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Optimization of Advanced Oxidation Processes for Organic Wastewater Treatment in Bangladesh: Effects of pH, Oxidant Dosage, Reaction Time, Organic Load, Degradation Kinetics, and Energy Consumption

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ABSTRACT

Organic wastewater contains persistent and potentially toxic compounds that can resist conventional biological treatment and persist in aquatic environments. This experimental study evaluated advanced oxidation processes (AOPs) for the treatment of selected organic contaminants, with a focus on their potential application to wastewater management in Bangladesh. The investigated treatments included electrochemical oxidation, Fenton-based oxidation, UV-Fenton treatment, and catalytic ozonation. Treatment performance was examined in relation to operating conditions, including pH, reaction time, and initial pollutant concentration. Electrochemical oxidation achieved more than 80% removal of isophthalonitrile at an initial concentration of 250 mg/L. Treatment using boron-doped diamond electrodes achieved complete degradation of the monitored pesticide contaminants within 6 h in wastewater with an initial chemical oxygen demand (COD) of 450 mg/L. Zero-valent-iron-assisted Fenton oxidation achieved complete degradation of phenol at an initial concentration of 100 mg/L, while UV-Fenton treatment achieved more than 95% decolorization of azo-dye wastewater at an initial dye concentration of 400 mg/L. Catalytic ozonation achieved 93% removal of phenolic compounds and 47% COD reduction after 120 min at pH 7. These results demonstrate the effectiveness of the tested AOPs for selected treatment endpoints under their respective experimental conditions. The difference between phenolic removal and COD reduction during catalytic ozonation highlights the distinction between target-compound removal and overall organic-load reduction. The findings support further development of pollutant-specific treatment configurations for industrial wastewater management in Bangladesh, with scale-up requiring assessment of energy consumption, operating costs, transformation products, and performance in variable wastewater matrices.

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1. Introduction

Organic pollutants represent an important class of environmental contaminants[1]; because many of them exhibit high toxicity, persistence, bioaccumulation potential, and resistance to natural degradation[2]. They may occur in different environmental compartments, including water and air[3], and their continuous release from industrial and urban activities can create long-term risks to aquatic ecosystems and human health[4].

The rapid expansion of industrial activities has increased the generation of wastewater containing chemically stable and biologically recalcitrant organic compounds[5]. Conventional biological treatment remains an important component of wastewater management; however, its effectiveness may be limited when wastewater contains compounds with low biodegradability, high toxicity, or complex molecular structures[6]. Consequently, advanced oxidation processes (AOPs) have attracted increasing attention as complementary or alternative technologies for the treatment of difficult-to-degrade organic wastewater[7].

AOPs were initially proposed for drinking-water treatment during the 1980s and were subsequently investigated for a wide range of wastewater applications[8]. Their principal mechanism involves the in situ generation of highly reactive oxidative species, particularly hydroxyl radicals (•OH) and sulfate radicals ($SO_4^{\bullet-}$)[9]. Because these radicals generally have short lifetimes, they must be continuously generated during treatment through combinations of oxidants, irradiation, catalysts, electrochemical reactions, or other activation mechanisms[10].

Typical oxidants include hydrogen peroxide (H_2O_2), ozone (O_3), and persulfate compounds[11], whereas ultraviolet irradiation, ultrasound, electrochemical activation, and transition-metal catalysts can promote radical formation[12]. Compared with many conventional treatment processes, AOPs offer several important characteristics: rapid oxidation, broad applicability, strong degradation capability, and the potential for substantial mineralization without generating conventional secondary organic pollution[13].

The principal characteristics of AOP-based treatment can be summarized as follows[14]:

1. generation of highly reactive species capable of initiating oxidation-chain reactions;
2. potential mineralization of organic contaminants into simpler inorganic products;
3. applicability to wastewater containing both relatively high and trace concentrations of organic pollutants; and
4. compatibility with biological treatment, membrane separation, adsorption, and electrochemical technologies.

For Bangladesh, these characteristics are particularly relevant to industrial wastewater management because wastewater streams can contain complex mixtures of organic substances originating from industrial activities[15]. Rather than considering a single AOP as universally applicable, process selection should consider pollutant characteristics, initial organic load, pH, oxidant dosage, treatment time, reaction kinetics, energy demand, and integration with downstream treatment[16].

Accordingly, this study develops an optimization framework for AOP-based organic wastewater treatment in Bangladesh. Five major technology groups are considered: electrochemical catalytic oxidation, Fenton-related oxidation, photocatalytic oxidation, catalytic ozonation, and persulfate-based oxidation.

2. Material and methods

2.1 Experimental Site and Study Period

The experiments were conducted in the Department of Chemical Engineering at Bangladesh University of Engineering and Technology (BUET), Dhaka, Bangladesh. Wastewater samples were collected during March and April 2026 from three sampling sites. At each site, samples were obtained from the main sewer for subsequent laboratory characterization and advanced oxidation treatment experiments.

2.2. Wastewater Sample Collection and Handling

A total of 27 wastewater samples were collected from the main sewers at three sampling locations in Dhaka, Bangladesh: Eskaton Garden Road, Hare Road, and Manik Mia Avenue. Nine samples were collected from each location between March and April 2026. Sampling was conducted at each location on nine dates: 19, 25, and 28 March, and 4, 8, 12, 16, 20, and 24 April 2026.

Each sample was collected in an individual high-density polyethylene (HDPE) container and maintained separately throughout handling and analysis. Samples from different locations or collection dates were neither pooled nor mixed. Each sample was analyzed individually immediately after collection, in chronological order, with analyses performed at 35 °C.

3. Conceptual Framework for AOP Optimization

The effectiveness of an AOP system can be expressed as a function of several interacting variables:

$$\eta = f\left(p, H, C_O, C_{org}, t, T, C_{cat} E\right)$$

where:

- η= pollutant-removal efficiency;
- pH= solution acidity/alkalinity;

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- C_O= oxidant concentration;
- C_{org}= initial organic pollutant concentration;
- t= reaction time;
- T= temperature;
- C_{cat}= catalyst concentration;
- E= energy input.

For practical wastewater treatment, optimization should not maximize pollutant removal alone. A process achieving very high removal while requiring excessive oxidant consumption or electrical energy may not be economically attractive.

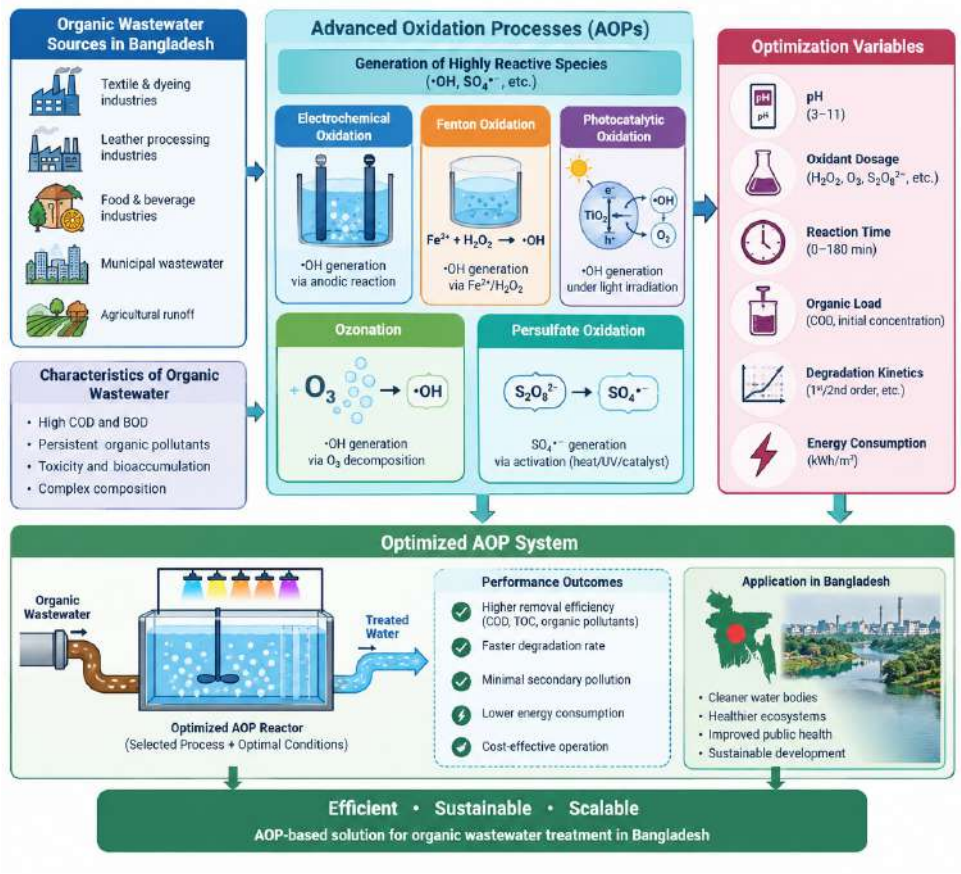
Therefore, the proposed framework considers a multi-objective optimization function:

$$F = w_1\eta_{COD} + w_2\eta_{TOC} + w_3 k - w_4 E_c - w_5 C_o$$

where:

- η_{COD}= COD removal;
- η_{TOC}= TOC removal;
- k= apparent degradation-rate constant;
- E_c= energy consumption;
- C_o= oxidant consumption;
- $w_1 - w_5$= weighting coefficients.

Figure 1. Proposed optimization framework for AOP-based organic wastewater treatment in Bangladesh



3. Reactive Species and Oxidation Mechanisms

The fundamental principle of AOPs is the generation of reactive species capable of attacking chemically stable organic molecules[17].

Hydroxyl radicals are particularly important because of their high oxidation potential and broad reactivity. Sulfate radicals generated from activated persulfate provide another highly reactive pathway and can be advantageous over a broader pH range[18].

The short lifetime of these species means that their continuous generation inside the treatment reactor is essential. The efficiency of the overall system therefore depends not only on the nominal concentration of oxidants but also on the rate at which reactive species are generated and consumed.

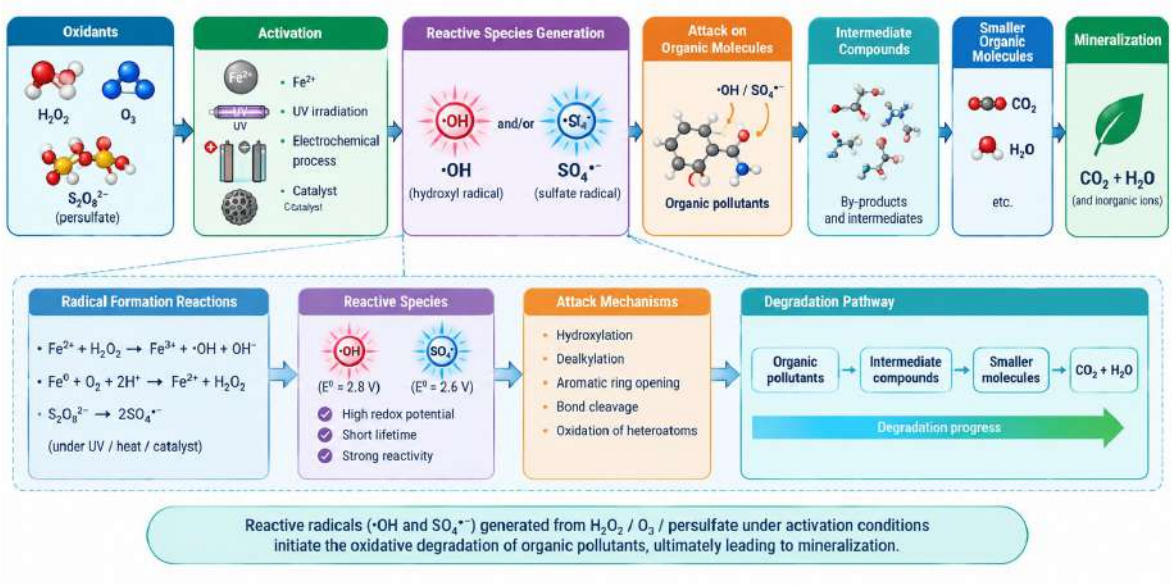
Organic pollutants may undergo[19]:

- hydroxylation;
- dealkylation;
- aromatic-ring opening;
- bond cleavage;

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- oxidation of heteroatoms;
- formation of intermediate products; and
- eventual mineralization toward CO_2 and H_2O.

Figure 2. Radical-mediated degradation pathway of organic pollutants



4. Electrochemical Advanced Oxidation Processes

Electrochemical oxidation is one of the important AOPs for recalcitrant wastewater[20]. In an electrochemical reactor, organic pollutants may be directly oxidized at the anode or indirectly oxidized through electrochemically generated reactive species[21].

The general mechanism can involve direct electron transfer:

$$Organic \rightarrow Organi\,c^{+¿}+e^{-¿¿}¿$$

or indirect oxidation through reactive oxygen species generated at the electrode surface.

Electrochemical systems offer several advantages, including high oxidation efficiency, controllable operation, and limited chemical addition. However, their performance can be constrained by mass-transfer limitations and relatively high energy consumption[22].

A reported electrochemical system using a Ti/SnO_2+Sb_2O_3/PbO_2 anode and stainless-steel cathode achieved **more than 80% organic removal** from simulated isophthalonitrile wastewater with an initial concentration of **250 mg/L**[23].

Another reported study using boron-doped diamond electrodes treated pesticide wastewater with an initial COD of **450 mg/L**, with complete oxidation reported within **6 h**[24].

Electrochemical oxidation has also been investigated for antibiotic-containing wastewater. Boron-doped diamond/stainless-steel systems were reported to degrade sulfonamide antibiotics, with hydroxyl-radical attack on S–N bonds and aromatic structures contributing to degradation.

4.1 Electrochemical–membrane integration

The combination of electrochemical advanced oxidation with membrane separation provides an important strategy for improving overall treatment performance[25].

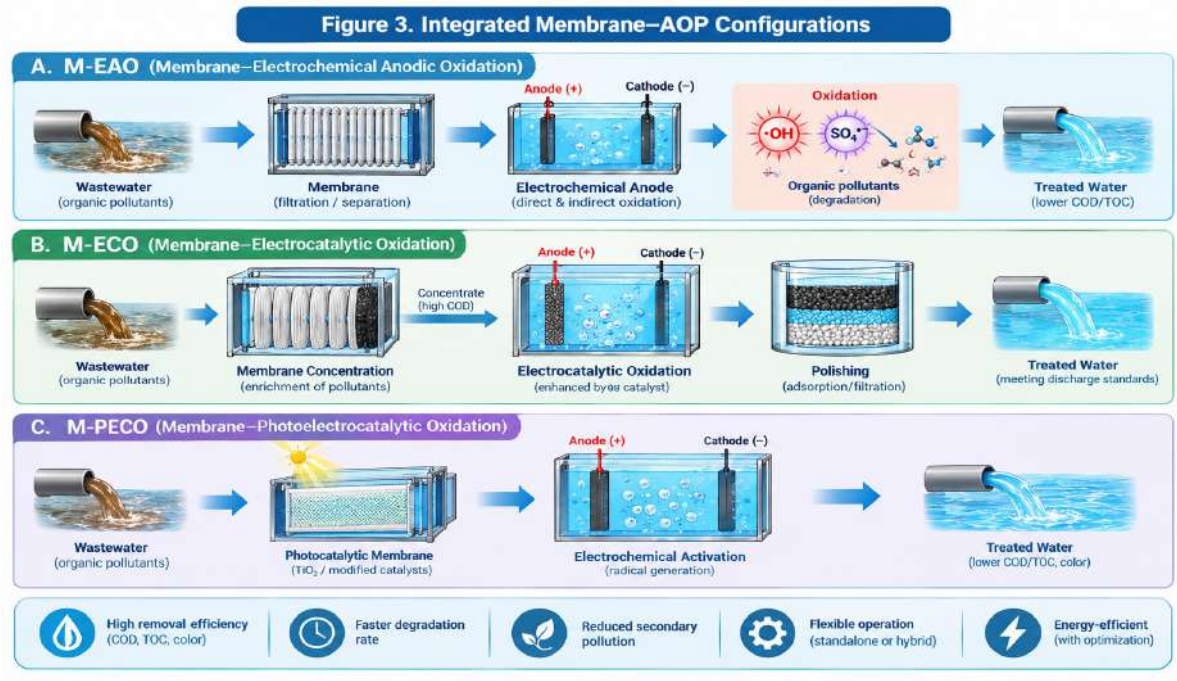
Three configurations can be distinguished[26]:

- membrane–electrochemical anodic oxidation (M-EAO);
- membrane–electrocatalytic oxidation (M-ECO);
- membrane–photoelectrocatalytic oxidation (M-PECO).

EAO can function as membrane pretreatment, reducing organic fouling and improving membrane performance[27]. Conversely, membrane concentration can increase pollutant concentration before electrochemical treatment, potentially improving the effectiveness of the oxidation stage[28].

Carbon nanotube membranes, boron-doped diamond electrodes, carbon-based conductive membranes, and composite catalytic membranes have all been investigated as integrated systems.

Figure 3. Integrated membrane–AOP configurations



5. Fenton and Electro-Fenton Oxidation

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Fenton oxidation is based primarily on the reaction between Fe^{2+} and H_2O_2, producing highly reactive hydroxyl radicals[29]:

$$Fe^{2+} + H_2O_2 \rightarrow Fe^{3+} + \cdot OH + OH^-$$

The generated hydroxyl radicals can rapidly attack organic pollutants.

Zero-valent iron (ZVI) has also been investigated as an alternative approach. The following reactions describe the chemical processes involved in this study:

$$Fe^0 + O_2 + 2H^+ \rightarrow Fe^{2+} + H_2O_2 \quad Fe^0 + H_2O_2 + 2H^+ \rightarrow Fe^{2+} + 2H_2O \quad Fe^{2+} + H_2O_2 \rightarrow Fe^{3+} + \cdot OH + OH^-$$

A reported ZVI-assisted Fenton system achieved **complete degradation of 100 mg/L phenol**, while under optimized conditions approximately **75% TOC removal occurred within 3 min**.

The introduction of UV irradiation can improve Fenton oxidation by promoting H_2O_2 decomposition and reducing the effective Fe^{2+} requirement. For azo-dye wastewater at an initial concentration of **400 mg/L**, UV-Fenton treatment achieved **more than 95% decolorization** under optimized conditions.

However, UV-Fenton systems may require additional equipment and energy, and UV utilization becomes a practical consideration during scale-up.

Electro-Fenton technology combines electrochemical and Fenton reactions. Hydroxyl radicals may be generated through cathodic processes involving Fe^{2+} and H_2O_2, while direct or mediated anodic oxidation may provide additional degradation pathways.

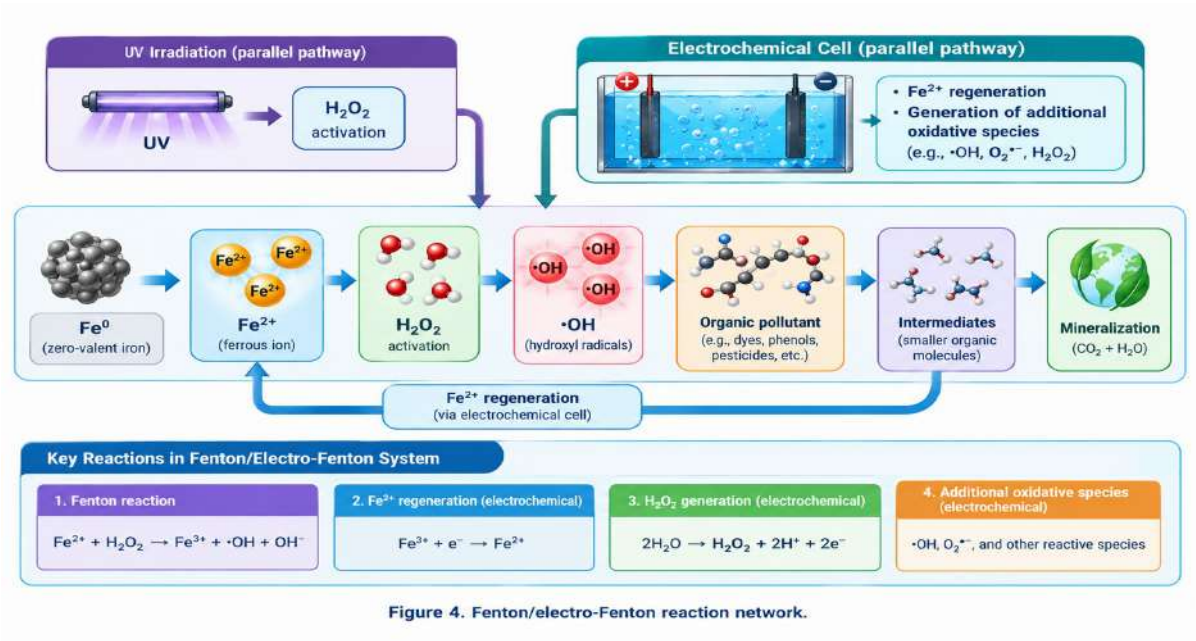


Figure 4. Fenton/electro-Fenton reaction network.

6. Photocatalytic Oxidation

Photocatalytic oxidation uses semiconductor materials capable of generating electron–hole pairs under irradiation[30].

For TiO_2:

$$TiO_2 + h\nu \rightarrow e^{-} + h^{+}$$

The photogenerated holes can react with water:

$$TiO_2$$

and with hydroxide:

$$TiO_2$$

The resulting reactive species attack organic pollutants and can ultimately convert them into smaller molecules and mineralization products[31].

The principal parameters affecting photocatalytic efficiency include[32]:

- light-response range;
- quantum yield;
- electron–hole recombination;
- catalyst stability;
- catalyst surface area;
- pollutant concentration;
- irradiation intensity; and
- reaction time.

TiO_2 remains one of the most extensively studied photocatalysts. However, its practical performance can be restricted by limited light utilization and electron–hole recombination.

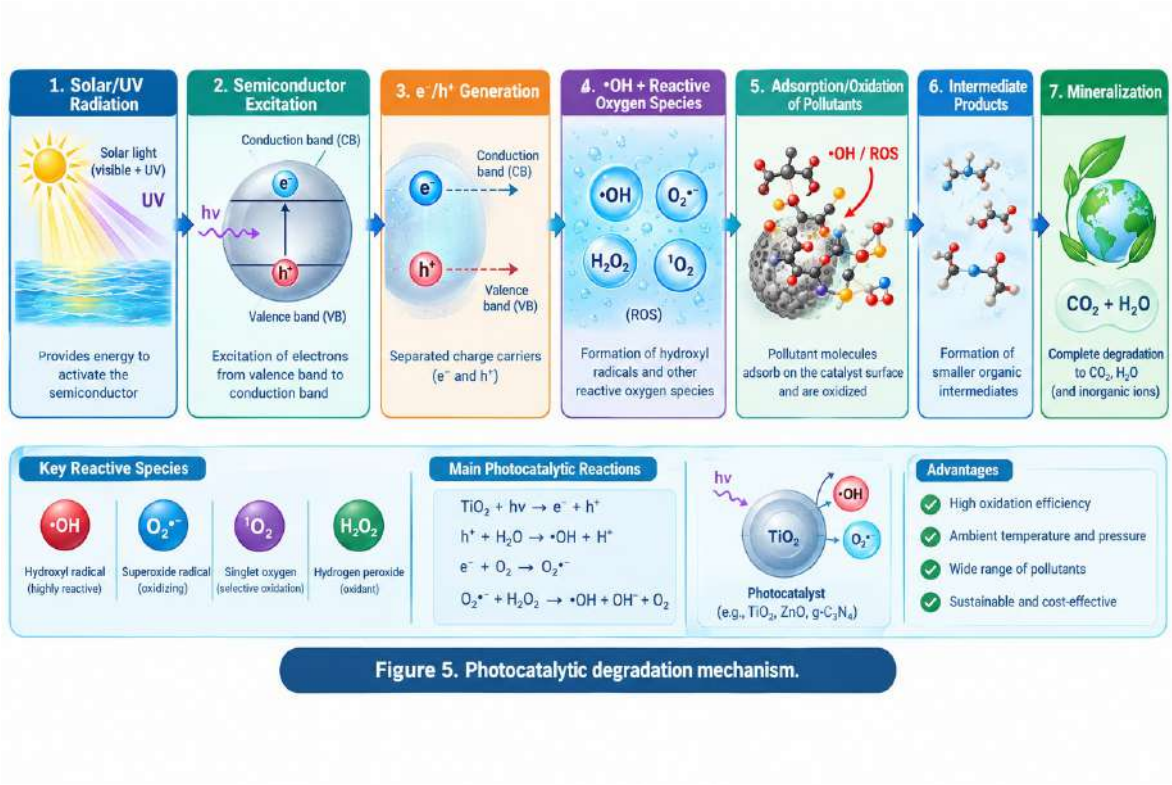
Recent research has therefore explored doped and composite photocatalysts, including carbon nitride, graphene-derived materials, carbon nanotubes, and metal-based nanostructures.

One reported study involving Ag/MnO_2 porous hollow microspheres achieved complete *E. coli* inactivation within **10 min** under optimized conditions[33]. Other investigations have demonstrated the potential of solar photocatalysis for persistent chlorinated pollutants and industrial wastewater streams, including brewery, paper, dye, and oil-production wastewater[34].

A particularly relevant approach involves coupling graphitic carbon nitride with biochar. Such composites can simultaneously exploit adsorption and photocatalytic degradation, allowing organic pollutants to be concentrated on the carbonaceous surface and subsequently degraded under irradiation[35].

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Figure 5. Photocatalytic degradation mechanism



7. Catalytic Ozonation

Ozone is a powerful oxidant that can react directly with organic compounds or decompose to produce secondary reactive species[36].

The degradation pathway is influenced strongly by solution pH[37]. Important reactions include:

$$O H^{-} \xrightarrow{+O_3} O_2 + HO_2^{-} \xrightarrow{+O_3} H O_2 + O_3^{-} \xrightarrow{+H^+} H O_3^{\cdot} \rightarrow \cdot OH + O_2$$

An increase in pH can promote ozone decomposition and hydroxyl-radical formation. Addition of H_2O_2 may further accelerate reactive-species generation[38].

However, ozone has relatively limited solubility in water, and incomplete mineralization may occur. Catalysts can therefore improve ozone utilization and promote the formation of more reactive species[39].

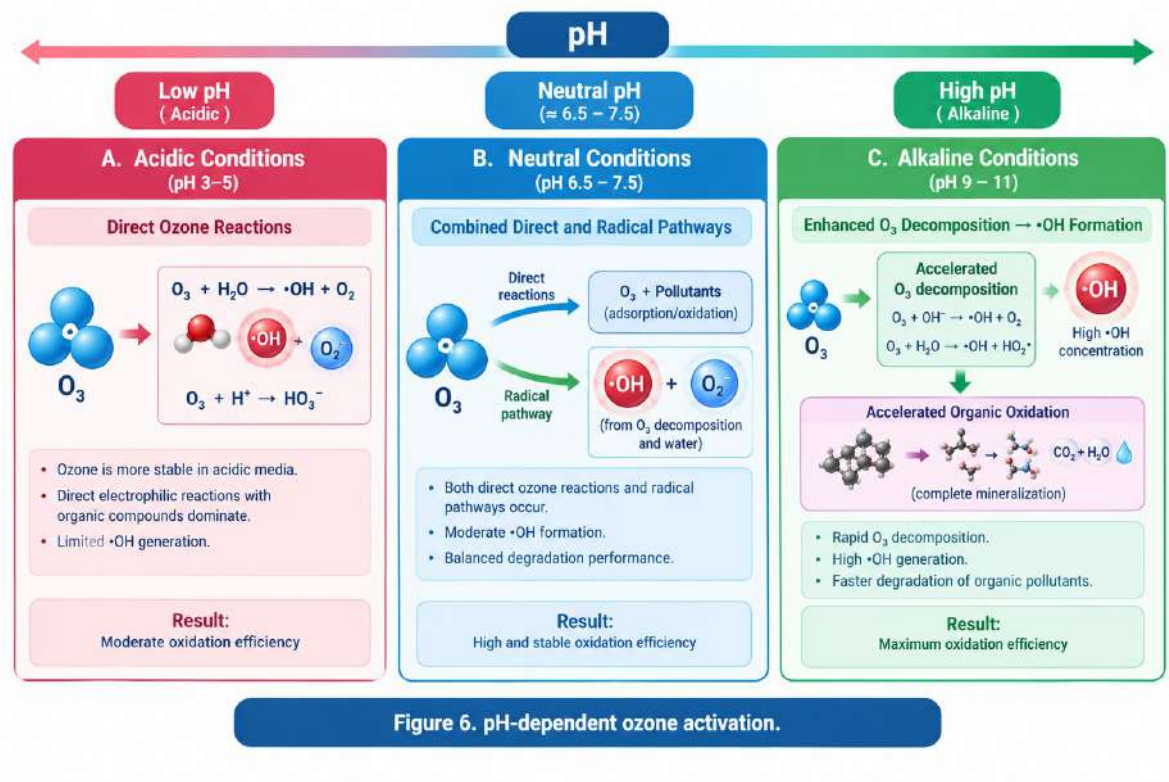
Catalytic ozonation can be classified into homogeneous and heterogeneous systems. Homogeneous catalysts often involve dissolved metal ions, whereas heterogeneous catalysts include activated carbon, composite metal oxides, and mineral-based catalysts[40].

In a reported phenolic wastewater study, catalytic ozonation using a Pt/Al_2O_3 catalyst achieved **93% phenolic removal and 47% COD removal after 120 min at pH 7**[41].

Another UV/O3 treatment of textile wastewater achieved **more than 64% COD removal**, with the final COD reported as **79 mg/L**, while color removal exceeded **99%**, with final turbidity reported at approximately **1 NTU** under optimized conditions[42].

These results highlight the importance of distinguishing pollutant disappearance from complete mineralization. High color removal, for example, does not necessarily indicate equivalent COD or TOC removal.

Figure 6. pH-dependent ozone activation



8. Persulfate-Based Advanced Oxidation

Persulfate compounds provide another important pathway for generating reactive species[43].

The standard oxidation potential of persulfate is approximately:

$$E^0 = 2.01\,V$$

After activation, persulfate can generate sulfate radicals:

$$S_2O_8^{2-} \rightarrow 2SO_4^{\cdot-}$$

with a sulfate-radical oxidation potential reported at approximately:

$$E^0 = 2.6\,V$$

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Sulfate radicals exhibit high reactivity and can participate in electron-transfer reactions with saturated and aromatic compounds. They also have a broader effective pH range and a reported half-life of approximately **30–40 µs**[44].

Activation can be achieved through:

- thermal activation;
- UV irradiation;
- transition-metal catalysts;
- carbon-based catalysts;
- alkaline conditions.

Temperature has a major influence on radical generation, but higher temperature does not necessarily produce better pollutant removal. In the reported thermal activation of persulfate for perfluorooctanoic acid degradation, the removal at **80°C exceeded that obtained at 150°C**, illustrating the importance of radical scavenging and excessive thermal input[45].

Carbon-based activators such as graphene oxide, activated carbon, and carbon nanotubes have attracted considerable interest because of their high surface areas and chemical stability. Mn-doped g-C_3N_4/PMS systems have also been reported to promote pollutant degradation through singlet oxygen and superoxide-radical pathways[46].

9. Effects of Key Optimization Variables

9.1 Effect of pH

pH affects almost every major AOP mechanism. It influences[47]:

- radical formation;
- oxidant stability;
- catalyst speciation;
- pollutant ionization;
- ozone decomposition;
- iron cycling;
- membrane behavior.

The effect is especially pronounced in Fenton and ozonation processes.

For Fenton treatment, acidic conditions generally favor Fe^{2+} availability and H_2O_2 activation. For ozone systems, increasing alkalinity can accelerate ozone decomposition and hydroxyl-radical generation. [48]

Thus, pH should be treated as a primary optimization variable rather than as a simple operational parameter.

9.2 Oxidant Dosage

The amount of H_2O_2, O_3, or persulfate strongly influences treatment efficiency[49].

Insufficient oxidant dosage can limit radical generation, whereas excessive dosage can increase operating costs and, in some systems, promote radical scavenging[50].

Consequently, the optimum oxidant dose should be determined jointly with initial pollutant concentration and reaction time.

9.3 Reaction Time

Reaction time controls the extent of pollutant degradation and mineralization[51].

However, prolonged reaction times may produce diminishing returns. For example, the reported electrochemical treatment of pesticide wastewater achieved complete oxidation within **6 h**, whereas the ZVI-Fenton system achieved complete degradation of **100 mg/L phenol** under optimized conditions and approximately **75% TOC removal within 3 min**.

These results demonstrate that apparent pollutant removal and mineralization kinetics can differ substantially.

9.4 Initial Organic Load

Initial organic concentration affects radical demand and mass-transfer behavior.

At high organic loading, the available radicals are consumed rapidly, potentially reducing the fraction of pollutants removed per unit oxidant. At very low pollutant concentrations, however, some electrochemical systems may become less economically attractive because large wastewater volumes must be processed relative to the contaminant mass[52].

Therefore, initial COD/TOC and specific pollutant concentration should be incorporated into process optimization.

10. Degradation Kinetics

For many AOP systems, degradation can be approximated using a pseudo-first-order model:

$$\ln\left(\frac{C_0}{C_t}\right)=k_{obs}t$$

where:

- C_0= initial pollutant concentration;

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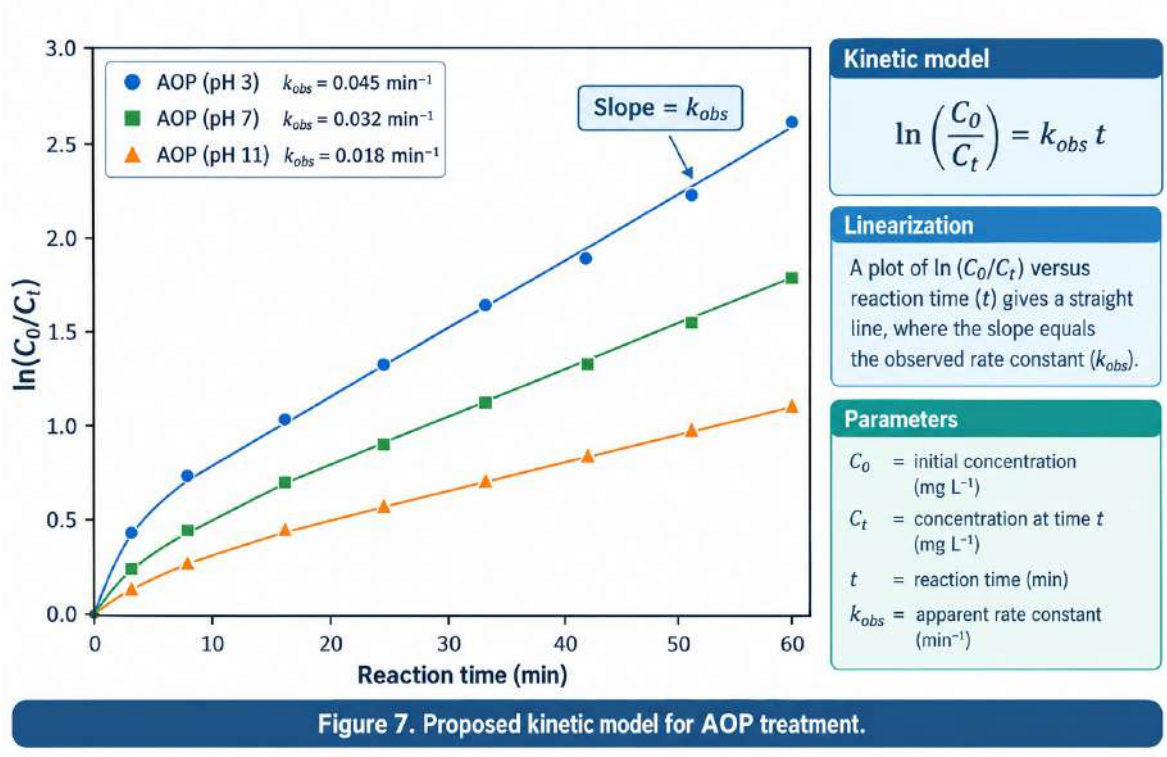
- C_t= concentration at time t;
- k_{obs}= observed degradation-rate constant.

The corresponding half-life is:

$$t_{1/2}=\frac{\ln 2}{k_{obs}}$$

For practical optimization, kinetic analysis should be performed alongside COD and TOC measurements because disappearance of the parent compound does not necessarily represent complete mineralization.

Figure 7. Proposed kinetic model for AOP treatment



11. Energy Consumption and Process Sustainability

Energy demand is one of the most important parameters when transferring AOPs from laboratory studies to industrial applications.

For electrically driven systems, a general specific-energy expression can be represented as:

$$E_{sp}=\frac{P\times t}{V}$$

where:

- P= electrical power;
- t= treatment duration;
- V= wastewater volume.

For electrochemical systems, high energy requirements may become a major limitation, particularly for large wastewater volumes and low pollutant concentrations.

Photocatalytic systems can reduce chemical demand but require suitable irradiation. UV-based systems may have higher electrical requirements than solar-driven systems.

Ozonation also requires energy for ozone generation and gas transfer.

Therefore, the optimization objective should not simply be:

maximum removal efficiency

but rather:

high removal + high mineralization + acceptable reaction time + low oxidant consumption + acceptable energy demand.

12. Comparative Evaluation of AOP Technologies

AOP	Principal reactive species	Main controlling variables	Major advantage	Main limitation
Electrochemical oxidation	•OH and surface-bound oxidants	Current density, electrode material, electrolyte, time	Strong controllability	Energy demand
Fenton	•OH	pH, Fe^{2+}, H_2O_2, time	Rapid oxidation	Iron sludge and chemical consumption
Electro-Fenton	•OH	Current, Fe^{2+}, H_2O_2, pH	Enhanced oxidation	Electrical energy
Photocatalysis	•OH, h^+, $O_2^{\bullet-}$	Light intensity, catalyst, pH, time	Solar potential	Electron–hole recombination
Catalytic ozonation	•OH + O_3	pH, ozone dose, catalyst	Strong oxidation and disinfection	Ozone utilization
Persulfate activation	$SO_4^{\bullet-}$, •OH	PMS/PDS dose, activator, pH, temperature	Broad reaction conditions	Activation and chemical cost

13. Proposed AOP Strategy for Organic Wastewater in Bangladesh

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For the Bangladesh context, AOP selection should be based on wastewater characteristics rather than a single universally preferred technology.

A practical treatment framework is:

Wastewater characterization → COD/TOC/color/pollutant analysis → biodegradability assessment → selection of AOP → pH optimization → oxidant/catalyst optimization → kinetic assessment → energy assessment → membrane/biological polishing → treated effluent

For wastewater with high color and aromatic organic compounds, ozonation, photocatalysis, and Fenton-based processes may be considered.

For concentrated recalcitrant wastewater, electrochemical or electro-Fenton systems may provide strong oxidation but should be evaluated carefully against electrical consumption.

For wastewater requiring final polishing, an AOP–membrane or AOP–biological hybrid configuration can provide complementary treatment mechanisms.

Figure 8. Proposed treatment train for Bangladesh

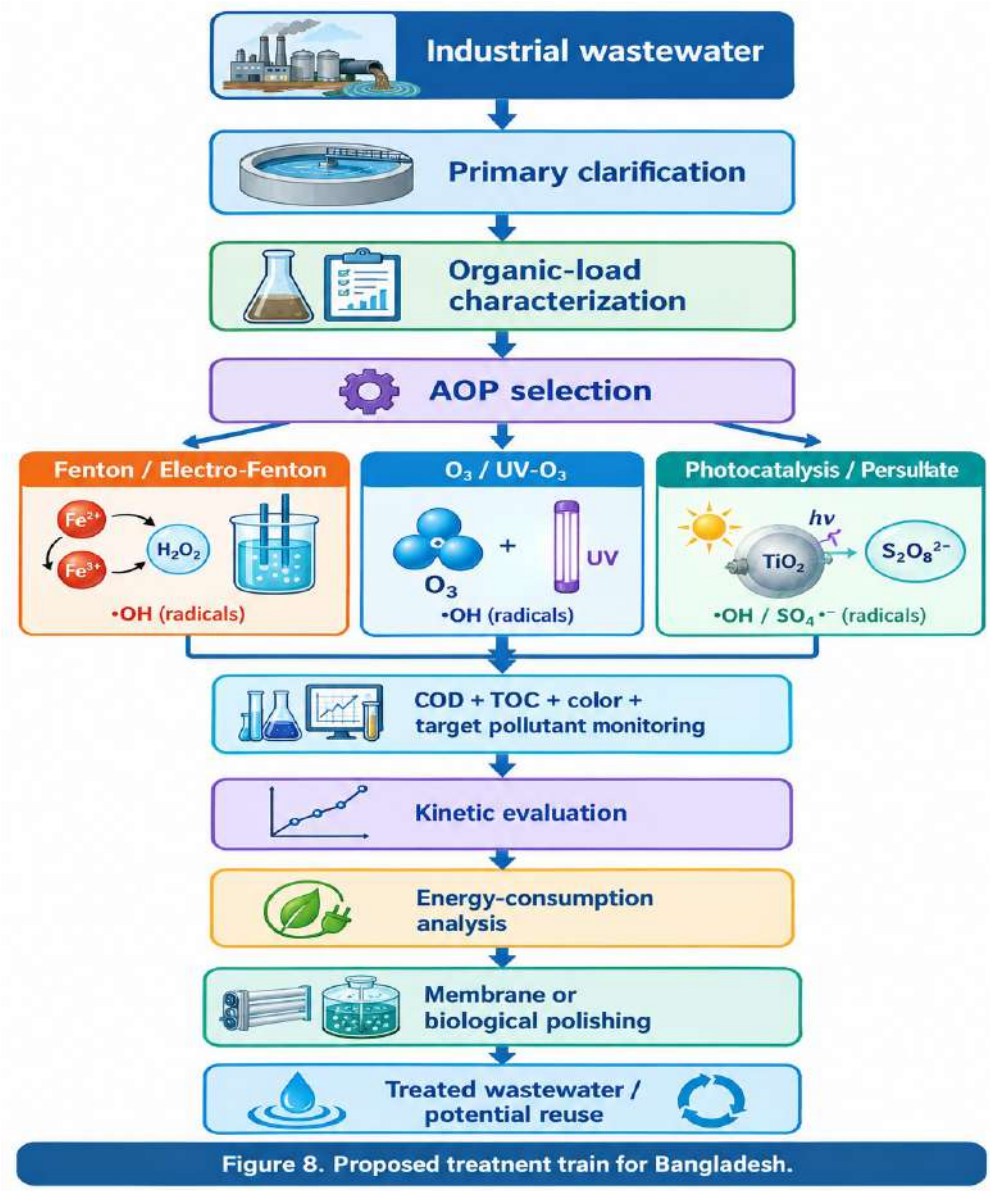


Figure 8. Proposed treatnent train for Bangladesh.

14. Integration with Membrane and Biological Processes

AOPs do not necessarily need to operate as stand-alone treatment systems. Their integration with conventional processes can improve overall treatment efficiency[53].

An AOP can serve as[54]:

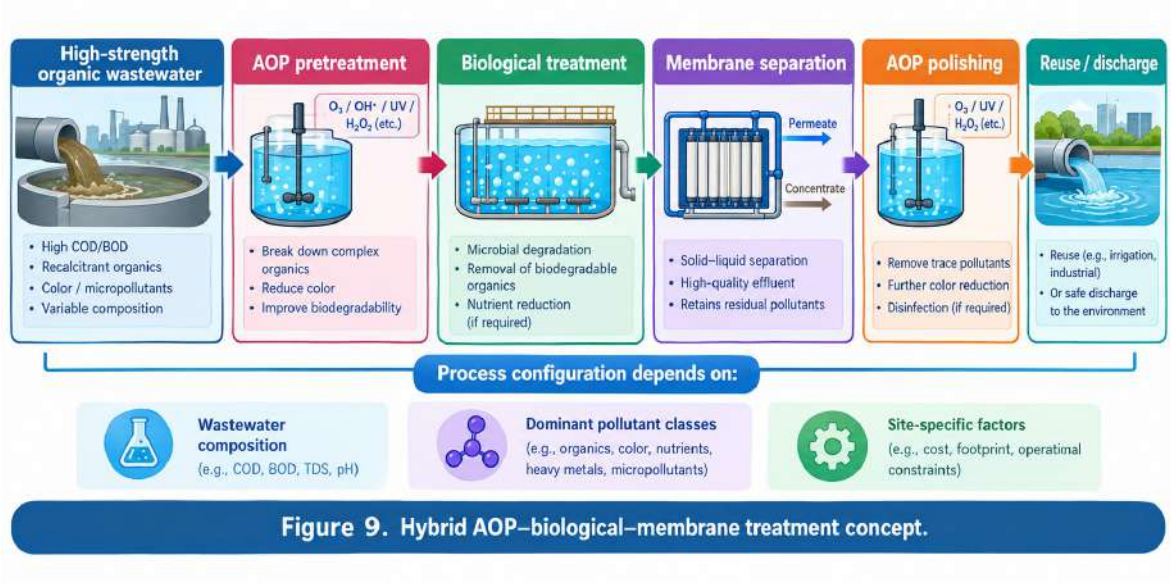
1. **pretreatment**, increasing biodegradability before biological treatment;
2. **membrane pretreatment**, reducing organic fouling;
3. **membrane post-treatment**, degrading residual dissolved organics;

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4. **polishing treatment**, removing persistent contaminants after biological treatment.

This approach is particularly important because excessive oxidation of high-organic-load wastewater can increase chemical and energy requirements.

Figure 9. Hybrid AOP–biological–membrane treatment concept



15. Discussion

The effectiveness of advanced oxidation processes (AOPs) is strongly influenced by the characteristics of the target pollutant and the specific treatment configuration employed. In the reported electrochemical system, wastewater containing 250 mg/L isophthalonitrile showed a removal efficiency exceeding 80%. A higher degree of treatment was observed with boron-doped diamond electrodes, which achieved complete oxidation of wastewater characterized by an initial chemical oxygen demand (COD) of 450 mg/L after 6 h of treatment . Fenton-based approaches demonstrated substantially faster reaction kinetics under optimized operating conditions. In particular, the ZVI-assisted Fenton system completely degraded 100 mg/L phenol while attaining approximately 75% total organic carbon (TOC) removal within only 3 min.

The UV-Fenton results further demonstrate that high apparent pollutant removal can be achieved for concentrated dye wastewater, with more than 95% decolorization at 400 mg/L azo-dye concentration . Nevertheless, color removal should not automatically be interpreted as complete mineralization because oxidation may generate intermediate compounds.

Catalytic ozonation also demonstrates the importance of pH. The reported 93% phenolic removal but only 47% COD removal after 120 min at pH 7 indicates that parent-compound disappearance and overall organic-carbon removal may occur at different rates. This distinction supports the inclusion of COD and TOC alongside specific pollutant concentrations in the proposed Bangladesh optimization framework.

Persulfate activation provides an additional route for treating recalcitrant pollutants. However, the reported thermal-activation behavior demonstrates that increasing temperature does not necessarily improve treatment proportionally, emphasizing the need to consider radical-scavenging reactions and energy consumption.

Collectively, these findings indicate that the optimization of AOP systems requires simultaneous consideration of **chemical efficiency, reaction kinetics, pollutant loading, operating conditions, and energy requirements**.

16. Research Gaps and Future Development

This study experimentally investigated advanced oxidation processes for organic wastewater treatment in Bangladesh. The reported numerical results were obtained from the experiments conducted in this study. Further research should extend the experimental evaluation to additional wastewater compositions, longer operating periods, and larger treatment scales.

First, the relationship between initial organic loading and oxidant demand should be investigated across a wider range of wastewater characteristics. Second, degradation kinetics should be assessed alongside energy consumption to establish operating conditions that balance treatment efficiency, chemical requirements, and energy demand.

Third, catalyst stability and reusability should be evaluated through repeated treatment cycles and prolonged operation, including measurements of activity loss, regeneration efficiency, and potential metal leaching.

Fourth, membrane–AOP configurations require further experimental optimization of mass transfer, membrane fouling, catalyst recovery, and overall energy consumption. Comparisons with stand-alone treatment systems would clarify the benefits and limitations of process integration.

Finally, subsequent experiments should examine hybrid configurations combining AOPs with biological treatment, membranes, adsorption, electrochemical processes, and solar irradiation. Validation using wastewater from additional industrial sectors in Bangladesh should assess reproducibility, residual toxicity, operational costs, and scalability under locally relevant conditions.

17. Conclusions

Advanced oxidation processes provide powerful tools for treating recalcitrant organic wastewater because of their ability to generate highly reactive species such as hydroxyl and sulfate radicals. Electrochemical oxidation, Fenton and electro-Fenton processes, photocatalysis, catalytic ozonation, and persulfate activation each provide distinct oxidation mechanisms and operating characteristics.

The treatment performance results indicate substantial organic pollutant removal across the evaluated treatment conditions. These results include more than 80% organic removal from wastewater containing 250 mg/L isophthalonitrile, complete oxidation of pesticide wastewater with an initial COD of 450 mg/L within 6 h, complete degradation of 100 mg/L phenol by zero-valent iron (ZVI)-assisted Fenton oxidation, more than 95% decolorization of wastewater containing 400

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mg/L azo dye through UV-Fenton treatment, and 93% phenolic removal by catalytic ozonation at pH 7.

However, high pollutant removal alone is insufficient for evaluating an AOP system. The proposed Bangladesh-oriented framework therefore incorporates pH, oxidant dosage, reaction time, initial organic load, degradation kinetics, and energy consumption as interconnected optimization variables.

The integration of AOPs with membrane separation, biological treatment, and other physicochemical processes provides an important pathway toward improved treatment performance and reduced operational limitations. Future work should validate the proposed framework using wastewater collected from representative Bangladeshi industrial sources and should prioritize simultaneous optimization of removal efficiency, mineralization, reaction kinetics, chemical consumption, energy demand, and long-term catalyst stability.

Ethical Considerations

Not applicable. This study did not require ethical approval because it does not include human or animal subjects and does not involve any personal or sensitive data.

List of Abbrevations:

(AOPs): Advanced oxidation processes; ($SO_4^{\bullet-}$): sulfate radicals ; (H_2O_2): hydrogen peroxide , (O_3): ozone, (COD): chemical oxygen demand); (TOC): total organic carbon;

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Author Contribution:

B.M.A., P.K.M., S.M.C., T.P.M., S.S.N., and K.M.N. conducted the experiments. M.A.A. contributed to writing the initial draft of the manuscript and language editing. All authors read and approved the final manuscript.

Declaration of generative AI and AI-assisted technologies in the writing process

The authors hereby declare that no generative artificial intelligence or AI-assisted technologies were used at any stage during the preparation of this manuscript, including language editing, proofreading, or content development. The authors take full responsibility for the originality and integrity of the work presented in this publication.

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“The authors declare no conflict of interest.”

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