

# From Photoreceptors to Photoelectrodes: Integrating Biological Light-Harvesting Mechanisms with Nanostructured Photoelectrochemical Systems

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## Abstract

*The efficient conversion of solar energy into electrical and chemical energy is a major scientific challenge of the twenty-first century. Natural photoreceptors provide valuable models for addressing this challenge because they have evolved highly efficient mechanisms for capturing and converting light energy. Biological systems such as rhodopsins, bacteriorhodopsins, proteorhodopsins, cryptochromes, phototropins, and phytochromes employ chromophore-driven photoinduced electron and proton transfer processes to initiate a wide range of physiological responses, including vision, phototaxis, circadian regulation, and photosensory signaling. These processes demonstrate exceptional efficiency in light absorption, charge separation, and energy transduction. In parallel, photoelectrochemical (PEC) technologies, including dye-sensitized solar cells (DSSCs), photocatalytic hydrogen generation systems, and semiconductor-based water-splitting devices—have emerged as promising routes for sustainable energy production. The performance of these systems depends on efficient photon harvesting, charge carrier generation, transport, and interfacial electron transfer. Advances in nanotechnology have significantly enhanced these capabilities through the development of nanostructured photoelectrodes with increased surface area, improved light absorption, and optimized charge transport pathways. This review explores the fundamental molecular mechanisms of biological photoreceptors and their relevance to the design of advanced PEC systems. Emphasis is placed on photoinduced charge separation, semiconductor interface dynamics, depletion layer formation, and nanoscale engineering strategies that improve energy conversion efficiency. The integration of biological light-harvesting principles with engineered semiconductor architectures is examined as a pathway toward next-generation solar energy technologies. Furthermore, recent progress in hybrid bio-photoelectrochemical platforms is discussed, highlighting their potential to combine the selectivity and functionality of biological systems with the robustness of inorganic materials. These developments offer promising prospects for sustainable solar fuel production and efficient renewable energy conversion.*

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## INTRODUCTION

Solar radiation is the most abundant and sustainable renewable energy resource available on Earth, providing a virtually inexhaustible source of energy for future generations. Conversion of solar energy into electrical and chemical forms remains one of the most significant scientific and technological challenges of the twenty-first century. Over billions of years of evolution, biological organisms have developed

highly sophisticated photochemical systems capable of capturing, transferring, and utilizing solar energy with remarkable efficiency. These naturally occurring systems provide valuable inspiration for the design of advanced solar energy conversion technologies. Understanding the molecular mechanisms underlying biological light harvesting can therefore contribute significantly to the development of next-generation photoelectrochemical devices [1].

Recent advances in nanotechnology, semiconductor engineering, and biomimetic materials have significantly improved the performance of photoelectrochemical systems by enhancing light absorption, charge separation, and interfacial charge transport. Consequently, integrating biological light-harvesting mechanisms with nanostructured semiconductor architectures has emerged as a promising strategy for developing efficient and sustainable solar energy conversion technologies.

Photo electrochemistry is an interdisciplinary field that combines photonic excitation with electrochemical processes occurring at semiconductor-electrolyte interfaces. [2]. Since the pioneering demonstrations of semiconductor-driven water splitting, substantial progress has been achieved in the development of dye-sensitized solar cells, photocatalytic hydrogen production systems, and photoelectrochemical fuel generation technologies. These systems offer promising pathways for sustainable energy production by directly converting solar energy into electricity or chemical fuels. Despite these advances, several challenges continue to limit their widespread application, including inefficient charge separation, rapid electron-hole recombination, restricted utilization of the solar spectrum, and long-term material instability under operating conditions [3].

Biological photoreceptors possess exceptional capabilities for light absorption, charge transfer, and signal transduction that far exceed many artificial systems in terms of selectivity and efficiency. Proteins such as bacteriorhodopsin and proteorhodopsin utilize retinal chromophores to convert photon energy into transmembrane proton gradients through highly coordinated photochemical cycles. Similarly, plant photoreceptors employ precisely regulated photoinduced molecular transformations to control growth, development, and environmental responses. These biological systems demonstrate efficient strategies for photon capture, charge separation, and energy transduction that can serve as models for the design of artificial photoelectrochemical architectures. Consequently, the integration of biological principles with nanostructured semiconductor materials has emerged as a promising strategy for overcoming current limitations in solar energy conversion technologies and improving the performance of sustainable energy systems [4].

The objective of this review is to examine the molecular mechanisms underlying biological photoreceptors and evaluate their relevance to modern photoelectrochemical systems. The review discusses the principles of biological light harvesting, semiconductor photoelectrode operation, dye-sensitized solar cells, photoelectrochemical water splitting, semiconductor interface dynamics, and emerging hybrid bio-photoelectrochemical platforms. Furthermore, it highlights how bio-inspired design strategies can contribute to the development of efficient and sustainable solar energy conversion technologies [5].

## BIOLOGICAL LIGHT-HARVESTING SYSTEMS

### Rhodopsin Family Proteins

Rhodopsins constitute a diverse family of membrane-associated photoreceptor proteins that contain retinal chromophores covalently linked to the protein through Schiff-base bonds. These proteins are widely distributed among archaea, bacteria, algae, and other microorganisms, where they perform various light-dependent physiological functions. The fundamental photochemical event in rhodopsins involves the absorption of a photon by the retinal chromophore, resulting in rapid cis-trans isomerization. [6]. This structural transformation initiates a sequence of conformational and electronic changes within the protein that ultimately lead to biological responses such as ion transport, signal transduction, or energy conversion. The rhodopsin family includes bacteriorhodopsins, halorhodopsins,

proteorhodopsins, xanthorhodopsins, heliorhodopsins, and schizorhodopsins, each exhibiting distinct structural and functional characteristics. Their ability to convert light energy into electrochemical gradients and biological signals has attracted considerable attention for applications in bioelectronics and bio-inspired energy conversion systems [7].

### **Bacteriorhodopsin as a Natural Proton Pump**

Bacteriorhodopsin is one of the most extensively investigated biological photoreceptors and serves as a model system for understanding biological solar energy conversion. It is found in the purple membrane of halophilic archaea, where it functions as a light-driven proton pump. Upon absorption of visible light, the retinal chromophore undergoes photoisomerization, triggering a series of conformational changes that facilitate directional proton transport across the cell membrane. This process generates a proton gradient that can subsequently be utilized for ATP synthesis and other cellular energy requirements. The photocycle of bacteriorhodopsin proceeds through a sequence of spectroscopically distinguishable intermediates designated as K, L, M, N, and O before returning to the initial ground state. Each intermediate represents a unique structural and electronic configuration that contributes to efficient proton translocation. The remarkable stability, quantum efficiency, and directional charge transport properties of bacteriorhodopsin make it an attractive model for the development of bio-inspired photoelectrochemical devices and artificial energy conversion systems [8].

### **Plant Photoreceptors**

Plants possess multiple classes of photoreceptors that enable them to sense and respond to environmental light conditions with extraordinary precision. These photoreceptors include phototropins, cryptochromes, phytochromes, and UVR8 receptors, each specialized for detecting specific regions of the electromagnetic spectrum. Through complex signaling networks, these proteins regulate a wide range of physiological processes, including phototropism, chloroplast movement, stomatal opening, gene expression, circadian rhythms, and photomorphogenesis. Light absorption induces conformational and electronic changes within the photoreceptor molecules, initiating signaling cascades that ultimately influence plant growth and development. The high sensitivity, selectivity, and adaptability of plant photoreceptor systems provide valuable inspiration for designing artificial light-responsive materials and advanced photoelectrochemical systems capable of efficient solar energy utilization [9].

## **FUNDAMENTALS OF PHOTOELECTROCHEMICAL SYSTEMS**

### **Semiconductor Photoelectrodes**

Photoelectrochemical devices are fundamentally based on semiconductor materials capable of absorbing solar radiation and converting it into electrical or chemical energy. Semiconductors possess a valence band and a conduction band separated by a characteristic energy gap known as the band gap. When incident photons possess sufficient energy to overcome this gap, electrons are excited from the valence band into the conduction band, generating electron-hole pairs. These charge carriers are responsible for driving oxidation and reduction reactions at the semiconductor-electrolyte interface [10]. The overall performance of a photoelectrode depends on its ability to efficiently absorb light, generate charge carriers, separate electrons and holes, and transport them to reactive sites before recombination occurs. Semiconductor materials such as titanium dioxide, cadmium sulfide, hematite, tungsten oxide, and zinc oxide have been extensively investigated for photoelectrochemical applications because of their favorable optical and electronic properties. The optimization of semiconductor composition, morphology, and electronic structure remains a critical factor in improving solar energy conversion efficiency [11].

### **Depletion Layer Formation**

When a semiconductor is brought into contact with an electrolyte, charge redistribution occurs at the interface until thermodynamic equilibrium is established. This process leads to the formation of a depletion region, also known as a space-charge layer, characterized by a reduction in mobile charge

carriers near the semiconductor surface. The resulting charge separation generates an internal electric field and causes bending of the semiconductor energy bands. The direction and magnitude of band bending depend on the semiconductor type, doping concentration, electrolyte composition, and applied potential [12]. The electric field within the depletion layer plays a crucial role in promoting charge separation by driving photogenerated electrons and holes in opposite directions. This process minimizes recombination losses and enhances the probability that charge carriers will participate in useful electrochemical reactions. Consequently, the properties of the depletion layer strongly influence photocurrent generation, photovoltage development, and overall photoelectrochemical efficiency. Effective engineering of semiconductor-electrolyte interfaces is therefore essential for achieving high-performance solar energy conversion systems [13].

### Minority Carrier Dynamics

Minority carrier dynamics represent one of the most critical factors governing the efficiency of photoelectrochemical devices. Upon illumination, photogenerated electron-hole pairs must be rapidly separated and transported before recombination can occur. In n-type semiconductors, electrons are present in higher concentrations and serve as majority carriers, while holes are minority carriers. In contrast, p-type semiconductors contain holes as majority carriers and electrons as minority carriers. Because minority carriers exist in lower concentrations and generally possess shorter diffusion lengths and lifetimes, their successful transport to the semiconductor-electrolyte interface often determines overall device performance. The movement of minority carriers is influenced by carrier mobility, diffusion coefficients, carrier lifetime, defect density, and the strength of the electric field within the depletion region [14]. Recombination processes occurring in the bulk semiconductor, at grain boundaries, or at surface defect sites can significantly reduce carrier collection efficiency and lower photocurrent generation. To address these limitations, nanostructured photoelectrodes such as nanowires, nanotubes, and mesoporous films have been developed to reduce carrier transport distances and increase active surface area. These architectures promote more efficient charge separation and extraction, leading to improved photoelectrochemical performance. Consequently, understanding and controlling minority carrier behavior remains essential for the development of advanced solar energy conversion technologies with enhanced efficiency and stability [15].

### DYE-SENSITIZED SOLAR CELLS

Dye-sensitized solar cells (DSSCs) represent one of the most successful examples of biomimetic solar energy conversion technologies. Inspired by natural photosynthetic systems, DSSCs utilize molecular sensitizers to harvest sunlight and initiate charge-transfer processes that ultimately generate electrical energy. Since their introduction, these devices have attracted considerable attention because of their relatively low production cost, simple fabrication methods, and ability to operate efficiently under diffuse illumination conditions. Unlike conventional silicon-based photovoltaic cells, DSSCs separate the functions of light absorption and charge transport, thereby providing greater flexibility in material design and device architecture. The fundamental concept underlying DSSCs closely resembles biological light-harvesting mechanisms, where photoexcited molecules transfer electrons through highly organized pathways to achieve efficient energy conversion as summarized in Table 1 [16].

**Table 1.** Comparison of biological and artificial light-harvesting systems.

| Feature             | Biological systems   | Artificial PEC systems |
|---------------------|----------------------|------------------------|
| Light Absorber      | Retinal, Flavin      | Semiconductor/Dye      |
| Charge Separation   | Protein-mediated     | Band-gap excitation    |
| Energy Storage      | Proton gradients     | Electrical/Chemical    |
| Self-Repair         | Present              | Limited                |
| Efficiency Control  | Molecular regulation | Material engineering   |
| Spectral Tunability | Moderate             | High                   |

### **Operating Principle**

The operation of a dye-sensitized solar cell begins with the absorption of sunlight by a photosensitive dye molecule adsorbed onto the surface of a semiconductor, typically titanium dioxide (TiO<sub>2</sub>). Upon photoexcitation, electrons within the dye are promoted to higher energy states and are subsequently injected into the conduction band of the semiconductor. These electrons travel through the interconnected semiconductor network toward a conductive substrate and then through an external electrical circuit, producing useful electrical work. Simultaneously, the oxidized dye molecules are regenerated by accepting electrons from a redox electrolyte, which in turn receives electrons from the counter electrode to complete the circuit. Efficient electron injection, rapid dye regeneration, and minimized charge recombination are essential for achieving high photovoltaic performance. The sequence of events involved in DSSC operation bears strong similarities to the electron-transfer processes observed in natural photosynthetic reaction centers, making these devices important examples of bio-inspired solar energy technologies.

### **Nanostructured Photoelectrodes**

The introduction of nanostructured semiconductor photoelectrodes has played a crucial role in the advancement of dye-sensitized solar cells. Nano structuring significantly increases the available surface area for dye adsorption, thereby enhancing light-harvesting efficiency and photocurrent generation. Materials such as mesoporous titanium dioxide nanoparticles provide extensive internal surface area while maintaining effective pathways for electron transport. In addition to facilitating higher dye loading, nanostructured architectures improve light scattering within the photoelectrode, increasing the probability of photon absorption. The reduced dimensions of nanomaterials also shorten charge transport distances, thereby minimizing recombination losses and improving carrier collection efficiency. As a result, nanostructured TiO<sub>2</sub> remains the most widely employed photoelectrode material in DSSCs and continues to serve as a model platform for developing high-performance solar energy conversion devices.

### **Bio-Inspired Sensitizers**

The development of advanced sensitizers is a critical aspect of improving dye-sensitized solar cell performance. Inspired by natural light-harvesting systems, researchers have explored a variety of biomimetic molecules capable of efficient solar photon absorption and charge transfer. Retinal derivatives, porphyrins, chlorophyll analogues, and protein-based sensitizers have attracted significant interest because of their structural resemblance to naturally occurring chromophores. These molecules often possess broad absorption spectra, efficient excited-state charge separation, and tunable electronic properties. By mimicking the molecular architecture and energy-transfer pathways found in biological photoreceptors and photosynthetic complexes, bio-inspired sensitizers offer promising opportunities for enhancing solar energy conversion efficiency while maintaining environmental sustainability.

## **PHOTOELECTROCHEMICAL WATER SPLITTING**

Photoelectrochemical water splitting is one of the most promising approaches for converting solar energy directly into chemical fuels. In this process, semiconductor photoelectrodes absorb sunlight and utilize the generated charge carriers to drive the decomposition of water into hydrogen and oxygen. Hydrogen produced through this route is regarded as a clean and sustainable energy carrier because its utilization generates only water as a by-product. The overall water-splitting reaction requires the transfer of multiple electrons and protons and involves both hydrogen evolution and oxygen evolution reactions. Efficient implementation of this process depends on effective light harvesting, charge separation, charge transport, and catalytic activity at the electrode surface. Consequently, photoelectrochemical water splitting has become a major focus of research aimed at developing renewable and carbon-neutral energy technologies.

### **Hydrogen Production**

Hydrogen generation through photoelectrochemical water splitting provides a direct method for storing solar energy in the form of chemical bonds. During illumination, photogenerated electrons

participate in proton reduction reactions to produce hydrogen gas, while photogenerated holes oxidize water molecules to generate oxygen. The thermodynamic and kinetic requirements of these reactions necessitate semiconductors with suitable band-edge positions and efficient catalytic surfaces. Successful hydrogen production therefore relies on maximizing photon absorption, minimizing charge recombination, and accelerating surface reaction kinetics. As global demand for clean energy continues to increase, solar-driven hydrogen production is increasingly viewed as a key component of future sustainable energy infrastructures.

### Challenges

Despite significant progress, several challenges continue to limit the practical implementation of photoelectrochemical water-splitting technologies. One of the most important limitations is the slow kinetics of the oxygen evolution reaction, which requires multiple electron-transfer steps and often represents the rate-determining process. Photo corrosion of semiconductor materials under prolonged illumination can also lead to performance degradation and reduced operational lifetimes. Furthermore, recombination of photogenerated charge carriers decreases the number of electrons and holes available for chemical reactions, thereby lowering solar-to-hydrogen conversion efficiency. Another major challenge is the limited ability of many semiconductor materials to absorb visible light, resulting in inefficient utilization of the solar spectrum. Addressing these issues remains essential for the development of commercially viable photoelectrochemical systems.

### Nanomaterial-Based Solutions

Nanomaterials have emerged as powerful tools for improving the performance of photoelectrochemical water-splitting devices. Their unique structural and electronic properties enable enhanced light absorption, efficient charge separation, and improved catalytic activity. By reducing carrier diffusion distances, nanostructured materials increase the probability that photogenerated electrons and holes will reach reactive sites before recombination occurs. Their large surface-to-volume ratios provide abundant active sites for electrochemical reactions and facilitate more effective interactions with catalytic species. Recent research has focused on advanced nanomaterials such as carbon quantum dots and graphene quantum dots because of their tunable optical properties, excellent electrical conductivity, and ability to enhance visible-light absorption. These materials offer promising opportunities for improving solar hydrogen production efficiency and long-term device stability.

## SEMICONDUCTOR INTERFACE DYNAMICS

The semiconductor-electrolyte interface represents the central region where photogenerated charge carriers interact with the surrounding environment and initiate electrochemical reactions. Consequently, the physical and chemical processes occurring at this interface exert a profound influence on the overall efficiency of photoelectrochemical devices. Factors such as charge injection, carrier trapping, interfacial recombination, and surface passivation determine the effectiveness with which absorbed solar energy is converted into useful electrical or chemical outputs. Understanding and controlling interface dynamics are therefore essential for optimizing photoelectrode performance and enhancing long-term operational stability.

### Charge Injection

Charge injection is the process by which photoexcited electrons or holes are transferred from a light-absorbing material into a semiconductor or catalytic pathway. Following photon absorption, rapid charge transfer is necessary to prevent recombination and maximize energy conversion efficiency. The rate of charge injection depends on electronic coupling, energy-level alignment, and interfacial structure. Efficient charge injection facilitates directional carrier transport and enhances photocurrent generation, making it a critical parameter in both photovoltaic and photoelectrochemical systems.

### Surface Trapping

Surface defects, impurities, and structural imperfections often create localized electronic states capable of trapping photogenerated charge carriers. These trapped charges may remain immobilized for

extended periods or undergo non-radiative recombination processes that dissipate absorbed solar energy as heat. Surface trapping therefore reduces photocurrent generation, increases recombination losses, and lowers overall photoelectrochemical efficiency. The density and distribution of surface trap states are strongly influenced by material synthesis methods, crystal quality, and surface chemistry. Effective management of these defects is essential for achieving high-performance photoelectrodes.

### **Surface Passivation**

Surface passivation involves modifying semiconductor surfaces to reduce defect-related recombination and improve interfacial charge-transfer processes. Various passivation strategies have been developed, including the deposition of ultrathin oxide coatings, molecular monolayers, and catalytic overlayers. These treatments suppress undesirable surface states while maintaining efficient carrier transport to reaction sites. In addition to reducing recombination losses, surface passivation can improve chemical stability and protect semiconductors from photo corrosion under operating conditions. As a result, passivation has become a key approach for enhancing the performance and durability of advanced photoelectrochemical devices.

## **EMERGING HYBRID BIO-PHOTOELECTROCHEMICAL SYSTEMS**

Recent advances in biotechnology, materials science, and nanotechnology have enabled the development of hybrid bio-photoelectrochemical systems that combine the unique properties of biological photoreceptors with the robustness of engineered semiconductor materials. These systems seek to exploit the exceptional light-harvesting efficiency, molecular specificity, and self-assembly characteristics of biological components while benefiting from the stability and scalability of inorganic materials. The convergence of biology and photo electrochemistry has created new opportunities for sustainable solar energy conversion, bioelectronics, and artificial photosynthesis.

### **Bacteriorhodopsin-Based Devices**

Bacteriorhodopsin has emerged as one of the most promising biological components for hybrid photoelectrochemical applications because of its exceptional photostability, strong visible-light absorption, and highly efficient proton-pumping capability. Thin films containing oriented bacteriorhodopsin molecules can generate photocurrents and photovoltages upon illumination, making them attractive for bioelectronic and energy-conversion devices. The directional proton transport characteristics of bacteriorhodopsin closely resemble fundamental processes occurring in natural energy-transducing membranes and provide a unique mechanism for converting solar energy into electrochemical potential.

### **Proteorhodopsin-Modified Electrodes**

Proteorhodopsin-functionalized electrodes represent another important class of hybrid bio-photoelectrochemical systems. Proteorhodopsin is a retinal-based proton pump widely distributed among marine microorganisms and exhibits efficient light-induced charge-transfer behavior. When integrated with conductive substrates and semiconductor materials, proteorhodopsin can enhance photocurrent generation through biomolecular charge-separation mechanisms. Such systems demonstrate how biological photoreceptors can be directly incorporated into artificial energy-conversion architectures to improve solar energy utilization and device performance.

### **Artificial Photosynthesis**

Artificial photosynthesis seeks to emulate the fundamental principles of natural photosynthetic systems in order to convert sunlight, water, and carbon-containing molecules into useful fuels and chemical products. These systems typically integrate molecular catalysts, semiconductor light absorbers, and biological or biomimetic components to achieve efficient solar energy conversion. By reproducing the highly coordinated charge-separation and catalytic processes observed in nature, artificial photosynthetic platforms aim to produce hydrogen, carbon-based fuels, and value-added chemicals directly from renewable resources. The ultimate goal is the creation of sustainable solar fuel technologies capable of addressing global energy and environmental challenges while reducing dependence on fossil fuels.

**Table 2.** Emerging materials for bio-inspired PEC applications.

| Material                   | Application             | Key advantage    |
|----------------------------|-------------------------|------------------|
| TiO <sub>2</sub> Nanotubes | DSSC                    | Stability        |
| CdS Quantum Dots           | Visible-Light PEC       | Narrow Band Gap  |
| Carbon Quantum Dots        | Photocatalysis          | Biocompatibility |
| Graphene Quantum Dots      | Bioelectronics          | Conductivity     |
| Bacteriorhodopsin Films    | Hybrid Devices          | Proton Transport |
| Proteorhodopsin Systems    | Photocurrent Generation | High Sensitivity |

## CONCLUSION

Biological photoreceptors represent highly optimized natural light-harvesting systems capable of efficient photon utilization and energy transduction. Understanding the molecular mechanisms governing rhodopsins, cryptochromes, and other photoreceptors provides valuable inspiration for advanced photoelectrochemical technologies. Nanostructured semiconductors, dye-sensitized solar cells, and photocatalytic water-splitting systems have demonstrated considerable potential for sustainable energy conversion. The emergence of hybrid bio-photoelectrochemical platforms integrating biological components with engineered materials may overcome many limitations of current technologies. Continued advances in nanotechnology, materials science, and molecular photobiology are expected to drive the development of next-generation solar energy systems with improved efficiency, stability, and environmental compatibility.

Recent developments in bio-inspired photoelectrochemical systems demonstrate that integrating biological photoreceptors with nanostructured semiconductor materials can substantially improve light harvesting, charge separation, and photocatalytic efficiency. Advances in nanomaterials, interface engineering, and hybrid bio-photoelectrochemical devices have created new opportunities for renewable hydrogen production, artificial photosynthesis, and sustainable solar energy conversion. Continued interdisciplinary research involving materials science, molecular biology, and electrochemistry is expected to accelerate the development of highly efficient next generation photoelectrochemical systems.

## REFERENCES

1. Fujishima A, Honda K. Electrochemical photolysis of water at a semiconductor electrode. *Nature*. 1972;238(5358):37–38.
2. O'Regan B, Grätzel M. A low-cost, high-efficiency solar cell based on dye-sensitized colloidal TiO<sub>2</sub> films. *Nature*. 1991;353(6346):737–740.
3. Oesterhelt D, Stoeckenius W. Functions of a new photoreceptor membrane. *Proc Natl Acad Sci U S A*. 1973;70(10):2853–2857.
4. Hegemann P, Nagel G. From channelrhodopsins to optogenetics. *EMBO Mol Med*. 2013;5(2):173–176.
5. Blankenship RE. *Molecular Mechanisms of Photosynthesis*. 2nd ed. Oxford: Wiley-Blackwell; 2014.
6. Wang Q, Domen K. Particulate photocatalysts for light-driven water splitting: mechanisms, challenges, and design strategies. *Chem Rev*. 2020;120(2):919–985.
7. Meyer TJ. Chemical approaches to artificial photosynthesis. *Acc Chem Res*. 1989;22(5):163–170.
8. Hammes-Schiffer S, Stuchebrukhov AA. Theory of coupled electron and proton transfer reactions. *Chem Rev*. 2010;110(12):6939–6960.
9. Sancar A. Structure and function of DNA photolyase and cryptochrome blue-light photoreceptors. *Chem Rev*. 2003;103(6):2203–2237.
10. Gust D, Moore TA, Moore AL. Solar fuels via artificial photosynthesis. *Acc Chem Res*. 2009;42(12):1890–1898.
11. Wang Q, Domen K. Particulate photocatalysts for light-driven water splitting: mechanisms, challenges, and design strategies. *Chem Rev*. 2020;120:919–985.

12. Liu G, Wang L, Yang HG. Recent advances in semiconductor photocatalysts for solar energy conversion. *Energy Environ Sci.* 2021;14:112–145.
13. Li X, Yu J, Jaroniec M, Chen X. Cocatalysts for selective photoreduction of CO<sub>2</sub> into solar fuels. *Chem Rev.* 2019;119:3962–4179.
14. Zhang J, Wang H, Xu Y. Recent advances in photoelectrochemical water splitting using nanostructured semiconductors. *Adv Funct Mater.* 2022;32:2201156.
15. Chen S, Takata T, Domen K. Particulate photocatalysts for overall water splitting. *Nat Rev Mater.* 2023;8:37–56.
16. Wang Z, Li C, Domen K. Artificial photosynthesis for sustainable fuel production. *Nat Catal.* 2024;7:95–108.