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Photocatalysis Unveiled: Fundamentals, Mechanisms, and Material Innovations

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Abstract

The Industrial Revolution significantly enhanced living standards but also led to severe environmental degradation, making pollution a critical concern for both developed and developing nations. Photocatalysis, a light-driven chemical process, accelerates thermodynamically demanding reactions, such as photosynthesis, offering a promising alternative for deep solar energy storage. This method also minimizes chemical exposure and reduces environmental pollutants generated by industrial activities. A key advantage of photocatalysis is its ability to replace high-temperature pollution removal processes with more energy-efficient, low-temperature alternatives, thereby conserving fossil fuel resources. Various photocatalytic materials, including AgCl, P-doped g-C_3N_4, and Z-scheme photocatalysts coupled with Fe_3O_4/H_2O_2, have gained attention due to their multiple valence states and high catalytic efficiency. A critical focus of this review is the Z-scheme strategy, which enhances electron transport pathways by forming heterojunctions with optimal band alignments, thereby improving the photocatalytic activity of MnO_2. The article explores recent advancements in photocatalysis, MnO_2-based composite materials, and the Z-scheme charge carrier mechanism. Additionally, the electrical, photoelectric, and crystallographic properties of MnO_2 are examined, emphasizing the significance of the Z-scheme electron transfer process in enhancing photocatalytic performance. Various electron transport pathways in MnO_2-based composites are investigated using different characterization techniques to provide deeper insights into the Z-scheme mechanism. This review comprehensively discusses the fundamental principles, processes, and materials in photocatalysis, highlighting its potential for environmental sustainability and energy-efficient applications.

Keywords: Photocatalysis, Z-scheme mechanism, MnO_2-based composites, Heterojunctions, Electron transport pathways.

INTRODUCTION

The modern world is facing multiple crises due to rapid population growth in the twenty-first century, including water shortages, energy deficits, electricity scarcity, and food insecurity. Addressing these challenges requires alternative energy sources beyond conventional fossil fuels like coal and oil. Solar energy, an abundant and renewable resource, presents a promising solution. Even utilizing just 1% of the immense solar energy our planet receives annually could effectively mitigate the global energy crisis. However, only a fraction of this energy is currently harnessed for human use. Solar energy is an environmentally friendly and cost-effective alternative that poses minimal risks to both nature and human health.

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In recent years, solar-based technologies have garnered significant attention due to their ability to

function independently without generating harmful emissions. Various techniques have been developed to capture and utilize solar energy, including photovoltaics, photocatalysis, and photo electrocatalysis. Among these, photocatalysis draws inspiration from natural photosynthesis, leveraging optical energy to drive chemical reactions. First introduced in 1839, the concept of photocatalysis gained broader recognition in the late 1960s through the pioneering efforts of researchers. The growing emphasis on sustainability has further fueled interest in photocatalytic research, particularly in areas related to artificial photosynthesis and solar fuel generation.

Photocatalysts, often in the form of nanoparticles, exhibit unique electronic structures, efficient light absorption, and enhanced charge transfer properties. These characteristics make them highly valuable for applications such as sustainable energy production and environmental remediation. Due to their high surface area and tunable nanostructures, photocatalysts can be engineered to optimize performance. Materials capable of generating electron-hole pairs upon light absorption, thereby converting photons into useful energy, are categorized as photocatalytic materials. Chlorophyll in green plants serves as a natural photocatalyst during photosynthesis, facilitating the conversion of carbon dioxide and water into oxygen and carbohydrates.

Engineered photocatalysts mimic natural processes by utilizing photogenerated charge carriers to drive reactions such as water splitting and carbon dioxide reduction. The fundamental steps in a photocatalytic reaction include light absorption, charge separation, and interaction between charge carriers and reactants. Initially, exposure to light generates excited electrons and holes, which migrate to the photocatalyst surface to initiate redox reactions. The efficiency of this process depends on effective charge separation and suppression of recombination, which can be achieved through advanced nanomaterial designs.

The ongoing development of photocatalytic nanomaterials has led to remarkable advancements in oxidation processes and solar energy utilization. Recent innovations in photocatalysis aim to enhance energy efficiency and sustainability, with a particular focus on heterogeneous photocatalysis. Unlike homogeneous systems, heterogeneous photocatalysis involves an interface between a solid photocatalyst and a liquid-phase reactant solution, making it suitable for diverse industrial and environmental applications.

A promising advancement in this field is the integration of the Photo-Fenton-assisted AgCl and P-doped g-C_3N_4 Z-scheme photocatalyst. This hybrid system forms a highly efficient heterojunction that significantly enhances charge separation and transfer. The addition of hydrogen peroxide and iron ions further amplifies catalytic activity by generating reactive hydroxyl radicals, which play a crucial role in pollutant degradation. The synergy between Z-scheme photocatalysis and the Photo-Fenton reaction demonstrates superior efficiency in environmental remediation, highlighting the potential for integrating traditional photocatalytic materials with advanced chemical processes.

Different Photocatalytic Materials: P-Doped g-C_3N_4, AgCl, and MnO_2

The application of photocatalytic materials in energy conversion and environmental remediation has attracted significant attention. Among the various photocatalysts studied, MnO_2, AgCl, and P-doped g-C_3N_4 stand out due to their affordability, high catalytic efficiency, and ability to exist in multiple oxidation states. Additionally, the incorporation of Fe_3O_4 and hydrogen peroxide further enhances the performance of Z-scheme photocatalysts. This review explores recent advancements in MnO_2-based composites, emphasizing the role of the Z-scheme mechanism in boosting photocatalytic activity.

Enhancing Photocatalytic Activity Using MnO_2 as a Z-Scheme Photocatalyst

The Z-scheme photocatalytic system is a promising approach to improving MnO_2 efficiency. This method involves the formation of heterojunctions with optimized band alignments, facilitating efficient electron transport. In MnO_2-based composites, these heterojunctions enhance charge separation and prevent recombination, significantly increasing overall photocatalytic performance.

Extensive research has been conducted to explore electron transfer pathways in MnO_2-based composites, providing deeper insights into the Z-scheme mechanism. This system strategically aligns energy bands between different semiconductors to optimize charge separation and transfer. In this setup, photogenerated electrons from the conduction band of one semiconductor migrate to the valence band of another, preventing recombination and maintaining high redox potential.

Advanced characterization techniques such as photoluminescence spectroscopy, electrochemical impedance spectroscopy, and transient absorption spectroscopy have been used to investigate these electron transfer mechanisms. Studies indicate that the Z-scheme structure in MnO_2-based composites not only spatially separates charge carriers but also accelerates their transfer rates, resulting in significantly improved photocatalytic efficiency. A deeper understanding of these pathways is crucial for designing next-generation photocatalysts with enhanced performance and broader applications [1-3].

MnO_2-Based Composites for Photocatalytic Applications

Recent research has focused on the development of MnO_2-based composites for photocatalytic applications. These materials leverage the Z-scheme charge transfer mechanism, where electrons move from the conduction band of one semiconductor to the valence band of another, thereby enhancing catalytic efficiency. This review highlights the importance of this mechanism in achieving superior photocatalytic performance and explores the latest advancements in MnO_2-based composite materials.

HISTORIC DEVELOPMENT: PHOTOCATALYSIS

The process in which light triggers a chemical reaction by activating a catalyst, has a rich and multifaceted history that spans several centuries. Below is a brief overview of its historical development.

Discovery of Photocatalysis (1767–1839)

The origins of photocatalysis can be traced to the late 18th and early 19th centuries with key discoveries by Johann Wilhelm Ritter and Alexandre-Edmond Becquerel. Ritter observed the light-induced generation of hydrogen from water using silver chloride, while Becquerel discovered the photovoltaic effect, where certain materials produce an electric current when exposed to light. These early observations laid the groundwork for understanding the relationship between light and chemical reactions.

Early Photocatalytic Studies (19th and Early 20th Century)

In the late 19th and early 20th centuries, researchers such as Alexander Stoletov and Ferdinand Braun explored the photoconductivity of selenium and other materials. Their work helped establish the link between light absorption and chemical reactions in solid-state materials, setting the stage for the further development of photocatalysis [4].

Seminal Advances in Photocatalysis (20th Century)

The mid-20th century saw a significant leap in photocatalysis research with the development of semiconductor photocatalysts. In the 1960s and 1970s, Akira Fujishima and Kenichi Honda made groundbreaking discoveries about the photocatalytic properties of titanium dioxide (TiO_2) when exposed to ultraviolet (UV) light. Their research revealed the potential of photocatalysis for practical environmental applications, such as water purification and air detoxification.

Commercialization and Applications (Late 20th Century - Present)

From the late 20th century onward, photocatalysis evolved from a scientific curiosity into a commercially viable technology. The development of advanced photocatalytic materials, including doped TiO_2 and other semiconductors, expanded its applications to areas like organic synthesis, energy conversion, and environmental remediation. Today, photocatalysis is used in diverse fields, such as wastewater treatment, air purification, self-cleaning surfaces, solar energy conversion, and photovoltaics. Ongoing research continues to explore new materials, mechanisms, and applications.

BASIC PRINCIPLES OF PHOTOCATALYSIS

Photocatalysis is the process by which photonic energy is converted into chemical energy with the assistance of photocatalysts. The primary sources of photonic energy include sunlight, UV radiation, and visible light. Photons with energy greater than or equal to the photocatalyst's band gap (BG) generate electron (e^-) and hole (h^+) pairs. These pairs are crucial for oxidizing and reducing contaminants on the surface of the photocatalyst, creating the essential electron-hole couples. The process starts when electrons in the valence band (VB) gain enough energy to move to the conduction band (CB), releasing e^- in the process. For photocatalysis to be effective, both oxidation and reduction reactions must occur simultaneously. In this process, a material that accelerates a chemical reaction without being consumed itself is activated by light. This activation lowers the activation energy required for the primary chemical reaction, making the process more efficient [5-8].

TYPES OF PHOTOCATALYTIC MATERIALS AND PROCESSES

Photocatalysis, where light is used to trigger chemical reactions on a catalyst's surface, has gained significant attention for its potential in producing valuable compounds, cleaning the environment, and converting energy. While photocatalytic activity can be found in various materials, semiconductor-based materials have garnered the most research interest. This section explores several common photocatalytic materials and their properties [9].

Titanium Dioxide (TiO_2)

Titanium dioxide (TiO_2) is one of the most extensively studied photocatalytic materials, primarily due to its remarkable stability, low cost, and non-toxicity. TiO_2 exists in three crystalline forms: rutile, anatase, and brookite, with anatase being the most effective in photocatalytic activity. Its bandgap energy of approximately 3.2 eV (for anatase) allows TiO_2 to absorb UV light, leading to the generation of electron-hole pairs and initiating redox reactions on its surface. However, its wide bandgap restricts its photocatalytic activity to only UV light, limiting its efficiency under visible light conditions [10-11].

Zinc Oxide (ZnO)

Zinc oxide (ZnO) is another semiconductor photocatalyst with a wide bandgap of around 3.37 eV, making it capable of absorbing UV light. Similar to TiO_2, ZnO generates electron-hole pairs when exposed to light, which then participate in photocatalytic reactions. ZnO exhibits high photocatalytic efficiency and has attractive properties such as biocompatibility and transparency, making it suitable for applications in areas like biomedical engineering and wastewater treatment Figure 1.

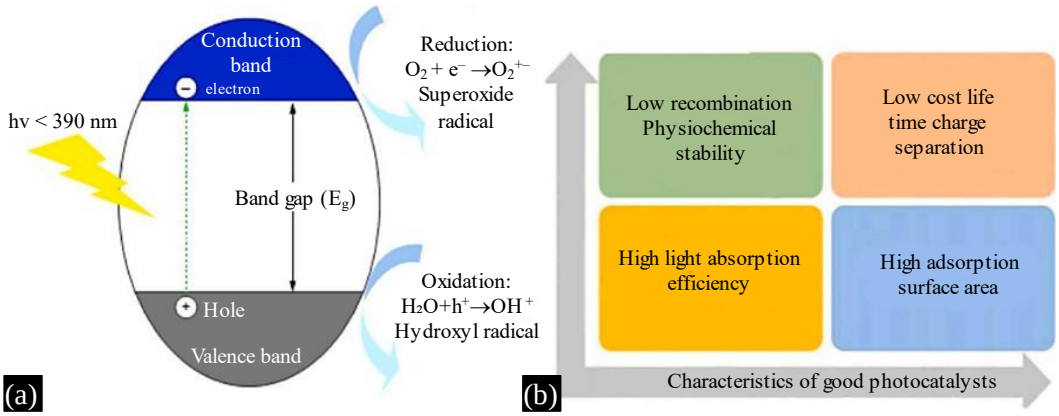

Figure 1. An example of both artificial and natural photosynthesis, (b) Characteristics of good photocatalysts.

Tungsten Trioxide (WO_3)

Tungsten trioxide (WO_3) is a transition metal oxide photocatalyst with a narrower bandgap (~2.5 eV) compared to TiO_2 and ZnO. This reduced bandgap allows WO_3 to absorb a wider range of light, including visible light, thereby enhancing its photocatalytic efficiency. WO_3-based photocatalysts have

shown potential in applications such as water splitting, pollutant degradation, and solar energy conversion Figure. 2.

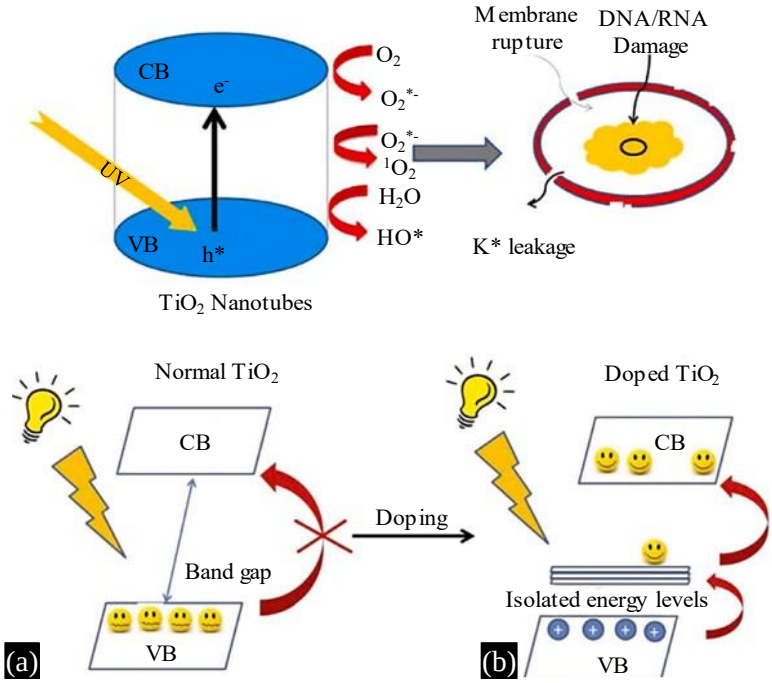

Figure 2. a) Representation of the bacterial photokilling using TiO_2, (b) The mechanism of band gap narrowing in anion-doped TiO_2

Bismuth Vanadate ($BiVO_4$)

Bismuth vanadate ($BiVO_4$) is a promising photocatalyst that is active under visible light, with a bandgap of about 2.4 eV. It exhibits strong photochemical stability and high quantum efficiency under visible light, making it ideal for solar energy applications. $BiVO_4$ has shown potential in water oxidation, pollutant degradation, and CO_2 reduction [12].

Metal-Organic Frameworks (MOFs)

Metal-organic frameworks (MOFs) are a family of porous materials composed of metal ions or clusters linked to organic ligands. MOFs are highly tunable, allowing for the design of photocatalysts with specific functions. Recent research has focused on enhancing the photocatalytic activity of MOFs for applications such as CO_2 reduction, hydrogen production, and pollutant degradation by incorporating photoactive components into their structure [13].

PHOTOCATALYTIC PROCESSES

Photocatalytic processes involve using light to initiate chemical reactions on the surface of a photocatalyst. When photons with energy equal to or greater than the photocatalyst's bandgap are absorbed, electron-hole pairs are generated. These excited electrons and holes engage in various chemical processes, such as the breakdown of organic pollutants, hydrogen production from water, and CO_2 transformation into value-added compounds. Photocatalytic processes are efficient, environmentally friendly, and occur under mild conditions, making them an attractive approach for sustainable chemistry, renewable energy production, and environmental remediation. Ongoing research aims to optimize these processes by developing new materials, improving reaction mechanisms, and exploring diverse applications [14].

Homogeneous Photocatalytic Process

A homogeneous photocatalytic system occurs when both the catalyst and the reactants are in the same phase (either gas or liquid). One notable example is the use of Fe^{2+}/H_2O_2 in ozone and photo-Fenton

systems. These processes, while affected by factors like pH, UV intensity, and hydrogen peroxide concentration, offer the advantage of using sunlight instead of costly UV lamps or electrical energy. However, a key limitation is that the low pH levels required for the Fenton process can lead to iron precipitation.

OVERVIEW OF PHOTOCATALYTIC MATERIALS

Photocatalytic materials come in various shapes and morphologies, including nanoparticles, nanowires, 2D materials, planar films, 3D porous films, and complex hierarchical nanostructures. Implementations of photocatalysis fall into two categories: particulate suspensions, where redox reactions occur in close proximity, and photoelectrochemical topologies, where reactions are intentionally separated. New materials such as plasmonic materials, quantum dots, and 2D materials are emerging in photocatalysis. Combining photovoltaics and electrolysis is seen as an optimal method for converting solar light into chemical energy. A fuzzy analytic hierarchy process (FAHP) is used to assess aspects like reaction selectivity, stability, cost, convenience, and scalability. Semiconductor photocatalysts are particularly useful due to their electronic structures, light absorption properties, and charge transport characteristics. Research continues to explore a broad range of materials and their applications in photocatalysis.

TiO_2 as a Photocatalyst

Titanium dioxide (TiO_2) is often considered the "golden" photocatalyst due to its low cost, non-toxicity, and chemical stability. It has been widely used in heterogeneous photocatalysis, particularly in addressing energy and environmental challenges, such as splitting solar water into hydrogen and breaking down pollutants in air and water at low concentrations. Although TiO_2 photocatalysis has made significant advancements in the last two decades, many questions remain unresolved, especially regarding the fundamental mechanisms of charge carrier production, separation, transfer, recombination, and bond formation. Understanding these mechanisms is crucial for developing new photocatalysts and improving photocatalytic processes [15-17].

Properties of TiO_2

TiO_2 exists in three main mineral forms: rutile, anatase, and brookite. These minerals consist of TiO_6 octahedra arranged in various distortions. The rutile phase is the most stable, while anatase and brookite are metastable. Crystalline TiO_2 materials naturally contain vacancies and interstitial ions, which can significantly affect their electrical conductivity, mass transport, and catalytic activity. The properties of these materials are influenced by Ti-O bonds, and the introduction of point defects creates new electronic states called defect states, which can enhance photocatalytic activity. TiO_2's wide bandgap makes it an electrical insulator, but defects can introduce states that improve charge transfer efficiency, as explored by Deskins et al.

Molybdenum Oxides as Photocatalysts

Molybdenum trioxide (MoO^3) is a notable transition metal oxide with promising photocatalytic properties, particularly for applications involving visible light. The visible light spectrum makes up more than 43% of sunlight that reaches Earth, making MoO_3 and similar photocatalysts important for harnessing this energy efficiently. MoO_3 is not only useful for photocatalysis but also finds applications in areas such as smart materials, gas sensors, lithium-ion batteries, and as host materials for intercalation processes. It demonstrates properties like thermochromism, electrochromism, and photochromism.

Research into MoO_3 has shown its excellent photocatalytic effectiveness, especially when combined with other materials. For instance, a study on TiO_2-MoO_3 core-shell nanoparticles found that doping MoO_3 into TiO_2 lowers the bandgap, improving photoabsorption and enhancing photocatalytic performance. The band gap of TiO_2 can be reduced when MoO_3 is incorporated, which extends the material's light absorption rang [18].

Quantum Dots as Photocatalysts

Quantum dots (QDs) are tiny semiconductor particles whose electronic properties are governed by the quantum confinement effect. These nanoscale particles have been extensively explored for their

optical and redox properties, making them highly suitable for photocatalysis. Carbon quantum dots (CQDs), in particular, have gained attention for their ability to modify the optical properties of composites by extending absorption into the visible region. This is achieved by introducing new energy levels between the conduction band of semiconductors and the π states of CQDs.

QDs, including carbon-based dots and cadmium selenide (CdSe) QDs, exhibit unique characteristics such as size-dependent fluorescence emissions, which can be harnessed in energy conversion applications. Despite their potential, quantum dots have faced challenges in visible-light photocatalytic applications, such as CO_2 reduction and water splitting, where their performance has often been limited [19].

PHOTOCATALYTIC PROCESSES

Photocatalysis is a process where light, often ultraviolet or visible, activates a catalyst to accelerate chemical reactions. This technique is especially useful in sustainable energy generation and environmental remediation. Key applications include:

Water Splitting

Water splitting, using solar energy to produce hydrogen, is a key process for addressing global energy demands. Photocatalytic water splitting uses sunlight to generate hydrogen from water, providing an environmentally friendly and renewable energy source. This process is a step toward achieving energy storage solutions for solar energy, as hydrogen can be stored and used to generate electricity when needed. Researchers have been exploring various photocatalysts, such as $Co_3(PO_4)_2$/g-C3N4 heterostructures, to enhance water splitting efficiency.

Solar Energy Production

The sun releases vast amounts of energy in the form of photons, which can be harnessed using photocatalytic components in solar cells. Solar cells, including color-sensitive, organic, and photoelectrochemical types, utilize photocatalysts to convert photon energy into electricity. Metal halide perovskites (MHPs) are a promising class of photocatalysts for solar energy production due to their adjustable band gaps and high light absorption coefficients, although challenges such as limited stability remain.

Treatment of Wastewater and Drinking Water

Photocatalysis has shown great potential for treating various contaminants in wastewater and drinking water, including toxic organic compounds and resistant inorganic materials. Traditional water treatment methods often fail to effectively remove emerging pollutants. Photocatalytic processes offer an alternative solution by breaking down harmful substances like phenols, nitrogen compounds, and pesticides, thus improving water quality and reducing health risks.

In summary, photocatalytic processes hold great promise for sustainable energy production, water treatment, and environmental remediation, with ongoing research focusing on improving the efficiency and practicality of photocatalytic materials [20-25].

Challenges and Opportunities in Photocatalysis

Efficiency and Selectivity

A key challenge in photocatalysis is improving both efficiency and selectivity. Achieving high yields of desired products while minimizing undesirable byproducts requires precise control over the catalyst's properties and the reaction conditions.

Visible Light Absorption

Traditional photocatalysts like titanium dioxide (TiO_2) primarily absorb ultraviolet (UV) light, limiting their effectiveness under direct sunlight, which contains more visible light. Expanding photocatalytic applications will depend on developing catalysts capable of efficiently utilizing visible light.

Catalyst Stability

Ensuring the long-term stability of photocatalysts in practical settings remains a significant challenge. Photo-corrosion, catalyst degradation, and surface fouling over time can diminish performance. To address this, there is a need for robust materials and advanced coating techniques to extend catalyst life.

Scale-up and Implementation

Translating laboratory-scale photocatalytic research to large-scale applications poses both practical and financial challenges. To scale up efficiently, it is essential to optimize reactor design, catalyst loading, and operating parameters while maintaining cost-effectiveness and efficiency.

Integration with Existing Technologies

For photocatalytic processes to be practically implemented, they must be integrated with existing infrastructures, such as solar energy systems or wastewater treatment plants. Overcoming technological and regulatory hurdles will be essential to ensure compatibility, safety, and efficiency in real-world applications.

Advanced Materials Design

The ongoing advancements in materials science offer new opportunities to design photocatalysts with enhanced properties like better light absorption, charge separation, and catalytic activity. Emerging materials such as perovskites, quantum dots, and metal-organic frameworks (MOFs) could help overcome current limitations and enable new applications.

Photocatalytic Hybrid Systems

Combining photocatalysis with other technologies, such as electrochemistry, membrane filtration, or catalytic converters, can enhance performance and address specific challenges. Hybrid systems offer improved efficiency, selectivity, and versatility across various applications, including air pollution control, water purification, and renewable energy production.

Environmental Remediation

Photocatalysis holds great potential for sustainable environmental remediation, offering solutions for removing heavy metals, degrading organic pollutants, and cleaning air and water. Utilizing photocatalytic processes in environmental applications can contribute to ecological sustainability, resource conservation, and pollution reduction.

Energy Conversion and Storage

Photocatalysis plays a promising role in renewable energy applications, such as solar water splitting for hydrogen production, CO_2 reduction for carbon capture, and solar-driven organic synthesis. Expanding photocatalysis in energy conversion and storage processes can help accelerate the transition to sustainable energy and contribute to achieving carbon neutrality.

Cross-Disciplinary Collaboration

To overcome the challenges and unlock the full potential of photocatalysis, collaboration across various disciplines—including chemistry, materials science, engineering, and environmental science—is crucial. Multidisciplinary approaches foster innovation, knowledge-sharing, and the development of comprehensive solutions to address real-world problems.

Future Directions in Photocatalysis

Development of Active Photocatalysts for Visible Light

Future advancements in photocatalysis will focus on developing catalysts that effectively utilize visible light. This is crucial for applications in environments with limited UV radiation, such as indoors or in overcast climates. Innovations in material synthesis, heterostructure design, and surface

modification will help improve charge separation and light absorption in the visible spectrum, expanding photocatalysis' practical applications.

Selective and High-Value Product Formation

Future research will aim to improve the selectivity of photocatalytic processes, allowing for the targeted formation of specific products while minimizing byproducts. The use of advanced reaction engineering, molecular engineering, and rational catalyst design will enhance product yields, reduce energy consumption, and minimize waste, making photocatalysis more efficient and sustainable.

Integration with Renewable Energy Sources

Photocatalysis can be integrated with renewable energy sources, such as solar and wind, to create sustainable, energy-efficient systems. Future directions could involve combining photocatalytic reactors with solar panels or wind turbines, using renewable energy to drive photocatalytic reactions. These integrated systems could reduce dependence on fossil fuels and contribute to sustainable energy solutions.

Application in Sustainable Chemistry and Manufacturing [26]

Photocatalysis is expected to play a significant role in sustainable chemistry and manufacturing, particularly in resource conservation, waste valorization, and green synthesis methods. The development of photocatalytic processes to produce materials, chemicals, and medicines with minimal environmental impact will contribute to the shift toward a circular economy and zero-waste manufacturing.

Advanced Reactor Design and Process Optimization

Scaling up photocatalytic processes for practical applications will require innovations in reactor design and process optimization. Future work will focus on developing efficient photocatalytic reactors, flow systems, and continuous manufacturing techniques. These advancements will improve productivity, scalability, and cost-effectiveness, making photocatalysis more viable for large-scale operations.

Emerging Applications in Biomedicine and Healthcare

Photocatalysis is poised to make significant strides in biomedicine and healthcare, with applications such as antimicrobial coatings, drug delivery systems, and photodynamic therapy. Future research may explore the use of photocatalytic materials for clinical applications like targeted drug release, sterilization, and disinfection, contributing to advancements in public health and healthcare technologies.

Cross-Disciplinary Collaboration and Knowledge Exchange [27]

The future of photocatalysis will rely heavily on cross-disciplinary collaboration between experts in chemistry, materials science, engineering, biology, and medicine. Collaborative, multidisciplinary approaches will foster creativity, accelerate knowledge transfer, and facilitate the translation of fundamental research into practical, real-world solutions. These collaborations will be key to addressing complex societal challenges and advancing the field.

CONCLUSIONS

Photocatalysis is a highly effective and adaptable solution to address pressing environmental and energy challenges. By utilizing light energy, photocatalytic processes can degrade pollutants, convert solar energy, and produce clean fuels. The core principles of photocatalysis involve the absorption of photons, generation of electron-hole pairs, and subsequent redox reactions, which drive the breakdown of contaminants or the synthesis of valuable compounds.

Numerous materials, such as TiO_2, ZnO, MnO_2, AgCl, and P-doped g-C_3N_4, have been thoroughly investigated and optimized due to their distinct properties and effectiveness in photocatalytic

applications. The development of low-cost and efficient photocatalytic materials, including MnO_2, AgCl, and P-doped g-C_3N_4, has shown significant potential for environmental remediation and energy conversion. Specifically, the Z-scheme photocatalyst, when paired with Fe_3O4/H_2O_2, demonstrates enhanced photocatalytic activity through the efficient separation and transfer of photogenerated charge carriers. The synergistic effects seen in systems combining Fe_3O_4/H_2O_2 with Z-scheme photocatalysts emphasize the importance of strategic material design to maximize photocatalytic performance.

Furthermore, studies on electron transfer mechanisms in MnO_2-based composites have provided valuable insights into the processes that enhance photocatalytic activity. MnO_2, AgCl, and P-doped g-C3N4 exhibit strong potential due to their intrinsic properties and ability to form effective heterojunctions. The Z-scheme approach, especially in MnO_2-based composites, has been crucial in boosting photocatalytic activity by promoting efficient electron transfer.

Future research should focus on further understanding the underlying mechanisms and optimizing these materials to enhance catalytic efficiencies. The successful application of the Photo-Fenton assisted AgCl and P-doped g-C3N4 Z-scheme further exemplifies innovative approaches that improve photocatalytic efficiency. These advancements underline the bright future of photocatalytic materials in solving energy and environmental issues.

REFERENCES

1. Yuping Chen, Chunliang Lu, Lin Xu, Ying Ma, Wenhua Hou, Jun-Jie Zhu, "Single-crystalline orthorhombic molybdenum oxide nanobelts: synthesis and photocatalytic properties," *CrystEngComm*, 12(11) (2010) 3740–3747.
2. Wei Wang, Moses O. Tadé, Zongping Shao, "Research progress of perovskite materials in photocatalysis and photovoltaics-related energy conversion and environmental treatment," *Chem. Soc. Rev.*, 44(15) (2015) 5371–5408.
3. Prabhakarn Arunachalam, Abdullah M. Al Mayouf, "Photoelectrochemical water splitting," in *Noble Metal-Metal Oxide Hybrid Nanoparticles*, Woodhead Publishing, 2019, pp. 585–606.
4. Takumi Kinoshita, Rentaro Kakeno, Hiroshi Segawa, "Solid-state dye-sensitized solar cells using (CH3NH3)2SnI6 perovskite with wideband sensitizer," *Chem. Lett.*, 48(7) (2019) 637–639.
5. A. Malathi, Prabhakarn Arunachalam, Andrews Nirmala Grace, J. Madhavan, Abdullah M. Al-Mayouf, "A robust visible-light driven BiFeWO6/BiOI nanohybrid with efficient photocatalytic and photoelectrochemical performance," *Appl. Surf. Sci.*, 412 (2017) 85–95.
6. Saradh Prasad, G. Durai, D. Devaraj, Mohamad Saleh AlSalhi, J. Theerthagiri, Prabhakarn Arunachalam, M. Gurulakshmi, M. Raghavender, P. Kuppusami, "3D nanorhombus nickel nitride as stable and cost-effective counter electrodes for dye-sensitized solar cells and supercapacitor applications," *RSC Adv.*, 8(16) (2018) 8828–8835.
7. J. Theerthagiri, R.A. Senthil, P. Arunachalam, J. Madhavan, M.H. Buraidah, A. Santhanam, A.K. Arof, "Synthesis of various carbon incorporated flower-like MoS_2 microspheres as counter electrode for dye-sensitized solar cells," *J. Solid State Electrochem.*, 21(3) (2017) 581–590, https://doi.org/10.1007/s10008-016-3485-5.
8. J. Theerthagiri, R.A. Senthil, P. Arunachalam, K.A. Bhabu, A. Selvi, J. Madhavan, K. Murugan, A.K. Arof, "Electrochemical deposition of carbon materials incorporated nickel sulfide composite as counter electrode for dye-sensitized solar cells," *Ionian*, 23(4) (2017) 1017–1025, https://doi.org/10.1016/j.ionian.2017.03.007.
9. S. Sadhishkumar, T. Balusamy, "Performance improvement in solar water heating systems—a review," *Renew. Sustain. Energy Rev.*, 37 (2014) 191–198, https://doi.org/10.1016/j.rser.2014.05.057.
10. G. Chen, J. Seo, C. Yang, P. Prasad, "Nanochemistry and nanomaterials for photovoltaics," *Chem. Soc. Rev.*, 42(16) (2013) 8304–8338, https://doi.org/10.1039/C2CS35240B.
11. M. Kitano, M. Hara, "Heterogeneous photocatalytic cleavage of water," *J. Mater. Chem.*, 20(3) (2010) 627–641, https://doi.org/10.1039/B914678K.

12. M.N. Chong, B. Jin, C.W.K. Chow, C. Saint, "Recent Developments in Photocatalytic Water Treatment Technology: A Review," *Water Res.*, 44(15) (2010) 2997–3027, https://doi.org/10.1016/j.watres.2010.02.039.
13. V.S. Reddy, S.C. Kaushik, K.R. Ranjan, S.K. Tyagi, "State-of-the-Art of Solar Thermal Power Plants—A Review," *Renew. Sustain. Energy Rev.*, 27 (2013) 258–273, https://doi.org/10.1016/j.rser.2013.06.016.
14. Y. Sakuragi, D.A. Bryant, "Genetic Manipulation of Quinone Biosynthesis in Cyanobacteria," in J.H. Golbeck (Ed.), *In Photosystem I: The Light-Driven Plastocyanin Oxidoreductase*, Springer, Dordrecht, 2006, pp. 1–12.
15. S. Zhu, D. Wang, "Photocatalysis: basic principles, diverse forms of implementations and emerging scientific opportunities," *Adv. Energy Mater.*, 7(12) (2017) 1700841.
16. D.G. Nocera, "The artificial leaf," *Acc. Chem. Res.*, 45(6) (2012) 767–776.
17. P.J. Boddy, "Oxygen evolution on semiconducting TiO_2," *J. Electrochem. Soc.*, 115(2) (1968) 199–203, https://doi.org/10.1149/1.2411525.
18. A. Fujishima, K. Honda, "Electrochemical photolysis of water at a semiconductor electrode," *Nature*, 238(5358) (1972) 37–38.
19. International Energy Agency (IEA), *Key World Energy Statistics*, IEA/OECD, Paris, 2017, https://www.iea.org/reports/key-world-energy-statistics-2017.
20. M.A. Hassaan, A. El Nemr, S. Ragab, "Green synthesis and application of metal and metal oxide nanoparticles," in *Handbook of Nanomaterials and Nanocomposites for Energy and Environmental Applications*, Elsevier, Amsterdam, 2021, pp. 1–27, https://doi.org/10.1016/B978-0-12-823418-2.00001-6.
21. A.A. Annu, S. Ahmed, "Green synthesis of metal, metal oxide nanoparticles, and their various applications," in *Handbook of Ecomaterials*, Springer, Cham, 2018, pp. 1–45, https://doi.org/10.1007/978-3-319-68255-6_115.
22. G. Ma, T. Hisatomi, K. Domen, "Semiconductors for photocatalytic and photoelectrochemical solar water splitting," in *From Molecules to Materials*, Springer, Cham, 2015, pp. 1–56, https://doi.org/10.1007/978-3-319-13800-8_1.
23. A. Saravanan, P.S. Kumar, S. Jeevanantham, M. Anubha, S. Jayashree, "Degradation of toxic agrochemicals and pharmaceutical pollutants: effective and alternative approaches toward photocatalysis," *Environ. Pollut.*, (2022) 118844, https://doi.org/10.1016/j.envpol.2022.118844.
24. M.C. Uribe-Lopez, M.C. Hidalgo-Lopez, R. Lopez-Gonzalez, D.M. Frías-Marquez, G. Núñez-Nogueira, D. Hernández-Castillo, M.A. Alvarez-Lemus, "Photocatalytic activity of ZnO nanoparticles and the role of the synthesis method on their physical and chemical properties," *J. Photochem. Photobiol. A: Chem.*, 404 (2021) 112866, https://doi.org/10.1016/j.jphotochem.2020.112866.
25. P. Spinelli, V.E. Ferry, J. Van de Groep, M. Van Lare, M.A. Verschuuren, R.E.I. Schropp, H.A. Atwater, A. Polman, "Plasmonic light trapping in thin-film Si solar cells," *J. Opt.*, 14(2) (2012) 024002, https://doi.org/10.1088/2040-8978/14/2/024002.
26. K. Sahu, A. Bisht, S.A. Khan, I. Sulania, R. Singhal, A. Pandey, S. Mohapatra, "Thickness dependent optical, structural, morphological, photocatalytic and catalytic properties of radio frequency magnetron sputtered nanostructured Cu_2O–CuO thin films," *Ceram. Int.*, 46(10) (2020) 14902–14912, https://doi.org/10.1016/j.ceramint.2020.03.017.
27. M.A. Hassaan, A. El Nemr, M.R. Elkatory, S. Ragab, M.A. El-Nemr, A. Pantaleo, "Synthesis, characterization, and synergistic effects of modified biochar in combination with α-Fe_2O_3 NPs on biogas production from red algae *Pterocladia capillacea*," *Sustainability*, 13(16) (2021) 9275, https://doi.org/10.3390/su13169275.

