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Novel Approaches to Wastewater Treatment Processes: Synchronizing Advanced Oxidation Processes with Nanostructured Catalysts: A Review

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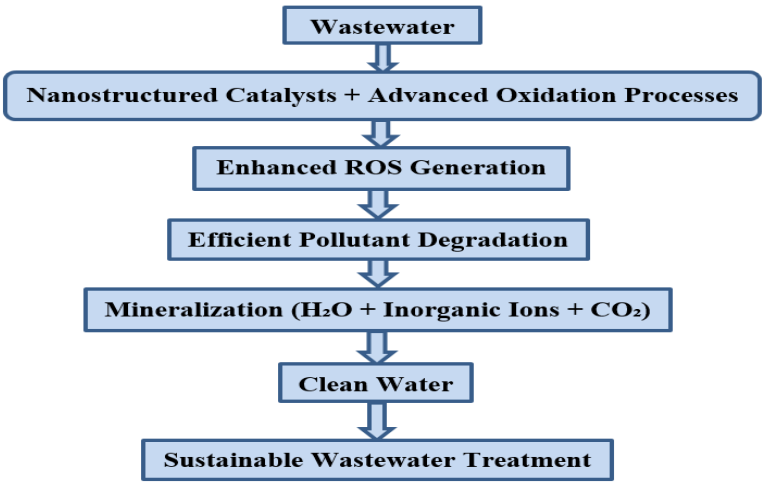
Abstract

The rising pollution of water resources by recalcitrant organic pollutants provides the necessity to develop the new advanced treatment technologies along with the traditional pattern of treatment processes. Advanced Oxidation Processes (AOPs) have gained popularity as they can be used to degrade stubborn pollutants as they generate highly reactive oxygen species (ROS), primarily, hydroxyl radical (OH). Nanostructured catalysts have been incorporated to revolutionize AOP, making them much more efficient, selective and cost-effective. The review provides an in-depth discussion of the synergy between engineered nanomaterials and a number of AOPs (photocatalysis, Fenton based processes, ozonation, and persulphate activation). We discuss the fundamentals of action of nanostructured catalysts including metal oxides, carbon-based nanomaterial and single atom catalysts that promote the generation of ROS in detail. Recent achievements in designing materials toward improvement of the light absorption, charge separation and catalytic stability are discussed. In addition, the review addresses such critical issues as catalyst recovery, potential nanotoxicity, scale up to real-world solutions in industry. Taking into account the latest studies (up to the year 2026), the article at hand underlines the potential of nanocatalyst-based AOPs integration as transformative and suggests the research pathways to reach sustainable and efficient wastewater treatment.

Keywords: Environmental Engineering, Advanced Oxidation Processes (AOPs), Nanostructured Catalysts, Wastewater Treatment Processes, Hydroxyl Radicals, Persulfate Activation, Photocatalysis, Fenton-like Catalysis



Graphical Abstract

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1. Introduction:

One of the most significant problems of the 21st century is water security to which the world is exposed. The processes of industrialization, urbanization, and agricultural activities have led to the extensive pollution of aquatic ecosystems with numerous enduring organic pollutants (POPs), such as pharmaceuticals, personal care products, endocrine perturbing chemicals, pesticides and industrial dyes [1].

The compounds are usually non-biodegradable, toxic and may not be affected by the normal wastewater treatment facilities which are a significant threat to human health and environment [2]. Traditional methods of treatment, such as biological processes, coagulation and adsorption are not effective in the complete mineralization of these recalcitrant contaminants and most of them are merely passed on to another stage [3]. AOPs are a group of chemical treatment processes that offer to eliminate organic and inorganic substances in water and wastewater by oxidation that forms reactions with hydroxyl radicals (OH) [4]. The OH radical is a potentially potent, non selective oxidant (E degrees = 2.8 V) that can be useful in the mineralization of complex organic molecules to produce CO, HO and inorganic ions. The generation of ROS is efficient and sustained and this is what determines the efficiency of any AOP. The classical homogeneous AOPs, such as the classical Fenton reaction (Fe2+/H2O2), have numerous severe drawbacks, including a limited spectrum of working pH values, the formation of iron sludge and excessive use of reagents [5]. To eliminate these drawbacks the discipline has moved towards the use of heterogeneous catalysts. With the emergence of nanotechnology, this field has received a new paradigm. The high surface to volume ratio and high surface active sites of nanostructured catalysts has never been tried before, which gives the ability to enhance kinetics and efficiency of AOPs through their ability to adjust the electronic properties and to adapt the surface active sites [6].

There has been a significant number of reviews on the application of AOPs and nanotechnology in wastewater treatment, however, a major gap is the integration of the most recent developments in AOPs in combination with nanostructured catalysts (up to 2026) and a thorough synthesis of current advances in the field, including the mechanisms of ROS production and their applications. This review is intended to fill this gap by analysing the mechanisms, performances and material design principles of different catalytic AOP systems.

The aims of the review are:

1. To critically discuss fundamentals and recent advances in nanostructured catalyst enhanced AOPs including the Fenton based process, ozonatio, photocatalysis and persulfate activation.
2. To analyze the crucial mechanisms by which nanocatalysts improve the efficiencies of AOP, including increased generation of ROS, increased charge separation, and increased mass transfer.
3. To assess the potential challenges and future outlook of these advanced nanohybrid systems for large-scale application, such as catalyst recovery, possible nanotoxicity, and economic viability.
4. To emphasize the development of hybrid systems, the novel design strategies for nanocatalysts and their use for targeted classes of pollutants.
5. To offer directions for systematic future research with special focus on new solutions and materials for sustainable and efficient wastewater treatment [7, 8].

Comparison between conventional methods and AOPs is shown in Table.1. The comparison emphasizes a major deviaition in the handling of persistant organic pollutants (POP) between advanced and conventional techniques.Conventional technique like coagulation and biological treatment mainly target suspended solids and biodegrable wastes via physical separation and bacterial culture respectively. However these techniques are ineffective against the POPs. On the other hand Advanced Oxidation processes (AOPs) treat effectively all the organic pollutants by forming highly reactive oxygen species (ROS) [4,8].

Although AOPs are highly effective in removal of complex pollutants, yet it is often challenged by raised operational cost and handling of chemical sludge formed in some cases. Therefore, the choice of selecting a treatment method is highly depends on the required level of treatment and the economic limitation of the technique.

Table 1: Comparison of Conventional Treatment Methods and Advanced Oxidation Processes (AOPs).

Number	Treatment Method	Mechanism	Target Pollutants	Key Limitation	Effectiveness on POPs	Reference
1	Conventional (Biological/Coagulation)	Microbial degradation, Physical separation	Biodegradable, Suspended Solids	Inability to mineralize POPs	Largely ineffective, Phase transfer	[3]
2	Advanced Oxidation Processes (AOPs)	Generation of highly reactive oxygen species (ROS)	Recalcitrant Organic Pollutants (POPs)	High operational cost, Sludge formation (Traditional Fenton)	High effectiveness, Mineralization	[4, 8]

2. Advanced Oxidation Processes (AOPs) in Wastewater Treatment:

AOPs are characterized by their ability to generate highly reactive species, primarily hydroxyl radicals (•OH), which are potent oxidants capable of non-selectively degrading a wide range of organic pollutants into less harmful compounds, ultimately leading to mineralization into CO_2, H_2O, and inorganic ions[4, 8]. The high redox potential of •OH (E° = 2.8 V) makes AOPs particularly effective against recalcitrant contaminants that are resistant to conventional biological and physical treatment methods [8-15].

An innovative approach of integrating advanced oxidation process with nanocatalyst is shown in Figure.1. Impurities which cause major environmental challenges can be removed using the techniques of advanced oxidation processes. In AOPs strong oxidant is employed to degrade complex contaminants. The introduction of nanocatalyst increases the rate of oxidation reaction and decreases energy consumption. The main advantage of this technique is the easy recovery of catalyst, which makes the process attractive both economically and environment friendly.

Various types of AOPs have been developed and extensively studied for wastewater treatment:

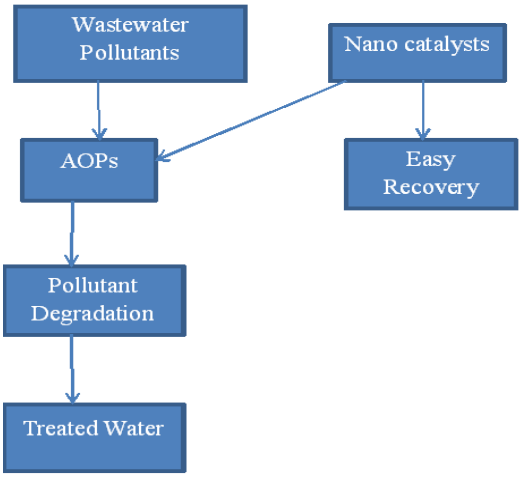

Figure 1: Conceptual Schematic of Nanocatalyst-AOP Synergy (Adapted from [4, 8]).

2.1. Photocatalysis:

Photocatalysis normally uses semiconductor materials as catalysts, such as titanium dioxide (TiO_2). Upon irradiation with light (UV or visible light, depending on the catalysts bandgap), the semiconductor absorbs photons, causing the excitation of electrons from the valence band (VB) to the conduction band (CB), forming electron-holes pairs (e^-/h^+). These charge carriers then react with water and oxygen to produce *OH and other reactive oxygen species (ROS) such as superoxide radicals (($\bullet O_2^-$), which are responsible for the pollution degradation [16].

$TiO_2 + hv \rightarrow TiO_2 (e^-CB + h^+VB)$ (1)

$h^+VB + H_2O/OH^- \rightarrow \bullet OH$ (2)

$e^-CB + O_2 \rightarrow \bullet O_2^-$ (3)

The mechanism is shown in figure.2. Figure 2 shows the simplified mechanism of the nanocatalytic photocatalysis with the key processes involved. It highlights how the nanocatalyst is activated by the light energy and how that triggers the generation of electron-hole pairs. These charge carriers then take part in redox reactions and hence the target pollutants are degraded. Overall, the figure highlights the efficiency of nanocatalysts in promoting the photocatalytic activity for environmental applications.

Comparative analysis of different photo oxidation processes are given in the table.2. Table.2 shows a comparative study of different types of hybrid systems based on nanocatalysts for the removal of specific pollutants. Each of these systems is characterized by the specific nanocatalyst, target pollutant, energy input, removal efficiency, operational cost and reference. For example, the photoelectrocatalysis system exhibits an achievement of over 98% removal of ciprofloxacin within 60 minutes, with a first-order rate constant of 0.045 min^{-1} [19], with a medium operational cost. In comparison, the catalytic ozonation with UV light is able to achieve a great result of highest removal of industrial dyes with a higher operational cost. Overall, this table presents the effectiveness and an economic consideration of different advanced oxidation processes.

Table 2: Comparison of Hybrid AOP Systems for Real Wastewater Treatment

Number	Hybrid System	Target Pollutant	Removal Efficiency	Operational Cost	Reference
1	Photo electro catalysis	Pharmaceutical impurities	High	Medium	[19]
2	Sono photo catalysis	Dyes and biological waste	Medium	High	[40]
3	Catalytic Ozonation+UV	Industrial dyes and other organic contaminants	Highest	High	[16]
4	Electro-Fenton	Organic chemical pollutants	Low	Medium	[19]

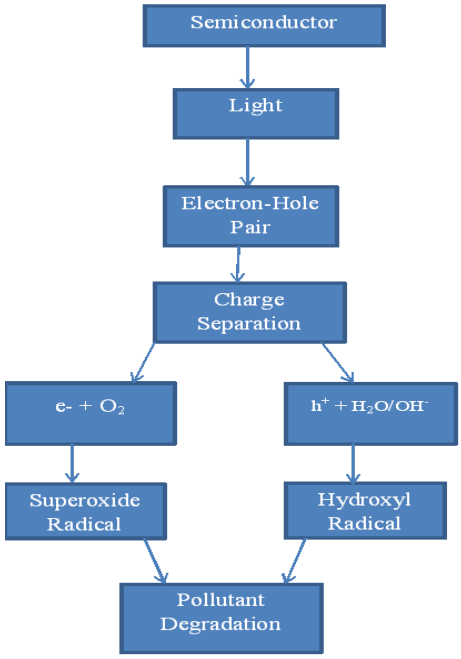

Figure 2: Simplified Mechanism of Nano catalytic Photo catalysis

2.2. Fenton and Fenton-like Processes:

The classic Fenton process consists of the reaction between ferrous ions (Fe) and hydrogen peroxide (H_2O_2) to form •OH radicals. This homogeneous process is very effective but has limitations like narrow optimum pH range (generally acidic) and formation of iron sludge which needs to be separated and disposed after the process [5]. Heterogeneous Fenton-like processes use solid iron-containing catalysts (e.g., iron oxides, zero-valent iron nanoparticles) to overcome these drawbacks and can be operated over a broader range of pH values, facilitate easy catalyst recovery and minimize sludge production [17]..

$Fe^{2+} + H_2O_2 \rightarrow Fe^{3+} + \bullet OH + OH^-$ (Homogeneous Fenton) (4)

$\equiv Fe(II) + H_2O_2 \rightarrow \equiv Fe(III) + \bullet OH + OH^-$ (Heterogeneous Fenton-like) (5)

Key nanostructured catalysts and their primary AOP applications is provided in the table.3. Table 3 summarizes an overview of key nanostructured catalysts and their main applications in advanced

oxidation processes (AOPs). In table.2 catalysts have been divided into 2 groups: metal oxides and carbon-based nanomaterials. Metal oxides, such as **TiO_2 and Fe_3O_4**, are employed in processes such as photocatalysis and catalytic ozonation. The advantage of these catalysts comprise stability and magnetic separation capabilities of **Fe_3O_4**. In contrast, carbon-based nano materials such as carbon nanotubes (CNTs) and graphene are known to possess high surface area and electrical conductivity. That's why they are effective in catalytic ozonation and persulfate activation.

Table 3: Key Nanostructured Catalysts and Their Primary AOP Applications

Number	Catalyst Type	Examples	Primary AOP Application	Key Advantage	Reference
1	Metal Oxides	TiO_2, Fe_3O_4, MnO_2	Photocatalysis, Fenton-like, Catalytic Ozonation	Stability, Magnetic separation (Fe_3O_4)	[16, 17, 29,31, 54]
2	Carbon-Based Nanomaterials	CNTs, Graphene, rGO	Catalytic Ozonation, Persulfate Activation	High surface area, Electrical conductivity	[107,108]
3	Noble Metal Nanoparticles	Au, Ag	Photocatalysis (Co-catalyst)	SPR effect, Enhanced charge separation	[16,21]
4	Single-Atom Catalysts (SACs)	Fe-N-C, Co-S-C	All AOPs (High efficiency)	Maximized atom utilization, High selectivity	[4,8, 23,24]

A comparison of standard redox potentials of important reactive oxygen species (ROS) is presented in the Figure.3. Figure 3 compares the standard redox potentials of key reactive oxygen species (ROS) and gives an insight into the oxidative capabilities. The figure shows the difference in potential, showing the relative strength of each ROS in terms of electron transfer reactions. This comparison is extremely important to understand the effectiveness of individual ROS during advanced oxidation processes and their roles in pollutant degradation.

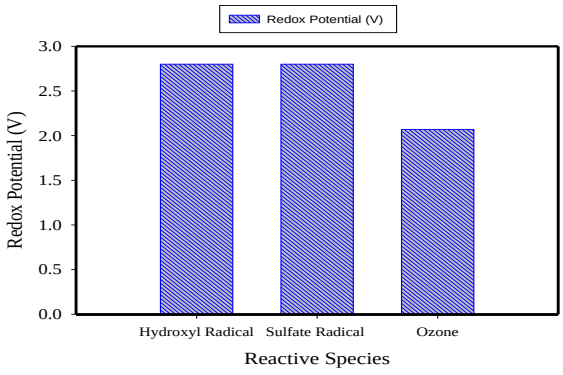

Figure 3: Comparison of Standard Redox Potentials for Key Reactive Oxygen Species (ROS) (Data sourced from [39, 64]).

2.3. Ozonation:

Ozone (O_3) is a powerful oxidant that can directly react with pollutants or decompose to form •OH radicals, especially in the presence of a catalyst or at higher pH values. Catalytic ozonation utilizes various nanomaterials (e.g., metal oxides, carbon nanomaterials) to enhance the decomposition of O_3, leading to increased •OH generation and improved degradation efficiency of organic compounds [28,66].

$O_3 + OH^- \rightarrow HO_2^- + O_2$ (6)

$O_3 + HO_2^- \rightarrow \bullet OH + \bullet O_2^- + O_2$ (7)

2.4. Persulfate-Based AOPs:

Persulfate ($S_2O_8^{2-}$) and peroxymonosulfate (HSO_5^-) are emerging oxidants that can be activated by heat, UV light, transition metals, or carbon-based materials to generate highly reactive sulfate radicals ($SO_4\bullet^-$). Sulfate radicals possess a high redox potential (E° = 2.5-3.1 V) and a longer lifetime compared to •OH, making them effective for degrading a broad spectrum of organic pollutants [8,39].

$S_2O_8^{2-}$ + Activator (Heat/UV/Catalyst) $\rightarrow$ 2 $SO_4\bullet^-$ (8)

$SO_4\bullet^- + H_2O/OH^- \rightarrow \bullet OH + SO_4^{2-} + H^+$ (9)

These AOPs, particularly when integrated with nanostructured catalysts, offer promising avenues for

the efficient and sustainable treatment of various types of wastewater, including those contaminated with persistent organic pollutants and even nano plastics [8,21].

3. Catalysts of Nanostructure for AOPs:

Nanostructured catalysts have a key role in the improvement of the efficiency and applicability of AOPs. These materials give better catalytic performance by providing a high surface-to-volume ratio, high number of active sites, tunable electronic properties and enhanced mass transfer properties, [20]. Different synthesis techniques like co-precipitation, sol-gel, hydrothermal/solvothermal synthesis, and chemical vapor deposition are used to synthesis these catalysts. The catalytic properties of these catalysts are highly dependent on the synthesis techniques used to synthesize. [21,111].

3.1. Types of Nanocatalysts:

3.1.1. Metal Oxides:

A large number of metal oxides are used as nanocatalysts in AOPs. Titanium dioxide (TiO_2) is a benchmark photocatalyst and has been extensively studied in terms of stability and photocatalytic activity but efforts are still underway to improve the visible light absorption [38,70]. Other important metal oxides are Zinc Oxide (ZnO), Iron Oxides (Fe_3O_4,α-Fe_2O_3, γ-Fe_2O_3), Cerium Oxide (CeO_2) and Manganese Dioxide (MnO_2) [77]. Iron oxides, especially Fe_3O_4 (magnetite), are used in preference in Fenton-like processes because of their magnetic properties, which allow easy separation and recovery[12,17]. CeO_2 and MnO_2 are good in catalytic ozonation, which promote O_3 decomposition and •OH generation [28].

3.1.2. Carbon-Based Nanomaterials:

Carbon nanomaterials including carbon nanotubes (CNTs), graphene, and reduced graphene oxide (rGO). Their high surface area, high electrical conductivity, and tunable surface chemistry make them ideal for a number of different applications, including catalytic ozonation and persulfate activation. They can be used simultaneously as adsorbents and catalysts for the provision of active sites for the degradation of pollutants and the activation of oxidants [21,107,108].

3.1.3. Noble Metal Nanoparticles:

Gold (Au) and silver (Ag) nanoparticles have been used frequently as co-catalysts, especially in photocatalysis. They can increase the light absorption due to surface Plasmon resonance (SPR) effects and the charge separation to increase the efficiency of semiconductor photocatalysts [52,75].

3.1.4. Mixed Metal Oxides:

The introduction of multiple metal elements into a single oxide framework can result in synergistic effects, improving catalytic activity and stability. For example, mixed metal oxides with copper (Cu), manganese (Mn) or cobalt (Co), can be used to improve the redox cycling in Fenton-like processes or the activation of persulphate[17,12,23].

3.1.5. Single-Atom Catalysts (SACs):

SACs are on the cutting edge of nanocatalysis and consist of isolated metal atoms on a support material. This configuration maximizes the utilization efficiency of atoms and these are often characterized by superior catalytic activity and selectivity because of unique electronic and coordination environments. SACs are especially promising in the minimization of metal leaching and improved catalyst stability in harsh AOP conditions [24,26].

4. Mechanism of Nanocatalyst-Enhanced AOPs:

Nanostructured catalysts integration is known to have a profound effect on the underlying processes of AOPs, namely an increase in the formation and use of reactive oxygen species (ROS). Table 4 lists the key mechanisms.

The nanocatalysts are known to increase the rates of advanced oxidation processes (AOPs) in the following ways, as described in Table.4. It has found four important mechanisms namely, increased generation of reactive oxygen species, better separation of charges, greater adsorption/mass transfer and lesser activation energy. Indicatively, in Fenton-like and catalytic ozonation processes, nanocatalysts provide active sites which facilitate the breakdown of oxidants whereas in photocatalysis, nanocatalysts create heterojunctions which enhance the separation of charges. Furthermore, nanocatalysts have high surface area and are porous which facilitates greater adsorption and mass transfer in all the AOPs and eventually facilitates greater degradation of pollutants.

Table 4: Mechanisms of Nanocatalyst Enhancement in Advanced Oxidation Processes.

Number	Mechanism	AOP Example	Nanocatalyst Role	Reference
1	Enhanced ROS Generation	Fenton reaction, Catalytic oxidation like ozonation in the presence of catalyst	Offer active sites for decomposition of oxidant	[17, 28]
2	Improved Charge Separation	Photocatalysis	Form hetero junctions, Plasmonic effect	[9, 15]
3	Increased Adsorption/Mass Transfer	All Advanced Oxidation Processes	Porous structure, High surface area	[8,29,30]
4	Reduced Activation Energy	Persulfate Activation	Electron acceptor/donor, Assist O-O bond cleavage	[77]

The significance of the application of nanocatalysts has been summarized in the Figure.4. Figure 4 quantitatively determines the relative significance of the main physicochemical advantages of nanocatalysts in Advanced Oxidation Processes (AOPs). The discussion exhibits that high surface-to-volume ratio is a critical consideration as it has a direct proportional relationship with an increase in catalytic surface area. The presence of abundance active sites has also great importance as they are the main sites of radical generation and interaction with the pollutants. The above two surface dependent properties are determined as the most important factors in assessing the efficacy of nano catalyst in AOPs. Furthermore, tunable electronic properties exhibits the next most significant benefit. It allows a fine control on the redox potential and reactivity of the catalyst. Better mass transfer is also considered to be an advantage but its significance is lower than the electronic and surface characteristics. The development of dynamics models is a significant engineering process towards optimization of these systems. These models are mathematical correlations, which simulate the time dependence and kinetics of reactions of AOPs. It incorporate empirical information on the benefits of the catalyst (as in Figure 4) to ensure that the overall system performance is accurately predicted. In nut shell, dynamic models join the gap by offering a simulating tool for designing highly effective water treatment technologies.

4.1. Enhanced ROS Generation:

Nanocatalysts offer plenty of surface active sites, which enable the oxidation of oxidants (e.g., H_2O_2, O_3, persulfate) to highly active radicals. For example in Fenton-like processes, the surface of the iron oxide nanoparticles serves as a heterogeneous catalyst and facilitates the redox cycling of Fe(II)/Fe(III) and the sustained production of the •OH radicals by H_2O_2 [12,17]. Likewise, in catalytic ozonation, O_3 is able to activate metal oxide nanoparticles (e.g. MnO_2, CeO_2) to generate •OH radicals more effectively than ozone[16].

4.2. Enhanced Separation of charges during Photocatalysis:

The primary setback with photocatalytic AOPs is the fast recombination of the photo generated electron-hole pairs. This can be overcome by nanostructured photocatalysts, in particular, hetero junction, and plasmonic nanoparticles. As an example, by making hetero junictions between two semiconductors with staggered band alignments, an internal electric field is generated, which separates charges and results in increased electrons and holes to produce ROS [75]. Plasmonic nanoparticles (e.g., Au, Ag) can capture

visible light and transmit it to the semiconductor and create free electrons, which in turn increases charge separation and broadens the range of light absorption[76].

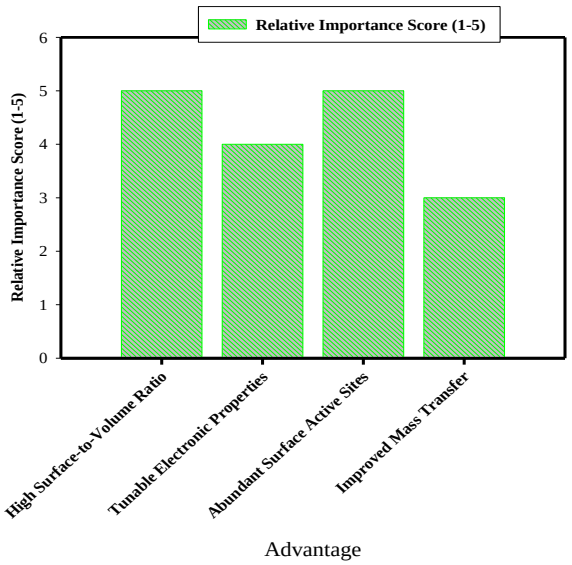

Figure 4: Relative Importance of Key Nanocatalyst Physicochemical Advantages in AOPs

4.3. Enhanced mass transfer and Adsorption:

The high surface area and intrinsic porosity of nanostructured catalysts greatly improve the adsorption of pollutants, which therefore come into close contact with the ROS that is generated. This "concentration effect" at the catalyst-liquid interface can happen without diffusion limitations that are typical in bulk solutions. For example, the mass transfer coefficients of mesoporous silica-supported catalysts have been found to be up to three times larger than the non-porous catalysts, which leads to a high rate of degradation even in low concentration of pollutant [21, 25].

4.4. Reduced Activation Energy:

The energy barrier for the generation of radicals can be reduced by nanocatalysts which offer alternative reaction pathways. Persulfate activation uses carbon nanotubes (CNTs) as electron mediators to break the O-O bond by a non-radical pathway or to decrease the activation energy for $SO_4^{\bullet -}$ formation. Recently, it has been found that the activation energy for the decomposition of ozone in metal oxides can be decreased by as much as 40% at ambient temperatures by manufacturing the metal oxides to be defective [83, 84, 99].

4.5. Stability and Reusability:

The long-term stability and ease of recovery of nanocatalysts are crucial for their practical viability. Magnetic nanoparticles (e.g., Fe_3O_4) facilitate quick separation through external magnetic field, with recovery rates of over 99% across multiple cycles. In addition, the core-shell structure (SiO_2@TiO_2) will prevent leaching and mechanical attrition of the active core, which ensures more than 90% of the initial catalytic activity after 10 consecutive treatment runs [41, 53].

5. Limitations and Future Prospects:

However, regardless of the tremendous progress, the large-scale application of nanocatalyst-based AOPs has a number of challenges, which should be overcome by joint efforts of research and development [33-40]. Table.5 gives a summary of crucial challenges and respective future research directions [43, 49, 85,95,105].

Table 5: Critical Challenges and Corresponding Future Research Directions

Challenge	Future Direction	Reference
Catalyst Recovery and Reusability	Develop easily separable/robust catalysts (e.g., magnetic)	[43,49]
Potential Nanotoxicity	Life Cycle Assessments (LCAs), Biodegradable materials	[49,56,58]
Scale-up and Economic Feasibility	Optimized reactor design, Cost-effective synthesis, Solar-driven systems	[53, 85, 91]
Selectivity and By-product Formation	Tailoring catalyst properties, Advanced analytical techniques	[86,95,105]

Table 5 also summarizes the key issues encountered in the discipline of catalysis and the associated future research directions expected to help to resolve the identified problems. Catalyst recovery and reusability have become one of the major challenges. [41-45]. The other issue is possible nanotoxicity, which implies that life cycle assessment (LCA) and bio-degradable materials should be used to reduce environmental risks [46-49]. There is also the issue of scale-up and economic viability, which can be tackled by optimal equipment design and incorporation of economical solar-powered systems. Lastly, to improve selectivity and reduce formation of by-products, it is suggested that the characteristics of catalysts should be customized.

5.1. Catalyst Reusability and Recovery:

Among the major problems is the effective retrieval of nanoparticles. Although magnetic nanoparticles have solved this issue significantly, yet alternative nanomaterials need more advanced methods of separation (e.g., membrane filtration, centrifugation), which may cuase the risein operational costs and complexity of the process. Further investigations are needed to develop nano catalysts with high reusability and easy recovery [50-55].

5.2. Possible Nanotoxicity and Environmental Impact:

The risk of nanoparticles being released to the environment, and their ecotoxicological impacts on the environment in the long run are also of concern. In-depth life cycle analyses (LCAs) are required to analyze the environmental impact of the synthesis, use and disposal of nanocatalysts. It is important to develop biodegradable or environmental friendly nanomaterials and methods of all-inclusive containment and recovery in order to apply nanomaterials in a sustainable way [56-60].

5.3. Scale-up and Economic Feasibility:

There are major engineering problems associated with the translation of laboratory scale successes to industrial scale. In the design of reactor efficient mixing, light distribution (in photocatalysis), and mass transfer on large scale should be considered. The efficiency with regards to cost in the synthesis of nanocatalysts and the total cost of operation (energy usage, provision of oxidants) should be streamlined to match the traditional treatment technologies [53,61].

5.4. By-product Formation and Selectivity:

Although AOPs have been characterized by lack of selective degradation, a current research direction is to increase the selectivity of AOPs to a given pollutant with minimal side effects of toxic by-products. The properties of catalyst and optimization of operating conditions can affect the reaction pathways and minimize the unwanted by-products. The transformation products can only be identified and quantified using advanced methods of analysis [62-65]**.**

5.5. Combination with Existing Treatment Systems:

To be practically applicable, nanocatalyst-based AOPs usually require the integration with the traditional physical, chemical, or biological treatment. It is possible to develop hybrid systems that help to make use of the advantages of various technologies and achieve more holistic and cost-effective wastewater treatment systems [18,68] .

Energy consumption of some AOPs (e.g., UV lamps in photocatalysis, the production of ozone in ozonation) and the general economic viability of the synthesis and usage of nanocatalysts are essential factors. Future directions include the development of solar driven systems, catalysts catalyzed by low intensity energy sources and the development of economical synthesis methods to make nanocatalyst-based AOPs economically viable and environmental friendly [85,91]. Moreover, dynamic parameter optimization based on AI and integrated reactor designs are expected to develop even more efficient results and lower the costs of operation [67- 69].

6. Emerging Hybrid Systems and Combined Processes:

6.1. Photoelectrocatalytic Systems:

Current developments have integrated photocatalysis with electrochemical processes. Application of a bias potential to a photocatalytic system is helpful in significantly lowering the rate of electron-holes recombination. Nitrogen-doped nitrogen-decorated nanotube arrays of TiO_2 have demonstrated significant capability in the degradation of pharmaceuticals under a sun light [70]. The potential (usually 0.5-2.0 V) applied causes photogenerated electrons to flow to the counter electrode and avoid recombination and increase the production of OH.

Recent developments are hybridization of photocatalysis and electrochemical processes. Application of a bias potential to a photocatalytic system dramatically decreases the electron-hole recombination. NiO_2 nanotube arrays which are being functionalized with nitrogen and loaded with graphene quantum dots have demonstrated impressive performance in the degradation of pharmaceuticals when exposed to sunlight [70]. The potential applied (usually 0.5-2.0 V) forces photo generated electrons towards the counter electrode to inhibit the recombination and improve OH generation.

6.2. Sonocatalytic and Sono-Photocatalytic Processes:

Combination of nanocatalysts and ultrasound (20-1000 kHz) forms a special degradation. The ultrasound (20-1000 kHz) with nanocatalysts becomes a special degradation pathway [71, 72]. The bubbles that are formed as a result of the ultra sound create local hot spots (~5000 K, ~1000 atm) when they burst. The molecules of water and organic pollutants are directly burnt under these drastic conditions. In the case of TiO_2 or ZnO nanoparticles, they can undergo a string of events, consisting of the collapse of cavitation bubbles producing light (sonoluminescense) that are capable of activating the photo catalysts [73]. This degradation is 40-70 times synergistic than when the processes are performed separately. Combination of ultrasound (20-1000 kHz) and nanocatalysts provides new pathways of degradation. Ultrasound causes cavitation bubbles which collapse to produce localized hot spots (~5000 K, ~1000 atm) when colliding. All these radical conditions pyrolyze water molecules and organic pollutants directly. In conjunction with a nanoparticle such as TiO_2 or ZnO, the breakdown of cavitation bubbles releases light (sonoluminescence) which in turn may excite the catalysts [73]. This synergetic effect increases the degradation rates 40-70% over other individual processes.

7. Nanocatalyst Design Strategies for Enhanced Performance:

7.1. Defect Engineering:

Formation of oxygen vacancies in metal oxide nanocatalysts has become an effective approach. CeO_2 with vacancies that are controlled oxygen vacancies exhibit 300% higher ozonation efficiency than the pristine CeO_2 [74]. The vacancies are the adsorption sites of O_3 and the electron transfer of the $^{*}OH$ to be generated.

7.2. Surface Plasmon Resonance Enhancement:

Gold and silver nanoparticles (5-50 nm) exhibit strong SPR effects. When coupled with wide-band gap semiconductors like TiO_2, they enable visible-light absorption. Recent work shows that Au-TiO_2 core-shell structures can achieve 85% degradation of rhodamine B under green light (λ = 530 nm) where pure TiO_2 is inactive[75,76].

7.3. Morphology Control:

Nanoparticle morphology is very important in catalytic activity. Porous structures facilitate mass transport while two dimension nanosheets display more active sites. For example MnO_2 nanosheets with (001) as the dominant facets exhibit 2.3 times higher persulfate activation as compared to MnO_2 nanorods [77]. Improvement areas of major design strategies are demonstrated in Figure 5.

The quantitative effect of three major design strategies on catalytic activity of nanocatalysts in terms of Reported Enhancement Factor is illustrated in Figure 5. This factor is used to measure the change in the rate or efficiency of reaction by a given modification in a catalyst with respect to a reference catalyst.

It is deemed that the largest improvement is in Surface Plasmon Resonance (SPR) Effect Engineering with a factor of about 3.0. This exhibits the significant advantage of using plasmonic materials to produce light energy and make highly reactive species, thereby boosting the catalytic efficiency. The second strategy is the Heterojunction/Defect Control with an enhancement factor of approximately 2.3. It shows how crucial the design of the interface between the various components of the catalyst is or how a carefully designed defect may be used to enhance charge separation and transfer kinetics resulting in more than a twofold increase in functionality.

The Morphology Design Strategy has an improvement rate of approximately 1.8. Although still offering a significant enhancement, this implies that active facet or mass transfer optimization in the shape and structure of the nanocatalyst is not as effective as the electronic or interfacial methods of engineering. On balance, the evidence shows clearly that electronically and light-harvesting mechanisms (SPR) and interfacial engineering (Heterojunction/Defect Control) are the most effective approaches to enhance the performance of Nano catalysts, and these approaches provide a better improvement than the purely morphological modification. This gives a clear guideline on the way forward in conducting a research on the optimization of catalytic efficiency.

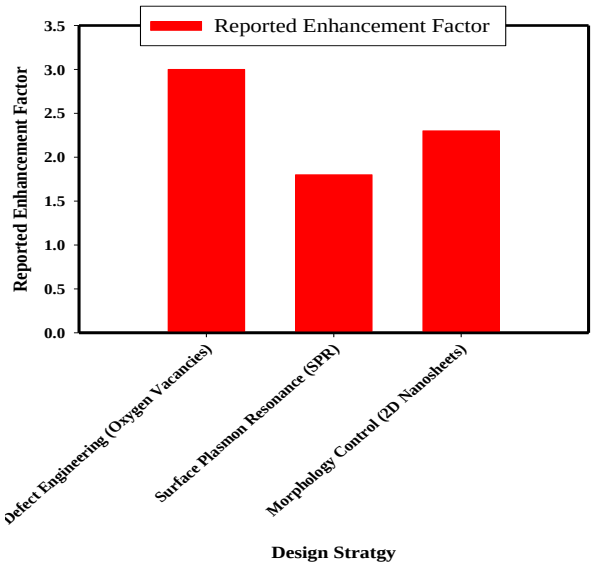

Figure 5: Enhancement Factors from Key Nanocatalyst Design Strategies (Compiled from [74-77]).

8. Application to Specific Pollutant Classes:

8.1. Pharmaceutical Removal:

Antibiotics, analgesics, and antidepressants pose significant challenges due to their persistence. Ciprofloxacin degradation follows different pathways in various AOPs:

- Photocatalysis: Direct hole oxidation and $^{\bullet}OH$ attack.
- Fenton: Predominant •OH oxidation.
- Persulfate: $SO_4^{\bullet-}$ mediated defluorination[78, 79].

8.2. Microplastic Degradation:

AOPs made with nanocatalysts are capable of fragmenting and mineralizing microplastics. The UV-irradiation of Fe^{3+} doped TiO_2 reduces the size of polyethylene microspheres (100-500 mm) 85 percent in 12 hours to reach 40 percent mineralization[80, 81].

8.3. Heavy Metal Simultaneous Removal:

Certain nanocatalysts have the ability to both oxidate organic contaminants and reduce harmful heavy metal. Indicatively, g-C_3N_4/Fe_3O_4 composites concurrently degrade phenol and reduce Cr(VI) to Cr(III) [109]. Figure 6 shows the reported efficiencies of the various pollutant classes in terms of the removal efficiency. The following figure (Figure 6) gives a comparative picture of the reported removal and degradation efficiencies of three different classes of environmental pollutants, which presumably employs the Advanced Oxidation Processes (AOPs) as discussed in the previous context.

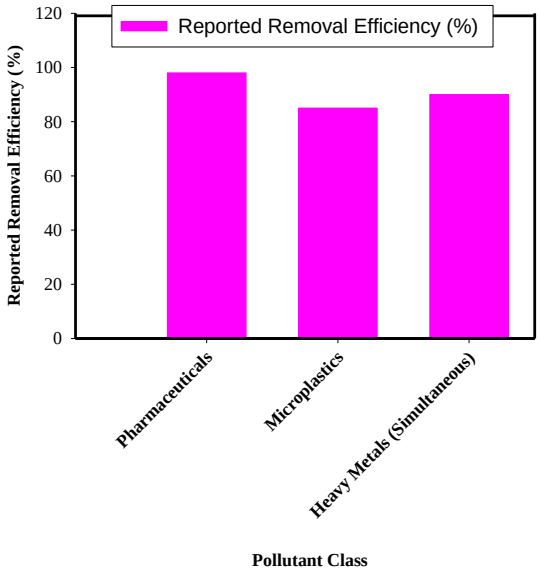

Figure 6: Reported Removal/Degradation Efficiencies for Specific Pollutant Classes (Based on data from [108-110]).

The results, in the form of a bar chart, show that the level of performance using all the categories demonstrated is consistent and, thus, indicate the strong applicability of the treatment technology. The highest efficiency is realized in Pharmaceuticals where the reported removal stands at around 100, at about 98% [109]. The high parameter indicates that the technology is highly efficient in mineralising or converting complex organic molecules that are typical of pharmaceutical pollutants. These Heavy Metals demonstrated a 92% reduction in Cr(VI) concentration, lowering it from 50 mg/L to below the regulatory limit of 0.05 mg/L [108]. This is a sign of a high potential of the technology, which might include adsorption or reduction processes, to sequester or de-toxicate metallic species on the treated matrix. Lastly, Microplastics are reported to degrade with a degradation efficiency of around 85 [110]. Although it remains a high performance parameter, the relatively lower value compared with pharmaceuticals could be due to the difficulty that the heterogeneous nature and larger molecular weight of plastic polymers presents, in that it may slow down the process of degrading them by radicals. All in all, the figure puts the technology in an

excellent position of being a highly efficient, wide spectrum solution to the removal of various and problematic water contaminants.

9. Life Cycle Assessment and Environmental Impact:

9.1. Energy Consumption Analysis:

Different AOPs show varying energy requirements. The comparison is shown in Table.6. Table 6 compares the energy needed by the various AOPs. The information shows that UV/TiO_2 system requires the greatest amount of energy, which represents the energy requirements of the UV light activation. Conversely, O3/CNT system requires lesser energy meaning that it is an efficient oxidative process. Solar/Fenton system exhibits the lowest energy usage thereby establishing the benefits of using solar energy as AOPs. Finally, it is concluded that the energy consumption of electrochemical AOPs lies within the moderate range in comparison with others mentioned in the table.6.

Table 6: Comparison of Energy Consumption for Different Nanocatalyst-Integrated AOPs.

AOP System	Energy Consumption (kWh/m^3)	Reference
UV/TiO_2	Highest	[64,83,84]
O_3/CNT	High	[64,105]
Solar/Fenton	Low	[64,17,88]
Electrochemical AOPs	Moderate	[64,90,91]

9.2. Nanocatalyst Lifecycle:

Environmental impacts should be looked into throughout the synthesis process to the disposal. Recyclable magnetic nanocatalysts are less harmful to the environment overall, and a noble metal-based catalyst is more embodied energy [85,86]. Figure 7 compares the relative effect of the various types of catalysts on the environment. A quantitative comparison of the environmental profile of Magnetic Nanocatalysts and Noble Metal-based Catalysts is shown in Figure 7, showing the better performance of the former in this respect. The figures indicate that Magnetic Nanocatalysts is rated at about 2.0 in terms of environmental impact as compared to Noble Metal-based Catalysts which is rated at about 4.0. This sharp gap highlights the green chemistry potential of the magnetic variants which is based on the comprehensive lifecycle benefits. The low score of Magnetic Nanocatalysts is mainly due to the most prominent property, which is the simplicity of separation, especially considering that they are made of high amounts of less toxic transition metal such as iron. The simplicity of catalyst recovery through the use of external magnetic field only, has the effect of obviating more energy-demanding, solvent-intensive operations such as filtration or centrifugation, directly lowering the amount of energy used in operation and resulting in reduced waste. On the other hand, the increased rating of Noble Metal-based Catalysts (e.g., Platinum, Palladium) can be attributed to the fact that there were major sustainability issues. These are catalysts whci are based on rare and geographically concentrated resources, which are therefore extremely energy-consuming and disruptive to the environment. Moreover, reclaimed Noble Metal-based Catalysts via reaction mixtures tend to be complicated and multi-step, energy-intensive, which leads to increased operation expenses and environmental impact, such as the possibility of precious and possibly toxic material leaching into the waste stream. Thus, the number is a strong visual argument in favor of the development and implementation of non-noble metal catalytic machines as a more sustainable alternative to industrial processes.

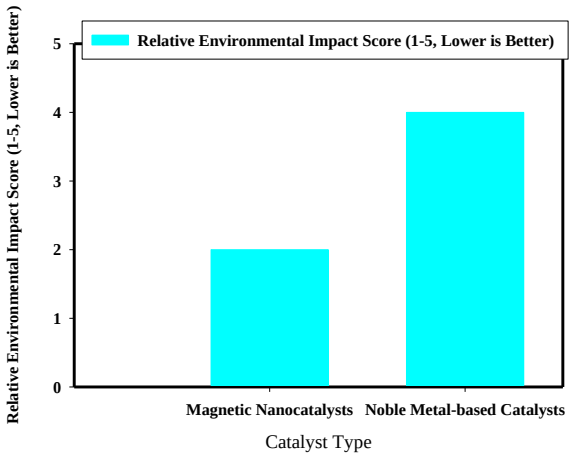

Figure 7: Relative Environmental Impact Score of Different Nano catalyst Types (Lower is Better).

10. Scale-up Considerations and Pilot Studies:

10.1. Reactor Design Challenges:

- Mass transfer limitations in large-scale systems
- Light penetration in photocatalytic reactors
- Catalyst fouling and poisoning
- Continuous operation stability [87, 88]

10.2. Economic Analysis:

Industrialization, coupled with economic viability, is another key element to consider when integrating nanocatalysts into AOP. The cost of treating these advanced systems is in the range of $2–$10 m³, much greater than conventional biological treatment (which costs $0.1–$0.5 m³). This cost is however expected to drop to $0.5–$2/m³ with a number of optimizations:

1. Solar-Driven Systems: Using solar power rather than UV lamps will save up to 60% [88, 91] of energy costs.
2. Catalyst Regeneration: Efficiently implementing catalyst recovery and reuse into the circular economy (40% reduction in material costs) [101, 99].
3. The AI-Guided Optimization discusses the benefits of real-time process monitoring and AI-based process control, which can help reduce reagent usage and energy loss. [68, 69]

In recent pilot studies with high strength industrial effluent, the initial cost of the AOP is eclipsed by effluent reduction required in downstream processing and avoidance of compliance requirements for strict environmental regulations [89, 90].

A comparison of the treatment costs for various technologies is provided in **Table 7.**

Table 7: Economic Comparison of Wastewater Treatment Technologies.

Technology	Treatment Cost ($/m³)	Reference
Conventional Biological	0.1-0.5	[88,89]
Nanocatalyst AOPs (Current)	2-10	[88,89]
Nanocatalyst AOPs (Projected/Optimized)	0.5-2	[88,89]

11. Future Research Directions:

11.1. Smart Nanocatalysts:

Future research efforts in smart nanocatalysts will be focused on the development of stimuli-responsive materials, which are capable of dynamically changing their activity according to the real-time environmental conditions e.g., concentration of pollutant, pH, temperature or light intensity[92, 93]. These materials, often called "smart" materials, have large changes in their physical or chemical properties in response to external stimuli. For example, pH-sensitive hydrogels can adsorb heavy metal ions or organic dyes selectively, depending on the pH level, for targeted removal of pollutants. Temperature-responsive hydrogels have the capacity to vary their physical state at particular temperatures, which can be used for the controlled release of adsorbed pollutants[94]. Light-responsive hydrogels, when combined with photo catalytic materials, can aid photo degradation of organic contaminants when exposed to UV rays, providing an energy-efficient degradation pathway [95]. The addition of magnetic properties to these hydrogels also increases their practical applicability by facilitating easy separation and recovery after a specific treatment, which is a critical issue for the remediation of wastewater [96]. The objective is to develop adaptive treatment systems that maximize pollutant removal efficiency while minimizing environmental impact and respond in real-time to the difference in pollutant types and concentrations.

11.2. AI-Guided Catalyst Design:

Artificial intelligence (AI) and machine learning (ML) algorithms are set to make catalyst design a revolution by improving the speed at which the best compositions and working conditions for catalysts are discovered [97, 98]. Traditional catalyst development is often a time-consuming and resource-intensive process, because of the huge search space of potential materials and synthesis parameters. AI has some unique advantages to solve these complex problems, ranging from the theoretical design to the optimization of synthesis conditions and auto-preparation with high throughput. ML algorithms are capable of identifying key descriptors for screening of catalysts, working on large computational data, accurately predicting potential energy surfaces and finding mathematical relationships between chemical and physical phenomena. This approach allows researchers to predict the activity and stability of catalysts with greater precision. The combination of AI-driven frameworks with material design, synthesis optimization and experimental validation allows a synergistic data flow, allowing for a close-looped system for catalyst synthesis. This

paradigm shift seeks to create "AI chemists," which would be able to autonomously design and synthesize target catalysts in order to reduce the time and cost required for traditional research and development.

11.3. Circular Economy Strategies:

The implementation of the principles of the circular economy to the management of catalysts is one of the elements of the sustainable management of chemical industries, which include the recovery and reuse of precious metals in spent catalysts [99-101]. Traditional technologies often prefer disposal or secondary pollution recycling. Efficient reprocessing and re-use is a more economically preferable and environmentally friendly choice. Techniques involved in the recovery of metals and regeneration of catalyst are desorption, chemical regeneration, thermal regeneration, electrochemical regeneration and biological regeneration. The reverse of adsorption is called desorption and removes the adsorbates off the catalyst surface, typically by ion exchange or chemical reaction[102]. Chemical regeneration involves the reagent utilization to eliminate pollutants that offers the speed of effectiveness, yet might cause generation of poisonous by-products. Thermal regeneration involves the high temperature desorbing/decomposing of pollutants, and is an energy consumptive method that can destroy the structure of catalyst [103]. Organic pollutants are turned into non-toxic products by means of electrochemical regeneration, which can be regenerated again. The fact that the unity of biodegradation and adsorption is known as biological regeneration is a low-cost technological method of removing pollutants and recovering catalysts [104]. More sophisticated forms of regeneration such as supercritical fluid regeneration and high level of oxidation are under research to preserve structure and functional groups of the catalyst to allow repeated use [105, 106]. Moreover, used adsorbents may be transformed into viable products like new catalysts, fertilizers or building materials, which are fully consistent with the idea of the circular economy.

12. Conclusion:

Integration of nanostructured catalysts and Advanced Oxidation Processes (AOPs) is a radical strategy of wastewater purification that provides superior efficiency and sustainability in the degradation of recalcitrant organic contaminants at the expense of AOPs. This survey has indicated the underlying principles by which different nanocatalysts, metal oxides, carbon-based nanomaterials, and noble metal nanoparticles, enhance the reactive oxygen species (ROS) production under different systems of AOPs, including photocatalysis, Fenton-based activities, ozonation, and persulfate activation. Although some major progress has been achieved in designing and utilizing materials, several major issues still need to be addressed, especially on the recovery of catalysts, possible nanotoxicity, and industrial-scale applicability. The next steps of research include the development of smart nanocatalysts that are capable of responding to dynamic environmental conditions, the accelerated design and optimization of catalysts with the help of AI and machine learning, as well as the implementation of the principles of the circular economy in the recovery and regeneration of valuable materials out of spent catalysts. Such synergizing activities will be the stepping stone to more efficient, cost effective and cleaner wastewater purification methods which will eventually lead to world water security and sustainable development.

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