



# Promises and Challenges in Photocatalysis

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**Keywords:** photocatalysis, green chemistry, semiconductor, solar energy, economic efficient photocatalysts

## INTRODUCTION

### Photocatalysis is a Promising Technology for Energy and Environmental Protection

The current rapid industrial development causes both a heavy reliance on non-renewable energy and a dramatic increase in atmospheric CO<sub>2</sub> concentration, which in turn lead to severe energy and environmental crises (Zhang et al., 2015; Li et al., 2019; Li et al., 2020; Li et al., 2021). Therefore, it is urgent to consider how to develop new energy to meet the sustainable development of society.

Nowadays, direct solar-to-fuel conversion through green photocatalysis technology has received increasing research interests due to its potential for solar energy utilization and storage to relieve the growing energy demands and greenhouse effect (Habisreutinger et al., 2013). With the expansion and deepening of the research, photocatalysis technology has been extended to many fields, such as energy, health, environment, pollution control and value-added chemicals synthesis (Lu et al., 2020). As a result, the relevance of photocatalysis and human life has been increasing steadily.

The grand challenge of photocatalysis today is to further expand the practical application of photocatalytic technology in the industrial field, which requires future research to pay attention to the following aspects:

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### Edited and reviewed by:

Frank Hollmann,  
Delft University of Technology,  
Netherlands

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### Specialty section:

This article was submitted to  
Photocatalysis,  
a section of the journal  
Frontiers in Catalysis

**Received:** 11 May 2021

**Accepted:** 17 May 2021

**Published:** 28 May 2021

### Citation:

Xu Y-J (2021) Promises and  
Challenges in Photocatalysis.  
Front. Catal. 1:708319.  
doi: 10.3389/fctls.2021.708319

### System-Level Engineering of Photocatalyst

The overall catalytic performance of photocatalyst usually depends on three factors: light harvesting, photogenerated charge carriers separation and transfer, and surface reaction (Han et al., 2019). On the one hand, light absorption is closely related to the energy band structure of photocatalysts. However, most of the existing stable photocatalysts have a wide bandgap, indicating a narrow light absorption range, which restricts the photocatalytic efficiency. On the other hand, only the photogenerated electrons and holes that migrate to the photocatalyst surface can participate in the photocatalytic reaction, whereas most of them are readily recombined in the bulk phase of the photocatalysts. In addition, some photogenerated electrons or holes may corrode the photocatalyst rather than participate in the target reaction.

In the past four decades, a variety of strategies have been proposed to adjust the physical and chemical properties of semiconductor photocatalysts in order to effectively improve the scope of light absorption, reduce the recombination of photogenerated charge carriers, and accelerate surface reactions (Wu et al., 2021). In general, engineering special interfaces in composite photocatalytic systems with diverse individual components to form efficient interactions such as p-n junctions, heterojunctions, and Z-scheme systems is considered to be an effective strategy for enhancing the overall photocatalytic efficiency (Chen et al., 2020; Zuo et al., 2021). Nevertheless, this system-level photocatalyst engineering is clearly a time-consuming process. Therefore, it is important to deepen understanding of structure-activity relationships and various photoredox mechanisms, and the advances *in situ* characterization technique, theoretical calculation and artificial intelligence may allow this process more efficiently.

## Amplification of Photocatalytic Systems

Today, photocatalytic technology has been mainly applied in the treatment of the industrial wastewater, including papermaking, printing, dyeing and electroplating industry, etc. As for other photocatalysis research fields, such as solar water splitting (Mi et al., 2021), photocatalytic CO<sub>2</sub> reduction (He et al., 2019), photocatalytic CH<sub>4</sub> activation (Ma et al., 2021), nitrogen fixation (Chen et al., 2020), and photocatalytic fine chemicals synthesis (Leng et al., 2020; Tan et al., 2021), they often stuck at the proof-of-concept level.

Although a lot of work has been done on basic photocatalytic research, there is still a certain gap between laboratory and industrial application. Laboratory studies can take no account of the cost, catalyst recycle, energy consumption, environmental protection, and other issues, but only to prove the feasibility and mechanism of the photocatalytic system. However, in the case of amplifying industrial application, there are various uncontrollable factors in the actual production process, and the preparation conditions of the catalysts will not be as controllable and stable as in the laboratory (Tang et al., 2021). Therefore, the development of economical, feasible, and stable large-scale preparation methods is the key to realize the industrial application of photocatalytic systems.

The improvement and optimization of the reactor is also an important factor for the industrial application of photocatalytic technology (Danon et al., 2012; Reilly et al., 2017; Pieber et al., 2018). It is necessary to optimize the system design of the reactor to achieve the optimal photocatalytic efficiency, since a well-designed reactor can not only improve the reaction efficiency, but also reduce the waste of energy and catalyst and improve the economic benefit.

## Uniform Efficiency Standards

The lack of a reasonable activity evaluation standard is a huge obstacle to the development of photocatalytic technology. At present, most literatures usually normalize the activity of photocatalysts by their mass or surface area (Qureshi and Takanabe, 2017; Albero et al., 2020). However, this approach is ill-advised, because there is generally no linear correlation

between the production rate of the target product and the mass/surface area of the used photocatalyst. In addition, it is worth noting that standards for light sources used in photocatalytic systems vary from country to country, and the reactor and illumination distances commonly used by different groups also varies. Therefore, it is pointless to compare the photocatalytic activity from different literatures based on the yield of the target product alone.

Recently, the authors have apparently recognized this issue, and have tended to compare the photocatalytic activity of different systems using apparent quantum yield (AQY) instead of traditional yield (Wang et al., 2021). This is undoubtedly a good trend, provided that standardized AQY calculation tools or methods are developed.

## Is Photocatalysis Green?

Green, clean, low energy consumption and environmental friendliness is the general impression of photocatalytic technology. However, it is undeniable that we often add electrons or hole sacrificial agents, such as triethylamine, tetrachloromethane, lactic acid, triethanolamine, and various alcohols, into the photocatalytic system (Liu et al., 2021). Although the introduction of these scavengers can greatly promote the photocatalytic efficiency, it also causes undesirably product and environmental pollution (Wang et al., 2021). In comparison, integrating certain oxidation reaction with another reduction reaction (Qi et al., 2020; Han et al., 2021), for example, cooperatively coupling benzyl alcohol oxidation with hydrogen production in one system (Qi et al., 2020), may be a better path to simultaneously maintain high reaction efficiency and economic benefits. In this context, we urge all authors to use sacrificial agents with caution.

## AUTHOR CONTRIBUTIONS

The author confirms being the sole contributor of this work and has approved it for publication.

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**Conflict of Interest:** The author declares that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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