Treatment Technologies for Organic Pollutant Degradation in Semiconductor Wastewater: A Survey

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Abstract

This survey paper examines the study and application of treatment technologies, particularly photocatalysis and advanced oxidation processes (AOPs), for degrading organic pollutants in semiconductor wastewater. The paper underscores the significance of these technologies given the complexity and hazardous nature of semiconductor effluents, which contain volatile organic compounds and synthetic dyes like Methylene Blue. Photocatalysis, leveraging semiconductor materials, and AOPs, generating reactive radicals, are highlighted for their roles in environmental remediation. The integration of heterostructures and plasmonic catalysis is discussed as advancements enhancing photocatalytic efficiency. Furthermore, the paper explores the environmental impact of organic pollutants, emphasizing the need for innovative treatment technologies to mitigate their persistence and toxicity. Recent innovations in material science, such as the development of carbon-nitride polymorphs and reduced Graphene Oxide-Tin Oxide nanocomposites, are presented as pivotal in improving photocatalytic performance. The survey also addresses the integration of photocatalysis and AOPs, illustrating the synergistic effects that enhance pollutant degradation efficiency. Economic aspects, including cost-effectiveness and scalability, are evaluated alongside regulatory and sustainability perspectives, highlighting the broader implications of these technologies. The paper concludes by proposing future research directions focused on standardizing methodologies, optimizing material properties, and enhancing the applicability of these advanced treatment technologies in wastewater management.

1 Introduction

1.1 Significance of Semiconductor Wastewater Treatment

The treatment of semiconductor wastewater is vital due to its complex composition, which includes hazardous organic pollutants that pose significant environmental and health risks [1]. These effluents often contain volatile organic compounds (VOCs) that contribute to air contamination, posing toxic threats even at low concentrations [2]. Consequently, developing advanced treatment technologies to mitigate their environmental impact is essential.

Photocatalysis presents a promising approach, utilizing the unique properties of semiconductor materials to degrade organic pollutants. However, challenges such as the quenching of defect-related photoluminescence in materials like ZnO nanorods, when combined with gold nanoparticles, can diminish their photocatalytic efficiency [3]. Optimizing these processes requires a thorough understanding of these mechanisms.

The advancement of heterostructures based on two-dimensional (2D) materials and wide bandgap semiconductors (WBS) significantly enhances photocatalytic performance. Recent developments in synthesizing and applying these heterostructures address existing knowledge gaps and provide new pathways for improving pollutant degradation efficiency [4]. Furthermore, exploring localized

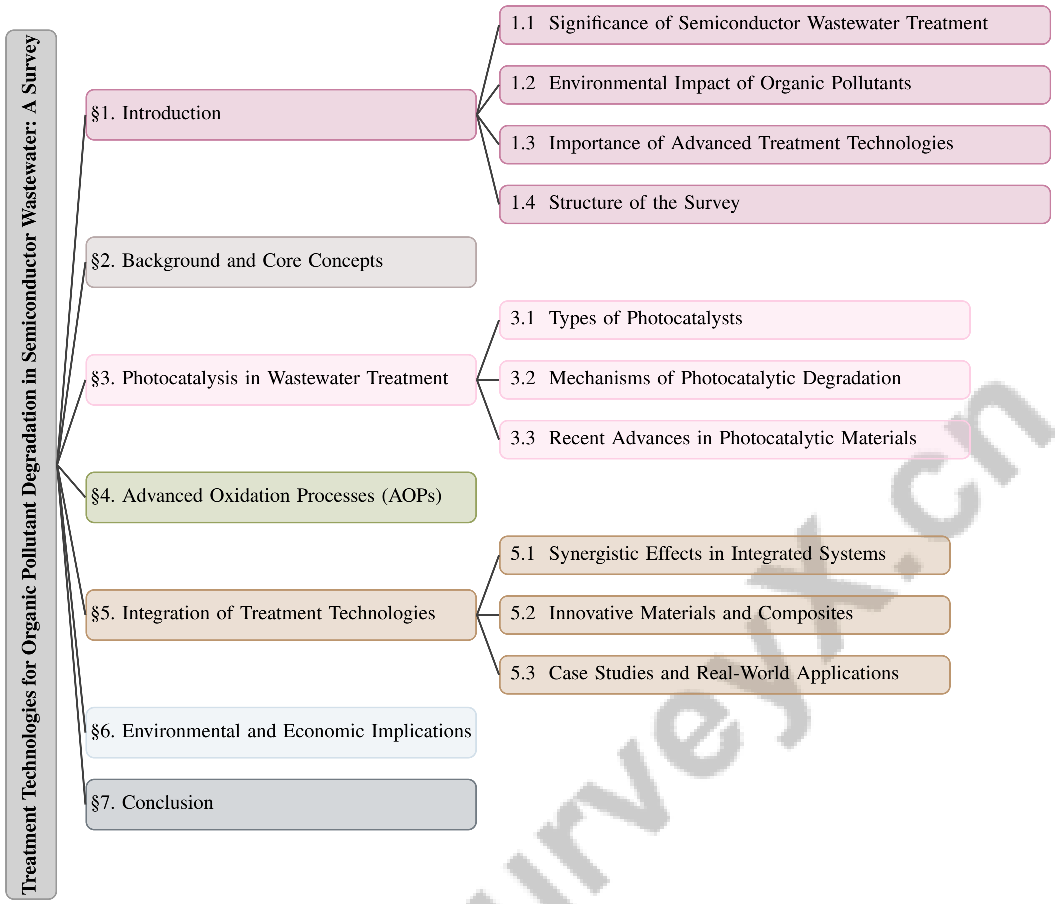

Figure 1: chapter structure

surface plasmon resonance (LSPR) in plasmonic catalysis can enhance chemical reactions, offering additional potential for effective wastewater treatment [5].

The environmental contamination caused by industrial dyes, such as Methylene Blue (MB), underscores the broader issue of pollutant degradation across various industries, including textiles [6]. Addressing these contaminants aligns with the overarching goal of semiconductor wastewater treatment, emphasizing the need for innovative solutions to prevent environmental damage.

Understanding defect diffusion mechanisms, such as those in the reoxidization processes of rutile TiO2, is crucial for enhancing the stability and efficiency of photocatalytic systems [7]. Additionally, the ability to convert CO2 to useful compounds through solar photocatalytic reduction highlights photocatalysis's potential in addressing inefficient conversion processes and contributing to environmental sustainability [8].

The significance of semiconductor wastewater treatment is further underscored by the necessity for effective pollutant degradation, paralleling the importance of controllable systems in fields like biomedicine [9]. This highlights the interdisciplinary nature of the challenges and solutions associated with semiconductor wastewater treatment, emphasizing advanced technologies' critical role in safeguarding environmental and public health.

1.2 Environmental Impact of Organic Pollutants

Organic pollutants, particularly those from semiconductor manufacturing, have a profound environmental impact due to their persistence and toxicity. These pollutants, including synthetic dyes like Methylene Blue, threaten aquatic ecosystems and human health [6]. Effective degradation and removal of such dyes from wastewater are crucial for improving water quality and reducing health hazards. Their persistence can lead to bioaccumulation, disrupting food chains and adversely affecting biodiversity and water quality [10].

Recalcitrant organic micropollutants, resistant to conventional treatment methods, exacerbate these environmental concerns, necessitating innovative treatment technologies. Understanding how operational conditions and the electron donor's density of states affect the stability and morphology of treatment system interfaces is essential [11]. This complexity calls for sophisticated models and processes to mitigate their effects [12].

A reliable and efficient method for generating hydroxyl radicals (OH•) is critical in addressing the environmental impact of organic pollutants, as these radicals are key to degradation processes. Current methods often fall short in effectively removing persistent compounds. The detrimental effects of organic pollutants are paralleled by challenges in interpreting experimental results in plasmon-assisted chemistry, which can lead to misinterpretations and environmental implications [13].

Accurate pH measurements in environments where traditional electrodes fail, particularly under high salinity conditions, further complicate the challenge [14]. Addressing these multifaceted challenges requires a combination of novel materials and processes to effectively reduce the environmental footprint of semiconductor wastewater and protect ecological and human health.

1.3 Importance of Advanced Treatment Technologies

Advanced treatment technologies, particularly photocatalysis and advanced oxidation processes (AOPs), are essential for addressing the challenges posed by organic pollutants in semiconductor wastewater. Photocatalysis utilizes semiconductor materials to break down hazardous compounds, offering a sustainable approach to environmental remediation [1]. Integrating plasmon-assisted photocatalysis, which leverages the hot electron mechanism, enhances these processes, although thermal effects often dominate [15]. Materials like bismuth vanadate (BiVO4) and bismuth ferrite (BiFeO3) are notable for their suitable absorption edges in the visible light range, enhancing photocatalytic applications.

Innovations in material science, such as developing carbon-nitride (C3N4) polymorphs, show promise for visible-light-responsive solar energy conversion and environmental remediation [16]. Band engineering through doping, particularly in newly fabricated carbon nitride monolayers, enhances efficiency for solar water splitting [17]. The synthesis of reduced Graphene Oxide-Tin Oxide (rGO-SnO2) nanocomposites significantly improves photocatalytic performance compared to traditional photocatalysts [6]. Transition metal doping in TiO2 monolayers further enhances photocatalytic properties, underscoring advanced technologies' role in effective pollutant degradation [18].

Understanding the electronic structure and photocatalytic properties of materials like black titania is crucial for effective pollutant degradation [19]. The role of polarization in enhancing semiconductor photocatalysis efficiency, specifically through charge separation mechanisms, further emphasizes the importance of these technologies [20]. Advanced computational methods, such as DFT+U and DMC, are employed to evaluate defect diffusion pathways in materials like rutile TiO2, which are crucial for optimizing photocatalytic systems [7].

AOPs complement photocatalysis by generating reactive hydroxyl radicals in situ, essential for degrading recalcitrant organic pollutants [21]. Electrochemical advanced oxidation processes (EAOPs) provide efficient and environmentally friendly alternatives to traditional methods, emphasizing the importance of advanced treatment technologies in effective pollutant degradation. The role of photothermal nonlinearity in plasmon-assisted photocatalysis further highlights the significance of these technologies in optimizing treatment processes [22].

These advancements underscore the critical role of advanced treatment technologies in addressing the inefficiencies of conventional wastewater treatment methods. By offering cost-effective and energy-sustainable solutions, these technologies significantly contribute to environmental sustainability and public health protection, effectively mitigating the impact of organic pollutants in semiconductor wastewater. The limitations of traditional photocatalytic methods highlight the necessity for new materials that efficiently harness solar energy, as research progresses to enhance the understanding of semiconductor electronic properties and improve bandgap predictions [23].

1.4 Structure of the Survey

This survey is systematically organized to provide a comprehensive understanding of advanced treatment technologies for degrading organic pollutants in semiconductor wastewater. The paper begins with an **Introduction** that outlines the significance of semiconductor wastewater treatment, the environmental impact of organic pollutants, and the importance of advanced treatment technologies such as photocatalysis and advanced oxidation processes (AOPs). This section sets the stage for a detailed exploration of the core concepts and methodologies addressed in subsequent sections.

In the **Background and Core Concepts** section, we delve into the composition of semiconductor wastewater, focusing on the nature and challenges posed by dissolved organic matter. This section also provides an in-depth explanation of the core principles of photocatalysis and AOPs, elucidating their mechanisms and relevance to wastewater treatment.

The subsequent sections, **Photocatalysis in Wastewater Treatment** and **Advanced Oxidation Processes (AOPs)**, explore the application of these technologies in degrading organic pollutants. These sections cover the types of photocatalysts and AOP methods used, their mechanisms, effectiveness, and recent advancements. The limitations and innovations in these fields are also highlighted, providing a balanced view of current capabilities and future potential.

The paper then examines the **Integration of Treatment Technologies**, analyzing the synergistic effects and potential benefits of combining photocatalysis and AOPs. This section includes discussions on innovative materials and composites developed for integrated systems, supported by case studies and real-world applications that demonstrate successful implementations.

The **Environmental and Economic Implications** section evaluates the environmental benefits of effective pollutant degradation and discusses the economic aspects of these technologies, including cost-effectiveness and scalability. Additionally, it considers regulatory and sustainability perspectives, emphasizing the broader impact of these technologies on environmental protection and public health.

Finally, the **Conclusion** synthesizes the key findings of the survey and proposes future research directions, emphasizing the importance of continued innovation and collaboration in this field to address the challenges and opportunities presented by semiconductor wastewater treatment. The experiments validate the effectiveness of leveraging unlabeled data in improving model performance, particularly in scenarios with limited labeled data [24].The following sections are organized as shown in Figure 1.

2 Background and Core Concepts

2.1 Composition of Semiconductor Wastewater

Semiconductor wastewater is a complex blend of organic and inorganic substances, posing considerable environmental challenges. Dissolved organic matter (DOM) is particularly problematic due to its variability and environmental impact, complicating its characterization and treatment. This wastewater includes volatile organic compounds (VOCs) like methyl ethyl ketone (MEK), which have low molecular weights and significant environmental ramifications [25]. These VOCs necessitate advanced treatment technologies to mitigate their effects.

Organic pollutants, such as synthetic dyes like Methylene Blue (MB), are prevalent in semiconductor wastewater, requiring effective treatment to prevent environmental harm [6]. Tailored nanocomposites have successfully addressed dye degradation, illustrating the potential for customized photocatalytic solutions. Additionally, pharmaceuticals, pesticides, and heavy metals in this wastewater require distinct treatment strategies to address multifaceted challenges.

Innovative materials, including two-dimensional gallium sulfide nanoflakes and halide perovskites, offer promising avenues for enhancing treatment efficiency. Advances in material science have led to the development of magnetic iron oxide-integrated photocatalysts and nanostructured titanium dioxide films, which improve adsorption and degradation mechanisms for complex organic pollutants in semiconductor wastewater [26, 27, 28, 29, 30].

Challenges in advanced pH measurement methods include sensitivity to light and pressure, high costs, and the need for specialized materials for stability [14]. The stability of electrochemical interfaces, analyzed through non-equilibrium thermodynamics and electron transfer kinetics, is crucial for

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optimizing treatment processes [11]. Porous semiconductors, with applications in electronics and catalysis, hold potential for improving wastewater treatment [31].

Understanding the components and characteristics of semiconductor wastewater, especially its organic matter content, is vital for developing effective treatment technologies. Insights into these compositions inform the selection and optimization of processes, ensuring they address the unique challenges of semiconductor effluents. Advanced techniques like hydrodynamic cavitation, cerium dioxide photocatalysis, and nanostructured material integration enhance treatment efficiency and sustainability, mitigating environmental impacts [32, 31, 28, 29, 30].

2.2 Core Concepts of Photocatalysis

Photocatalysis leverages semiconductor materials to convert light into chemical energy, facilitating the degradation of organic pollutants. Photon absorption generates electron-hole pairs, driving redox reactions that decompose contaminants [2]. The efficiency of these processes hinges on the electronic structure of the photocatalyst, influencing charge carrier dynamics [18].

Plasmonic nanoparticles, such as in the Au-TiO_2 system, enhance photocatalytic efficiency by generating hot electrons during photon absorption, significantly improving pollutant degradation [33]. Polarization—macroscopic, piezoelectric, and surface—plays a crucial role in enhancing charge separation and photocatalytic efficiency.

Advancements in material science, like van der Waals heterostructures for Z-scheme photocatalysis, reduce electron-hole recombination rates, enhancing performance. Exploring electronic structures through hybrid functional molecular dynamics and thermodynamic integration provides insights for optimizing materials [34]. The generation and utilization of photogenerated charge carriers are pivotal for pollutant degradation.

Bismuth vanadate ($BiVO_4$) is a well-studied photocatalyst known for its visible light activity. However, challenges like insufficient near-surface defect concentrations in ZnO single-crystals hinder efficiency. Strategies like low-energy self-implantation followed by thermal annealing enhance defect concentration, crucial for increasing surface reactivity and improving photocatalytic processes [35, 36]. Manipulating subsurface oxygen vacancies in anatase TiO_2 enhances O_2 interaction, improving photocatalyst efficiency.

Porphyrin-based metal-organic frameworks (MOFs) offer promising avenues for enhancing photocatalytic efficiency due to their unique electronic properties. These MOFs, alongside novel carbon nitrides synthesized electrochemically, provide new pathways for improved photocatalytic properties. For instance, g-C3N4/Zr-Fc MOF composites enhance benzene hydroxylation to phenol under visible light, achieving high phenol yield and selectivity [21, 37].

Enhancing photocatalyst efficiency for water splitting requires addressing band gap constraints and charge carrier recombination. Recent advancements in polarization techniques show promise in improving charge separation and photocatalytic performance [20, 38, 27]. Optimizing electron injection mechanisms, as explored in TiO_2 nanoparticles, emphasizes the importance of adsorption modes in enhancing photocatalytic processes. Classifying porous semiconductor research based on material types, growth mechanisms, and applications is crucial for developing new photocatalytic materials.

Advancements in material science and theoretical modeling enhance photocatalytic process efficiency for wastewater treatment. Strategies like improved charge separation via polarization methods, nanostructured substrates for increased surface area, and innovative solid-state materials optimize photocatalytic activity for environmental remediation [20, 30, 38, 27]. By optimizing electronic structures and leveraging advanced materials' properties, photocatalysis offers a promising approach for sustainable degradation of toxic organic pollutants in semiconductor wastewater.

2.3 Advanced Oxidation Processes (AOPs)

Advanced oxidation processes (AOPs) are vital for mineralizing persistent organic pollutants in wastewater into benign end products like CO_2 and H_2O. These processes generate highly reactive species, primarily hydroxyl radicals (•OH), facilitating the breakdown of complex organic compounds. Despite their effectiveness, existing AOP methods face limitations, necessitating innovative approaches to enhance efficiency and applicability [39].

A significant challenge in AOPs, especially with ZnO-based photocatalysts, is photocorrosion, which impairs performance. Enhancing interfacial charge transfer and stabilizing materials under operational conditions are essential [40]. Exploring new materials and engineering solutions to mitigate photocorrosion while maintaining high activity is crucial.

Advancements in porous semiconductor structures have improved device performance, offering advantages in AOPs by providing increased surface areas and enhanced mass transfer, critical for effective pollutant degradation [31]. Integrating these porous materials into AOP systems enhances reactive species generation and utilization, improving treatment efficiency.

Combining hybrid functional molecular dynamics simulations with thermodynamic integration offers insights into transition levels associated with polarons at interfaces, such as the $BiVO_4$-water interface. This approach aids in understanding the electronic and structural dynamics influencing photocatalyst reactivity and stability in AOPs [34]. By elucidating these mechanisms, researchers can develop more effective AOP systems tailored to semiconductor wastewater treatment.

Ongoing advancements in AOPs, bolstered by innovations in material science and computational modeling, present significant potential for addressing wastewater treatment challenges in industries like semiconductor manufacturing. These developments aim to enhance efficiency and sustainability, integrating non-thermal plasma technologies and advanced photocatalytic materials to effectively degrade persistent organic pollutants. By focusing on these cutting-edge techniques, the industry can progress toward environmentally friendly practices while reducing operational costs associated with traditional methods [30, 28, 29]. These processes remain integral to degrading recalcitrant organic pollutants, contributing to broader goals of environmental protection and public health.

3 Photocatalysis in Wastewater Treatment

Photocatalysis is pivotal in wastewater treatment, utilizing semiconductor materials to effectively degrade organic pollutants. The optimization of photocatalysts is crucial, necessitating a deep understanding of their structural and electronic characteristics. This section delves into the various photocatalysts employed in wastewater treatment, focusing on their traits and efficacy in contaminant degradation to bolster environmental remediation efforts. Table 2 presents a comprehensive comparison of the features of different photocatalysts, elucidating their roles in the mechanisms of photocatalytic degradation and recent advancements in material science relevant to wastewater treatment. Figure 2 illustrates the hierarchical structure of photocatalysis in wastewater treatment, detailing types of photocatalysts, mechanisms of photocatalytic degradation, and recent advances in photocatalytic materials. This figure categorizes traditional and innovative photocatalysts, explores charge dynamics and surface interactions in degradation mechanisms, and highlights material innovations and process enhancements in recent advancements. Such a comprehensive overview not only reinforces the importance of selecting appropriate photocatalysts but also emphasizes the ongoing developments that enhance their effectiveness in environmental applications.

3.1 Types of Photocatalysts

Photocatalysts are essential for degrading organic pollutants in wastewater, with titanium dioxide (TiO_2) being predominant due to its stability, non-toxicity, and strong oxidative potential. However, its wide bandgap restricts activity to ultraviolet light, prompting modifications for visible light enhancement. Innovations like TiO_2 nanotubes and graphene oxide composites have improved photocatalytic activity through enhanced charge separation and light absorption [41, 6].

As illustrated in Figure 3, the classification of photocatalysts highlights various modifications of TiO_2, emerging materials, and high-entropy oxides, each contributing to enhanced photocatalytic performance. Further advancements include codoping TiO_2 and $SrTiO_3$ to optimize electronic structures, while B_4C/SnO_2 composites achieve high degradation rates of dyes like Methylene Blue under sunlight [6]. Coupling TiO_2 with plasmonic metals increases surface area and light trapping, enhancing photocatalytic performance.

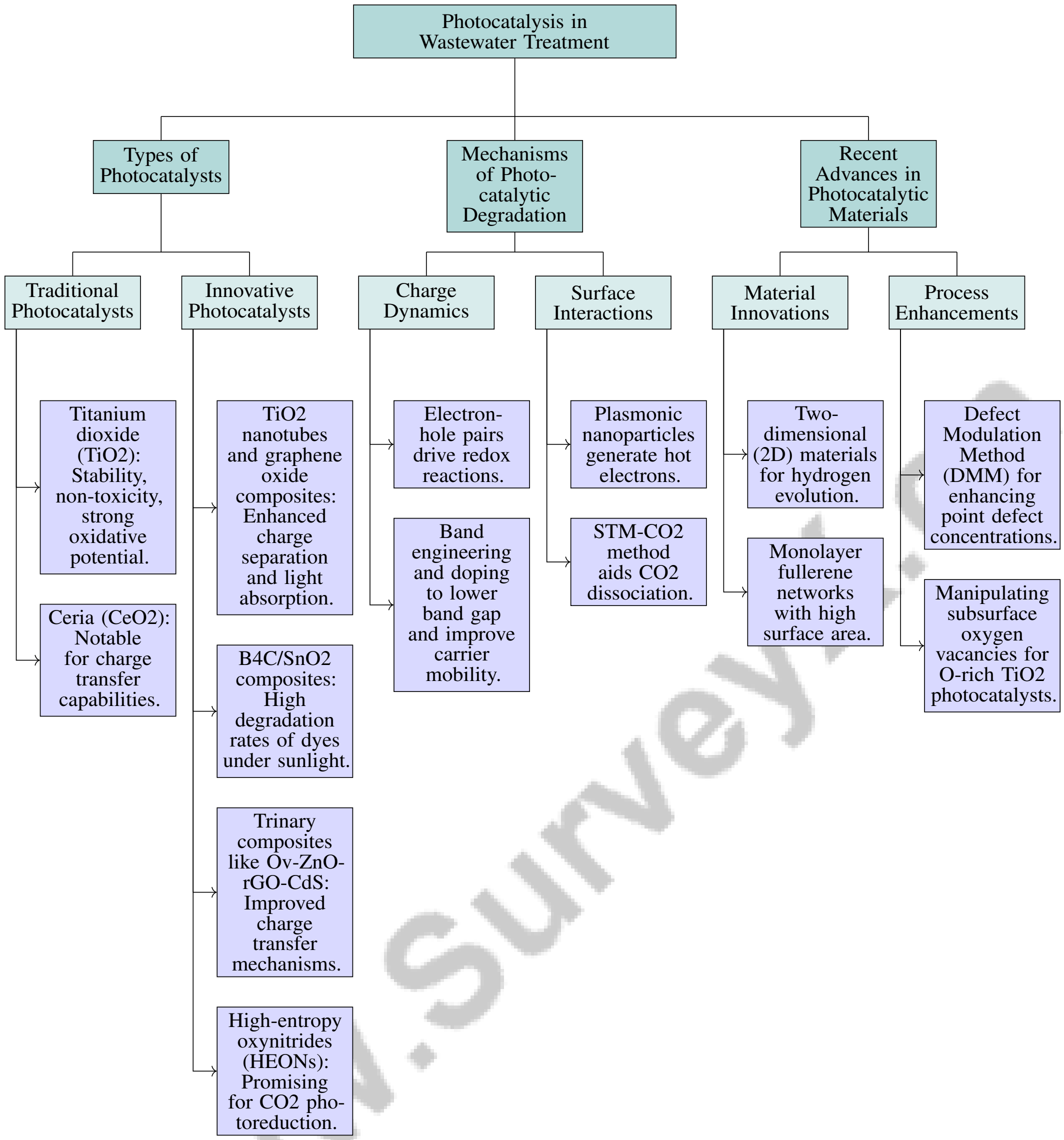


Figure 2: This figure illustrates the hierarchical structure of photocatalysis in wastewater treatment, detailing types of photocatalysts, mechanisms of photocatalytic degradation, and recent advances in photocatalytic materials. It categorizes traditional and innovative photocatalysts, explores charge dynamics and surface interactions in degradation mechanisms, and highlights material innovations and process enhancements in recent advancements.

Ceria (CeO_2) is notable for its charge transfer capabilities, and trinary composites like Ov-ZnO-rGO-CdS exhibit enhanced properties through improved charge transfer mechanisms. Emerging materials such as $BiVO_3F$ and Cu_2O nanostructures offer advantages over traditional photocatalysts [42]. The CTCN photocatalyst, combining g-$C3N_4$ with $CaTiO_3$, and MgO/GNPs nanocomposites demonstrate enhanced photocatalytic and antibacterial properties due to superior charge carrier dynamics. High-entropy oxynitrides (HEONs), like $TiZrNbHfTaO_6N_3$, with low bandgaps and reduced charge carrier recombination, are promising for CO_2 photoreduction [43, 44].

Recent advancements in photocatalyst design, including polarization enhancement and plasmonic nanostructures, underscore the significance of material science in wastewater treatment technologies, leading to improved degradation efficiency of organic pollutants, such as significant reductions in common contaminants like Carbamazepine [20, 30].

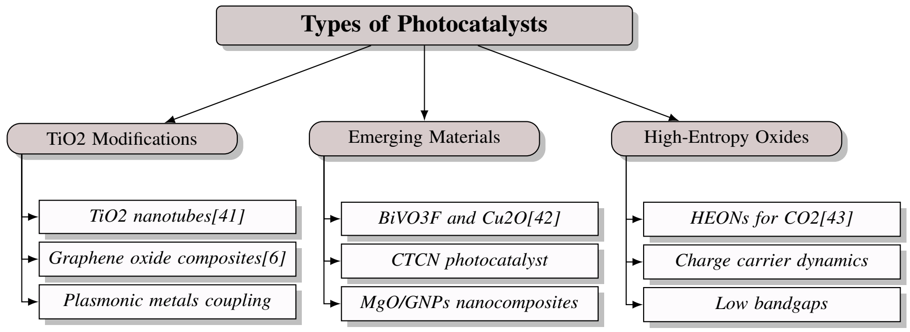


Figure 3: This figure illustrates the classification of photocatalysts, highlighting modifications of TiO2, emerging materials, and high-entropy oxides, each contributing to enhanced photocatalytic performance.

3.2 Mechanisms of Photocatalytic Degradation

Method Name	Charge Dynamics	Material Engineering	Photocatalytic Efficiency
CRP[2]	-	-	Degradation Efficiency
SLTCO[45]	Carrier Dynamics	Co-doping Strategy	Enhanced Photocatalytic Performance
NMD-TiO2[18]	Better Charge Separation	Noble Metal Doping	Enhanced Photocatalytic Performance
STM-CO2[8]	Electron Attachment	Reduced Rutile Tio2	Co2 Conversion Efficiency
HFMD-TI[34]	Electron-hole Pairs	Band Gap	Degrading Pollutants
N-TiO2[46]	Recombination Rates	Doping Procedures	Enhanced Performance
SHS[47]	Electron-proton Vibronic	Rutile Tio2(110)	Vibronic Coupling Resonance

Table 1: Overview of various photocatalytic methods, detailing the charge dynamics, material engineering techniques, and resulting photocatalytic efficiencies. This table highlights the diverse approaches employed to enhance photocatalytic performance, including carrier dynamics, doping strategies, and electron attachment mechanisms.

Photocatalytic degradation of organic pollutants involves light-induced interactions with semiconductor materials, generating electron-hole pairs that drive redox reactions. Charge transfer dynamics and optical properties of semiconductors significantly influence these processes. Tracer injection methods enhance understanding of flow behavior in photocatalytic reactors, facilitating the evaluation of degradation mechanisms [2].

Enhancing photocatalytic efficiency requires optimizing charge separation and migration. Band engineering, such as co-doping La and Cr into $SrTiO_3$, lowers the band gap while maintaining carrier mobility, thus improving performance [45]. Similarly, doping TiO_2 monolayers enhances charge separation and reduces the band gap, facilitating organic pollutant degradation [18].

Plasmonic nanoparticles interacting with semiconductor surfaces generate hot electrons that enhance photocatalytic activity, particularly in systems utilizing surface plasmons [33]. The STM-CO_2 method illustrates direct electron attachment to CO_2, aiding its dissociation into CO and oxygen, crucial for understanding photocatalytic degradation processes [8]. Studies on polarons in aqueous environments provide insights into optimizing photocatalytic activity [34].

Despite advancements, inconsistencies in reporting photocatalytic activities can lead to misleading efficiency claims [27]. Addressing these discrepancies is vital for accurately assessing and comparing the effectiveness of photocatalytic materials and processes.

The mechanisms underlying photocatalytic degradation highlight the need for optimizing material properties and interfacial dynamics, significantly influencing charge separation and transfer kinetics. This optimization is crucial for the sustainable degradation of toxic organic pollutants in wastewater, where rapid charge carrier recombination limits performance. Recent polarization strategies show promise in enhancing charge separation and photocatalytic activity, addressing challenges in environmental remediation and energy generation [20, 27].

As illustrated in **??**, photocatalysis in wastewater treatment leverages light to degrade pollutants, showcasing various mechanisms of photocatalytic degradation through diverse material structures. Nanostructured materials, depicted in high-resolution transmission electron microscopy (TEM), reveal interconnected, rod-like structures that enhance photocatalytic activity due to their large surface area. Molecular structures arranged in a grid format highlight the complexity and variety of chemical interactions in photocatalysis. Additionally, the circular diagram of piezoelectric and ferroelectric materials emphasizes the role of polarization types in influencing photocatalytic efficiency. Together, these visual examples underscore the intricate mechanisms at play in photocatalytic degradation, paving the way for innovative approaches in wastewater treatment [46, 47, 20]. Table 1 provides a comprehensive comparison of different photocatalytic methods, illustrating the interplay between charge dynamics, material engineering, and photocatalytic efficiency in the degradation of organic pollutants.

3.3 Recent Advances in Photocatalytic Materials

Recent advancements in photocatalytic materials have significantly enhanced their efficiency and applicability in wastewater treatment. Notably, two-dimensional (2D) materials and their composites exhibit promising photocatalytic properties for hydrogen evolution and solar energy conversion [38]. The integration of photoinduced spin centers in photocatalytic frameworks, detected through low-temperature EPR spectroscopy and UV irradiation, has opened new avenues for enhancing activity in materials like UiO-66 [48].

The role of thermal effects in photocatalytic processes has been revisited, emphasizing their importance as a straightforward mechanism compared to non-thermal contributions, challenging existing paradigms [49]. Tailoring the shape of TiO_2 nanoparticles has been shown to optimize charge injection mechanisms, enhancing TiO_2-based photocatalytic applications [50]. Additionally, the dynamic contribution to the Schottky barrier stabilizes electron-hole pairs, facilitating photocatalytic processes and promoting long-lived hot carrier lifetimes [51].

Innovations in synthesizing monolayer fullerene networks highlight their high surface area and unique electronic properties, enhancing photocatalytic performance compared to traditional materials [52]. The development of carbon nitrides with high specific surface area and pH-dependent adsorption properties has led to improved photocatalytic activity, providing alternatives to conventional carbon-based materials [53]. The influence of catechol on TiO_2 surfaces, with the highest adsorption degree among isomers, underscores the importance of surface chemistry in enhancing photocatalytic efficiency [54].

Layered nanoarchitectures, comprising titania nanoparticles, single-layer graphene, and two-dimensional Ti oxide films, significantly enhance photocatalytic activity by reducing electron-hole recombination and optimizing charge transfer dynamics [55]. The integration of bismuth vanadate into one-dimensional photonic crystals has demonstrated enhanced optical properties, allowing for tuning of the photonic band gap and optimization of photocatalytic activity [56]. Band bending configurations in Cu_2O/TiO_2 systems are proposed to enhance charge separation and photocatalytic activity under ultraviolet illumination [42].

The Defect Modulation Method (DMM), combining low-energy ion implantation with thermal annealing, effectively enhances point defect concentrations, improving photocatalytic efficiency in materials like ZnO [36]. Manipulating subsurface oxygen vacancies can lead to more active O-rich TiO_2 photocatalysts, representing a recent advance in photocatalytic materials [57]. Furthermore, studying hot electron dynamics in plasmonic structures reveals potential for improved energy conversion efficiencies, advancing the field [58].

Despite these advancements, comparative analyses reveal that many studies lack adequate experimental details, leading to unreliable claims about photocatalytic efficiencies based solely on reaction rates rather than quantum yields or apparent quantum efficiencies [27]. Addressing these inconsistencies is essential for accurately assessing and comparing the effectiveness of various photocatalytic materials and processes.

These advancements reflect a broader trend towards developing innovative photocatalytic materials that leverage unique structural and electronic properties for more effective and sustainable wastewater treatment solutions. By emphasizing innovative designs and advanced synthesis techniques, researchers are significantly enhancing the efficiency and versatility of photocatalysts, crucial for applications in solar energy conversion, air purification, and water treatment. These developments address key challenges in photocatalytic activity, including rapid charge carrier recombination and the need for improved surface area and light absorption, ultimately leading to more effective and sustainable solutions for environmental remediation and energy production [27, 59, 38, 20, 30].

Feature	Types of Photocatalysts	Mechanisms of Photocatalytic Degradation	Recent Advances in Photocatalytic Materials
Material Type	Tio2 Composites	Semiconductors	2D Materials
Charge Dynamics	Enhanced Separation	Electron-hole Pairs	Optimized Injection
Light Absorption	UV And Visible	Light-induced Reactions	Solar Conversion

Table 2: This table provides a comparative analysis of various features associated with different types of photocatalysts, mechanisms of photocatalytic degradation, and recent advances in photocatalytic materials. It highlights the distinctions in material types, charge dynamics, and light absorption characteristics, offering insights into the optimization strategies for improving photocatalytic efficiency in wastewater treatment.

4 Advanced Oxidation Processes (AOPs)

Advanced Oxidation Processes (AOPs) are transformative in degrading persistent organic pollutants, crucial for environmental remediation. This section delves into AOP mechanisms and efficiency, focusing on fundamental principles vital for optimizing performance in wastewater treatment.

4.1 Mechanisms and Efficiency of AOPs

AOPs effectively mineralize persistent organic pollutants by generating highly reactive hydroxyl radicals (•OH), which degrade contaminants into harmless end products. Electrochemical advanced oxidation processes (EAOPs) are notable for producing hydroxyl radicals through direct water oxidation on anodes or Fenton chemistry, which generates hydrogen peroxide in situ. These methods enhance degradation efficiency without requiring external reagents, making them promising for wastewater treatment. Recent advancements incorporating sulfate radicals (SO•) and non-thermal plasma technologies expand AOP capabilities, addressing recalcitrant organic micropollutants [12, 26, 60, 61, 28]. AOP efficiency is significantly influenced by materials' electronic properties and active site density, enhancing photocatalytic efficiency. Manipulating electric and magnetic fields improves optical responses, optimizing AOP mechanisms.

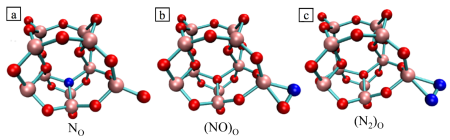
Minimizing radical recombination losses further enhances AOP efficiency, particularly in plasmon-assisted photocatalysis, where temperature distribution is dictated by illumination intensity [62]. Understanding the interplay between photothermal and hot-carrier mechanisms in plasmonic systems sheds light on collective heating effects and their impact on AOP effectiveness [13].

Despite the potential of hot electron mechanisms in plasmon-assisted photocatalysis, evidence suggests only a fraction of illumination power generates 'hot' electrons, with reaction rate increases not matching expectations from such mechanisms [49]. This underscores the importance of alternative mechanisms, such as thermal effects, in driving reactions within AOPs [15]. Optimizing TiO_2-based materials' design requires understanding how adsorption modes influence electron injection [50], crucial for optimizing charge transfer and improving AOP efficiency.

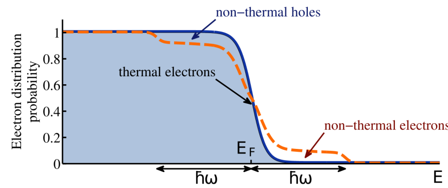
Electrochemical synthesis of high surface area materials, like carbon-based photocatalysts, boosts photocatalytic efficiency by providing more active sites for degradation [53]. While two-dimensional halide perovskites show promise, challenges with long-term stability under environmental conditions necessitate ongoing research for robust materials suitable for AOP applications [63].

Recent studies highlight subsurface oxygen vacancies' role in enhancing anatase TiO_2 photocatalytic activity, paralleling AOP mechanisms [57]. The photocatalysis-self-Fenton system's efficiency in degrading organic pollutants, particularly hydroxylating benzene, emphasizes AOP potential [21]. However, challenges with heterostructure quality, such as interface quality and synthesis scalability, impede progress [4].

AOP mechanisms and efficiency are pivotal in sustainably degrading organic pollutants in semiconductor wastewater, facilitating complex contaminant breakdown through photocatalysis and non-thermal plasma. These methods are essential for mitigating environmental impacts and fostering green innovation in wastewater treatment [64, 28, 29]. By leveraging advanced materials and optimizing process conditions, AOPs offer promising solutions for environmental remediation challenges.



(a) Three Molecular Structures[65]



(b) The distribution of electron probability in a quantum system[66]

Figure 4: Examples of Mechanisms and Efficiency of AOPs

As shown in Figure 4, AOPs involve chemical treatments to remove organic and inorganic materials via oxidation with hydroxyl radicals. The mechanisms and efficiency of AOPs involve complex interactions among molecular structures and quantum phenomena. The first image depicts molecular structures highlighting atomic configurations facilitating oxidative reactions. The second image presents electron probability distribution within a quantum system, illustrating energy levels crucial for understanding thermal and non-thermal electron behavior in oxidation processes. These examples underscore the interplay between molecular structure and quantum mechanics in AOP effectiveness [65, 66].

4.2 Comparative Analysis of AOP Methods

Benchmark	Size	Domain	Task Format	Metric
scPBE0[67]	30	Oxide Semiconductors	Band Gap Calculation	Mean Absolute Percentage Error, Ion-Clamped Dielectric Constant
2DSdb[68]	259	Semiconductor Physics	Material Screening	Formation Energy, Band Gap

Table 3: This table presents a summary of the representative benchmarks employed in the comparative analysis of advanced oxidation processes (AOPs) within the semiconductor industry. It includes details on the benchmark names, their respective sizes, domains, task formats, and the metrics used for evaluation. These benchmarks facilitate the assessment of AOP methods in terms of their effectiveness in degrading pollutants in semiconductor wastewater.

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A comprehensive comparative analysis of AOPs is essential for evaluating their efficiency and suitability in degrading various organic pollutants in semiconductor wastewater, significantly impacting the environment due to manufacturing contaminants' complexity. Table 4 provides a detailed overview of the representative benchmarks used in the comparative analysis of advanced oxidation processes (AOPs) within the semiconductor industry. This analysis aids in identifying sustainable treatment methods enhancing pollution prevention and supporting green innovation within the semiconductor sector [26, 61, 60, 28, 29]. AOPs like ozonation, Fenton and photo-Fenton processes, and sulfate radical-based oxidation each offer unique mechanisms and efficiencies for different treatment scenarios.

Ozonation uses ozone as a powerful oxidizing agent to degrade pollutants, with hydroxyl radical generation enhanced by ultraviolet (UV) radiation. This combination accelerates degradation rates of

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recalcitrant organic compounds. The synergy between UV irradiation and hydroxyl radicals improves contaminant removal efficiency in heterogeneous photocatalysis, leveraging dissolved organic matter properties to optimize photochemical processes in environmental remediation [12, 69, 27]. However, high operational costs and potential harmful by-products limit its widespread application.

Fenton and photo-Fenton processes generate hydroxyl radicals through hydrogen peroxide reactions with iron catalysts, proving highly effective for mineralizing organic pollutants. The photo-Fenton process benefits from additional energy input from UV or visible light, enhancing radical generation and degradation efficiency. However, managing iron sludge—a by-product of various wastewater treatment processes in the semiconductor industry—and the necessity for acidic conditions during treatment present operational challenges that increase costs and complexity [26, 61, 28, 29, 1].

Sulfate radical-based oxidation, using persulfate ($S_2O_8^{2-}$) or peroxymonosulfate (HSO_5^-) as precursors, offers a promising alternative due to sulfate radicals' high reactivity and selectivity. These radicals exhibit superior oxidation potential compared to hydroxyl radicals, effectively degrading a wide range of pollutants. The study by [60] emphasizes the challenge of predicting reaction kinetics for sulfate radical-driven processes, highlighting the need for accurate models to optimize these AOP methods. Despite their potential, issues related to persulfate activation and sulfate radical precursors' cost remain challenges to broader implementation.

Each AOP method presents distinct advantages and limitations, influencing their applicability in specific wastewater treatment contexts. The choice of AOP depends on pollutant nature, desired treatment efficiency, and economic and environmental considerations. By thoroughly examining the comparative efficiencies and limitations of various advanced wastewater treatment methods—such as non-thermal plasma processing, photocatalytic nanoparticles, and magnetic iron oxide-integrated photocatalysts—customized treatment strategies can be designed to enhance persistent organic micropollutant degradation, including pharmaceuticals and industrial waste, while addressing operational challenges like sludge management and resource sustainability. This tailored approach can significantly improve pollutant removal efficacy while minimizing environmental impact and operational costs [64, 28, 29, 26].

4.3 Innovations in AOPs

Recent innovations in AOPs have significantly enhanced their capabilities in treating semiconductor wastewater by addressing key challenges related to efficiency and applicability. Notable advancements include integrating a two-dimensional titanium oxide layer that induces p-doping in graphene and modifies titanium d states, reducing charge carrier recombination and enhancing AOP systems' photocatalytic activity [55]. Such structural innovations are crucial for improving organic pollutant degradation rates in wastewater treatment applications.

Exploring electronic structures in emergent semiconducting materials offers promising avenues for further innovations in AOP technologies. Methodologies developed for these materials can be extended to improve AOP systems' efficiency and stability, facilitating complex organic pollutant degradation [16]. This approach underscores material science's potential to drive AOP advancements, enabling more effective treatment solutions.

The development of co-substituted $BiFeO_3$ materials exemplifies another significant innovation, with applications in photocatalytic degradation of organic pollutants. These materials exhibit enhanced electronic and ferroelectric properties, contributing to improved photocatalytic performance and offering new possibilities for AOP technologies [41]. Such advancements highlight material modifications' importance in expanding AOPs' operational capabilities.

Furthermore, ongoing exploration of advanced materials is critical for the continued evolution of AOP technologies. The need for further research in this area is emphasized, as these innovations are essential for addressing complex challenges posed by organic pollutants in semiconductor wastewater [1]. By leveraging novel materials and synthesis techniques, researchers are paving the way for more sustainable and effective AOP solutions, enhancing wastewater treatment processes' environmental and economic viability.

5 Integration of Treatment Technologies

The integration of treatment technologies represents a significant advancement in managing wastewater, particularly in addressing organic pollutants from semiconductor sources. This section explores the fundamental concepts and mechanisms behind the integration of photocatalysis and advanced oxidation processes (AOPs), emphasizing their synergistic effects. Understanding these interactions unveils the complexities and innovations arising from combining these methods, with the following subsection highlighting their implications for enhancing pollutant degradation efficiency.

5.1 Synergistic Effects in Integrated Systems

Integrating photocatalysis with AOPs markedly enhances the degradation efficiency of organic pollutants in semiconductor wastewater. This is achieved through improved charge separation, reduced recombination rates, and enhanced catalytic performance, particularly with advanced materials and innovative system designs. The synergy of hydrodynamic cavitation, magnetic iron oxides, and advanced photocatalytic materials significantly boosts the degradation of organic compounds and pharmaceuticals in effluents [30, 29, 26].

A pivotal advancement is the understanding of thermal effects in plasmon-assisted photocatalysis, leading to optimized reaction conditions [15]. Utilizing reduced graphene oxide (rGO) with SnO_2 has demonstrated high degradation efficiency and rapid reaction times, offering a cost-effective solution for dye degradation in wastewater treatment [6]. Co-doping strategies further illustrate the potential of integrated systems to mitigate defects and enhance treatment efficiency by maintaining ideal stoichiometry [45].

Challenges such as electron back transfer, which diminishes the effectiveness of hot carriers in catalysis, necessitate research on stabilizing hybrid nanostructures and optimizing reducing agent conditions. This research should focus on enhancing reproducibility and performance, leveraging advancements in plasmonic and photonic hybridization techniques to optimize light absorption and catalytic activity, as evidenced in studies involving titanium dioxide (TiO_2) thin films and plasmonic nanoparticles [70, 30].

Inadequate material characterization and improper photocatalytic efficiency measurements pose significant challenges, highlighting the need for standardized methodologies that accurately account for photon involvement in reactions [27]. Addressing these challenges while leveraging the synergistic effects of integrated systems provides promising pathways for effective and sustainable wastewater treatment, enhancing both pollutant degradation and the environmental impact of semiconductor wastewater treatment.

5.2 Innovative Materials and Composites

The development of innovative materials and composites is crucial for enhancing the efficiency and applicability of integrated treatment technologies in organic pollutant degradation. One promising approach is the integration of graphene nanoplatelets with MgO, which facilitates charge transfer and enhances photocatalytic performance due to graphene's superior electrical conductivity [71].

Recent advancements include the synthesis of well-defined Cu_2O nanocrystals through facet engineering and hybridization, demonstrating enhanced photocatalytic activity and stability [72]. This underscores the importance of precise control over material properties for optimizing photocatalytic performance. Furthermore, integrating dielectric Cu_2O materials into photocatalytic systems has improved efficiency in dye degradation processes [59].

Interfacial engineering, such as incorporating a two-dimensional titanium oxide layer in graphene-titania composites, enhances photocatalytic efficiency by reducing charge carrier recombination [55]. Maintaining high crystallinity in TiO_2 while preserving carbon nanosheets is critical for enhancing photocatalytic activity, as demonstrated by methods that maintain structural integrity [73].

Exploring Tamm surface states in semiconductor materials allows for engineering decay rates and hot carrier production, further enhancing photocatalytic performance [74]. Future research should focus on developing hybrid structures, enhancing charge carrier mobility, and exploring new materials to improve photocatalytic hydrogen production efficiency [38]. The synthesis of STAO, uniformly dispersed in solution with unique electronic properties, highlights the potential for innovative material design [75].

Manipulating band structures in carbon nitride materials offers a novel approach to tuning the bandgap, enhancing photocatalytic performance and suggesting the development of innovative materials for integrated treatment technologies [17]. Additionally, understanding the role of ferroelastic strain in optical absorption is crucial for optimizing photocatalytic applications, providing insights into material modifications that enhance treatment efficiency [76].

These innovations in materials and composites are vital for advancing integrated treatment technologies, offering effective and sustainable solutions for organic pollutant degradation in semiconductor wastewater. By employing innovative materials and advanced synthesis techniques, researchers are significantly enhancing the efficiency and versatility of photocatalysts, crucial for applications in solar energy conversion, air pollution mitigation, and water purification. Recent studies emphasize the importance of proper characterization methods and reporting standards for accurate comparisons of photocatalytic performance, particularly regarding 2D materials that exhibit superior properties due to their unique structural advantages [38, 27].

5.3 Case Studies and Real-World Applications

The integration of photocatalysis and AOPs in wastewater treatment has been validated through numerous case studies and real-world applications, highlighting the practical benefits and effectiveness of these technologies. A notable example is the use of TiO_2-based photocatalysts for degrading organic pollutants, extensively studied for their efficiency in treating wastewater from semiconductor manufacturing. TiO_2 nanocomposites, particularly those integrated with graphene oxide, exhibit enhanced photocatalytic activity, resulting in significant pollutant concentration reductions [6].

The deployment of ZnO-based photocatalysts alongside AOPs has effectively treated industrial effluents containing recalcitrant organic compounds, achieving high degradation rates and underscoring ZnO's role in enhancing overall treatment processes. Furthermore, incorporating plasmonic metals into these systems has improved light absorption and charge separation, further boosting photocatalytic performance [40].

Real-world applications have also explored hybrid photocatalytic systems combining different semiconductor materials to optimize the degradation of complex organic pollutants. For instance, integrating $BiVO_4$ with other metal oxides has been successfully applied in pilot-scale wastewater treatment plants, demonstrating the scalability and effectiveness of these integrated systems. The enhanced photocatalytic activity of such composites is attributed to their ability to harness visible light and improve charge transport properties [34].

Additionally, implementing electrochemical AOPs in municipal wastewater treatment facilities has provided insights into the operational challenges and benefits of these technologies, effectively reducing organic pollutant concentrations and showcasing AOPs' potential to complement traditional treatment methods [21].

The case studies and practical applications presented in the literature illustrate the effective integration of photocatalysis and AOPs in wastewater treatment, highlighting advancements such as the development of magnetic iron oxide-based photocatalysts that enhance pollutant degradation and the innovative use of nanostructured titanium dioxide films that improve photocatalytic efficiency under various light conditions. These findings underscore the practical viability and scalability of these technologies for real-world wastewater remediation efforts [30, 26, 27]. By leveraging the synergistic effects of these technologies, treatment systems can achieve higher degradation rates and improved environmental outcomes, paving the way for more sustainable and effective wastewater management solutions.

As shown in Figure 5, the study of energy levels and structural properties of catalysts is crucial in integrating treatment technologies. The first image provides a detailed analysis of energy levels of various molecular species in a gas phase, focusing on the impact of varying parameters such as pressure and temperature. This series of plots highlights the energy differences between molecular species like N2, NO, N2O, and N2O+ and their respective ground states, offering valuable insights into their behavior under different conditions. The second image illustrates the structural and electronic properties of a TiO_2/CuO_2 catalyst through computational models, emphasizing the arrangement of

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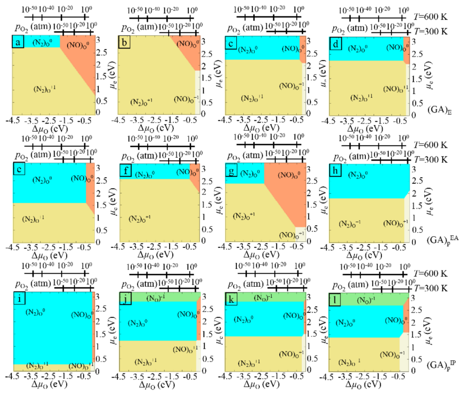
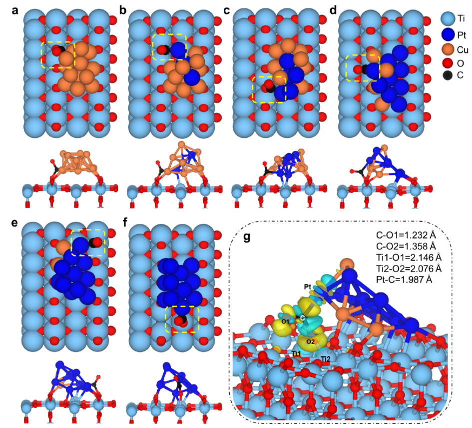


(a) The image shows a series of plots representing the energy levels of various molecular species in a gas phase, with different parameters such as pressure (pO2) and temperature (T) varying.[65]



(b) Structural and Electronic Properties of a TiO2/CuO2 Catalyst[77]

Figure 5: Examples of Case Studies and Real-World Applications

titanium dioxide and copper oxide layers in a hexagonal lattice. Together, these examples underscore the importance of understanding molecular interactions and catalyst structures in developing and integrating advanced treatment technologies [65, 77].

6 Environmental and Economic Implications

6.1 Environmental Benefits of Advanced Treatment Technologies

Advanced treatment technologies, particularly photocatalysis and advanced oxidation processes (AOPs), play a vital role in environmental protection and sustainability by effectively degrading organic pollutants in semiconductor wastewater. These technologies contribute to air pollution reduction and public health improvement, as demonstrated through various photocatalytic applications [2]. The enhancement of photocatalytic activity through noble metal doping, such as in TiO_2, leads to improved organic pollutant degradation, promoting environmental protection [18].

Innovative materials, including those utilizing plasmon-induced hot carriers, offer potential enhancements in photovoltaics and photochemistry, thereby supporting sustainable practices by increasing energy conversion efficiency [33]. Co-doping strategies have shown improvements in photocatalytic performance under visible light, emphasizing the environmental advantages of these technologies [45].

Advanced photocatalytic methods also significantly contribute to environmental protection by enhancing CO_2 conversion efficiency, thus mitigating greenhouse gas emissions [8]. By integrating innovative materials and optimizing catalytic processes, these technologies facilitate efficient pollutant degradation while minimizing environmental impacts, advancing sustainable environmental management and ensuring a healthier ecosystem for future generations.

6.2 Economic Aspects: Cost-Effectiveness and Scalability

The economic feasibility and scalability of advanced treatment technologies, including photocatalysis and AOPs, are crucial for widespread adoption in wastewater treatment. Sulfate radical oxidation methods (SROM) offer cost-effective solutions due to their computational efficiency and high accuracy [60]. Porphyrin-based metal-organic frameworks (MOFs) enhance economic feasibility by facilitating cost-effective solar fuel production [78]. Additionally, enhanced selectivity in CO_2 reduction reactions offers significant economic benefits by improving photocatalytic process efficiency [79].

The wafer-scale production of transition metal dichalcogenide (TMDC) layers is essential for the commercial application of these technologies [80]. Cost-effective methods, such as synthesizing

TiO_2 nanocrystals on graphene, further enhance scalability and economic viability [81]. However, challenges related to the scalability and long-term stability of photocatalysts must be addressed to ensure continuous operational efficiency [82]. Optimizing electrochemical advanced oxidation processes (EAOPs) for various dyes is crucial for improving cost-effectiveness and scalability [61]. Future research should explore novel electrode materials and understand the long-term effects of treatment byproducts on the environment.

6.3 Regulatory and Sustainability Perspectives

The implementation of advanced treatment technologies, such as photocatalysis and AOPs, in wastewater treatment requires careful consideration of regulatory frameworks and sustainability issues. Regulatory standards ensure these technologies meet environmental protection goals while adhering to safety and efficacy requirements. Understanding the stability and behavior of surface polarons in TiO_2 is crucial for regulatory compliance [83]. Refining computational methods to improve polaron modeling accuracy is essential for effective compliance.

Tuning stability in electrochemical interfaces is another regulatory consideration, as current models may not fully account for elastic strain effects [11]. Ongoing research is needed to improve model accuracy and ensure compliance. Additionally, optimizing charge transfer processes in TiO_2 through molecular combinations and modifier ratios can enhance material performance, aligning with regulatory standards [84].

Sustainability is paramount, as the long-term viability of treatment technologies depends on their environmental impact and resource efficiency. Improvements in carbon dot structures for enhanced pH sensitivity could lead to more sustainable processes by optimizing resource use and minimizing waste [14]. Addressing these sustainability challenges enables advanced treatment technologies to contribute to cleaner water and air, aligning with broader environmental goals and regulatory frameworks.

7 Conclusion

7.1 Future Research Directions

Advancements in wastewater treatment technologies hinge on the development of standardized protocols for reporting photocatalytic activities, which will enhance the consistency and comparability of research outcomes. A comprehensive investigation into mechanistic pathways and the resolution of methodological inconsistencies is essential for advancing the field. Furthermore, optimizing doping concentrations and exploring alternative co-dopants are pivotal for enhancing the stability and efficiency of photocatalytic materials, driving innovation and performance improvements.

Research into the impact of varying isomer concentrations and environmental conditions on microbial disinfection, particularly E. Coli inactivation, will provide insights into the broader applicability of photocatalytic processes. Additionally, refining spatiotemporal separation techniques and their role in enhancing plasmonic energy conversion efficiency is crucial for optimizing photocatalytic systems.

Exploring diverse interface configurations and extending these methodologies to other materials will optimize interfacial dynamics, broadening the scope and applicability of photocatalytic technologies across different treatment scenarios. Addressing these research areas will contribute significantly to the development and sustainability of advanced treatment technologies, effectively mitigating environmental impacts and enhancing the efficiency of wastewater treatment processes.

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