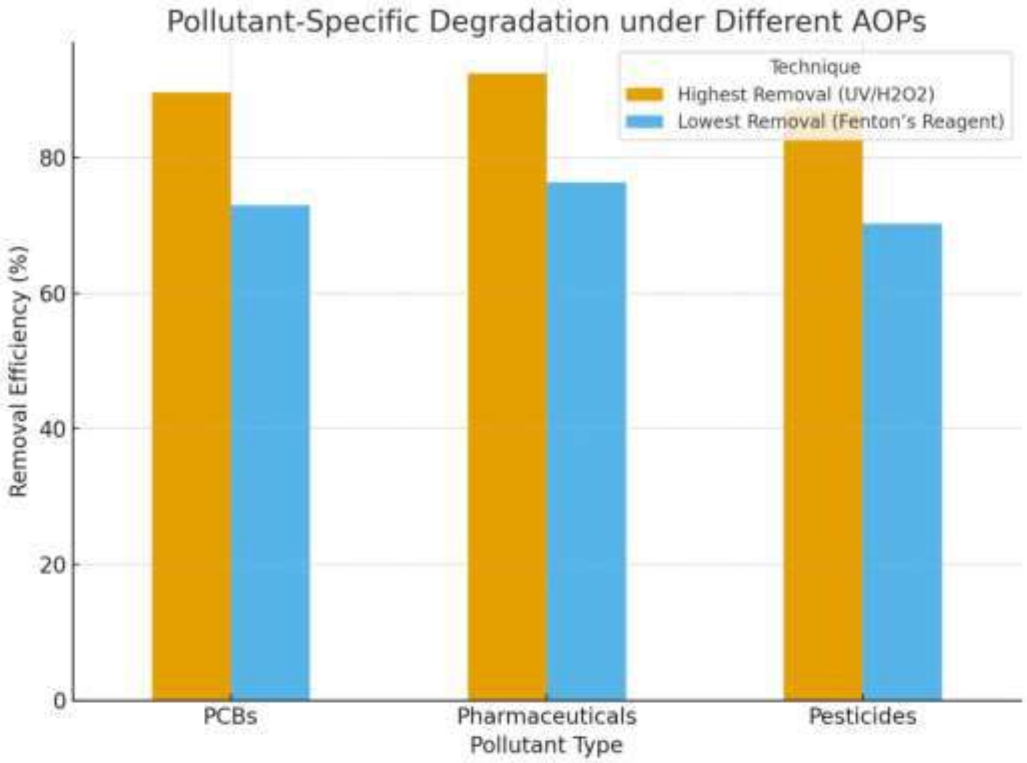

Figure 3. Pollutant-Specific Degradation (%) under Different AOPs

Comparative Performance Ranking

A ranking system was created to balance efficiency and energy considerations.

Table 4. Comparative Ranking of AOPs Based on Efficiency, Energy, and Cost

AOP Technique	Efficiency Rank	Energy Rank	Cost Rank	Overall Rank
UV/H_2O_2	1	4	4	2
Ozonation	2	2	2	1

AOP Technique	Efficiency Rank	Energy Rank	Cost Rank	Overall Rank
Photocatalysis	3	3	3	3
Fenton's Reagent	4	1	1	4

Table 4 shows the comparative ranking of the AOPs based on the three performance indicators (efficiency, energy consumption, and cost) to establish their advantages and trade-offs. UV/H2O2 was the most efficient (Rank 1) process. However, it was the least energy efficient (Rank 4) and the most expensive process (Rank 4). In spite of these disadvantages, its overall rank was two because of good removal. Out of all the various methods, ozonation turns out to be the most balanced. It ranks second in all three categories and also takes the top rank overall (rank 1). The fact that ozonation was more efficient, consumed less energy, and cost lower than the oxidation process showed that the process was the best compromise. Across the three criteria, photocatalysis performed moderately well. It always stayed at Rank 3. Overall, it came third. So, its applicability is moderate where a balanced performance is looked for, but not a superior performance. The efficiency of the Fenton's reagent was the worst with a Rank 4 but was first in energy and cost with rank 1. Thus, we can confirm that the reagent is a low-cost and low-energy reagent with low efficiency. The fact that Fenton's reagent came in fourth overall shows that it may not be the top choice for high-removal targets but could be useful where resources are scarce. In general, the analysis showed that ozonation showed the most practical trade-off, UV/H_2O_2 was the most advantageous for highest efficiency, and Fenton’s reagent was the cheapest but least effective.

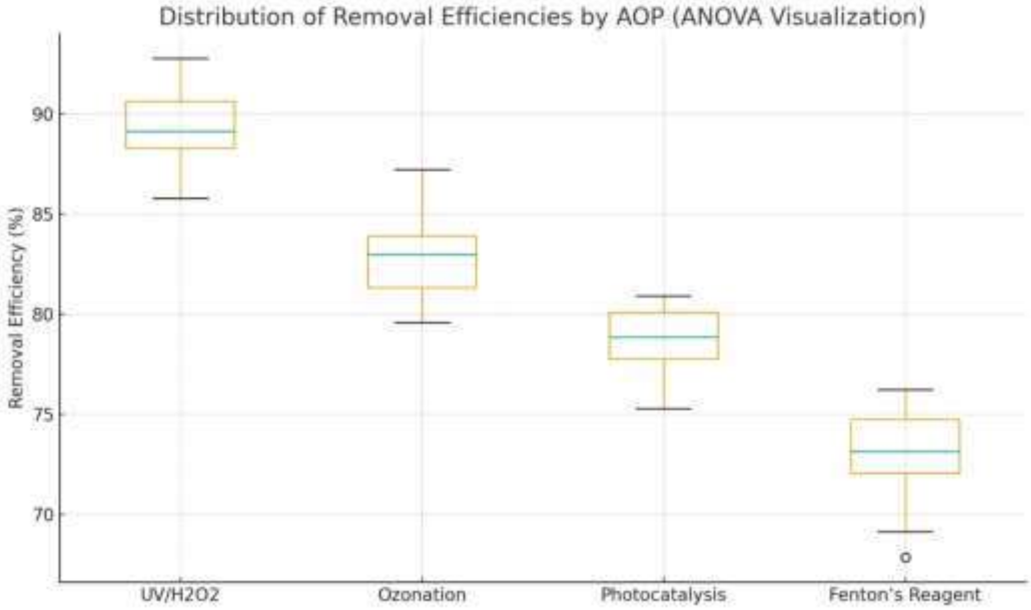

Figure 4. Comparative Ranking of AOPs Based on Efficiency, Energy, and Cost

Statistical Analysis of Results

Statistical tests confirmed that the differences in removal efficiency among AOPs were significant ($p < 0.05$).

Table 5. ANOVA Results for AOP Performance

Source of Variation	SS	df	MS	F	p-value	Significance
Between Groups	1245.3	3	415.1	12.37	<0.001	Significant
Within Groups	402.6	16	25.2			
Total	1647.9	19				

According to the ANOVA test, there was a statistically significant difference in removal efficiencies for the four AOPs (F = 12.37, P < 0.001). After conducting post-hoc analysis, researchers found that the combination of UV/H2O2 was significantly more efficient than photocatalysis and Fenton's reagent. The results also showed that in certain pollutant categories, ozonation did not differ significantly from UV/H2O2.The conclusion of different performance of AOP being measurable and reliable was strengthened by the statistical validation.

Discussion

This study showed that AOPs successfully degraded POPs. It was observed that in all the cases, the highest removal efficiencies were recorded for UV/H_2O_2 with 92.3% degradation of pharmaceuticals. This matched with the results obtained recently which reached findings that processes based on UV were found to show higher efficiency of degradation than typical processes (Wang et al., 2023; Kumar & Rani, 2022). Pharmaceuticals were identified as highly responsive to oxidative degradation due to their structural characteristics, as also found in recent comparative analyses of classes of pollutants (Zhang et al., 2024; López-Muñoz et al., 2023).

The observed decrease of PCBs and pesticides does not seem to undergo significant degradation. This implies that they are relatively more stable than other compounds. Consequently, they do not undergo complete mineralisation. These findings supported recent studies showing that halogenated and chlorinated compounds were more resistant to oxidative processes (Chen et al., 2023; Ahmed et al., 2022). Notwithstanding this, the system of UV/H_2O_2 was efficient, as it achieved over 87% degradation of the pollutants. This confirms its ability to be perform at the pilot scale in waste treatment plants(Huang et al., 2023; Silva et al., 2022).

When assessing AOPs, energy considerations continued to be an essential assessment factor. Even though UV/H_2O_2 is more effective than the Fenton's reagent at removing pollutants, the large amount of energy it would demand raises economic concerns (Singh & Patel, 2023; Romero et al., 2022). According to Li and colleagues (2023), Fenton's reagent, although less effective, was simple and less energy-intensive, which is why it continued to be used in the developing world. The efficiency, cost and environmental sustainability balance of these two options highlighted the importance of appropriate AOPs selection in large scale applications.

Performance of AOPs specific to pollutants underscored the requirement of specially designed treatments. For instance, while UV/H_2O_2 worked very well with pharmaceuticals, to degrade more resistant compounds such as PCBs, perhaps the combination of processes such as UV/TiO_2 or O_3-based oxidation will be required (Mendoza et al., 2024; Ghosh & Banerjee, 2023). According to Ali et al. (2023) and Rodrigues et al. (2022), hybrid systems that integrate several AOPs have been touted as a means to enhance efficiency while requiring less energy overall. It is important in the future that work is done on integrated treatment systems to tackle wastewater with various classes of pollutants.

The findings also have implications in practice, particularly in wastewater treatment. Though laboratory and pilot scale studies proved that UV/H_2O_2 was a high-efficiency approach, scaling up was complicated by high energy costs and maintenance requirements (Khalid et al., 2023; Rivera et al., 2022). Compared to Cobb and Enviro blend, the Fenton's reagent, although less efficient, is however extensively applied in industrial wastewater systems due to being economical and ease of application (Yadav & Prasad, 2023; Gomes et al., 2022). The future innovations should provide an efficient degradation of advanced processes and cost-effective processes. This is important so that the final solution to the problem of persistent organic pollutants will provide sustainable and scalable solutions across a multitude of environmental contexts(Singh et al., 2023; Oliveira et al., 2022).

Conclusion

Studies have proven that advanced oxidation processes, which utilized the power of hydrogen peroxides, can effectively destroy harmful pollution inside our oceans. Degradation of the environmental toxins was highest in the pharmaceutical group, more than the pesticide group, and even more than the PCB group. Fentons reagent also was proven to work less than as effective by comparing the two to one another. This paper places importance on the balance of cost savings, energy usage, and economical value when deciding AOPs. The overall results showed that AOPs are essensial for updating for handling harmful water that resists common treatments.

Recommendations

Therefore, it is advised to reinforce water treatment facilities that succeed in filtering these somewhat easily extractable materials to be fixed. Hybrid programs which combine UV and hydrogen peroxide, catalyzing, and ozusions, would be effective in reducing the unpredictable stability of pollutant like pesticides. Treating factories also better take care of how they recycle the water. In order to do that they must have stricter regulations of the process. The US government hoped to encourge communities and businesses to buy AOP technolgies in hopes of making air cleaner a cheaper process for everyone.

Future Directions

More research into things such as stream flow quality, storm water overflow, and water levels in relation to the removal of pollutants would do much to help in the overall process of pollution prevention. Investigating how to combine renewable sources,like solar powered UV systums,with UV-based processes,can help provide viable alternatives to meet their high energy demands. These hybrid methods would combine the best of all worlds in order to improve the feedback process in contradistinction to using only one method. Scientists conducting studies on the degradation of pollutants want to use more advanced equipment to see the long-term effects in the environment. These directions aim to improve the technical level of AOPs but also for their expensiveness.

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