2-2-1. Artificial Photosynthesis

Overview

In contrast to solar cells, which convert solar energy into electrical energy, artificial photosynthesis is defined as a method of storing solar energy within chemical substances. A pioneering study in artificial photosynthesis was the discovery of water splitting into hydrogen and oxygen using a TiO_2 photoelectrode, known as the Honda–Fujishima effect (Fig. 1). Building on this achievement, research on photocatalytic water splitting became active in Japan, the United States, and Europe from the 1980s ("2-1-1. Water Splitting" provides more detail on this field).

In addition to water splitting, photocatalytic CO_2 reduction has also been extensively studied in the field of artificial photosynthesis ("2-2-6. Photocatalytic CO_2 Reduction"). More recently, research on photocatalytic nitrogen reduction has gained momentum ("2-2-7. Photo-Nitrogen Reduction Reaction").

Artificial photosynthesis research lost momentum in many countries during the 1990s due to the emergence of new photocatalyst applications in environmental purification and decreasing crude oil prices. However, research continued steadily in Japan. Since the 2000s, when global warming became widely recognized as a critical international issue, artificial photosynthesis research has revived worldwide. One factor explaining why Japan remains a leading center of artificial photosynthesis research today is the continuous and long-term effort sustained throughout this period.

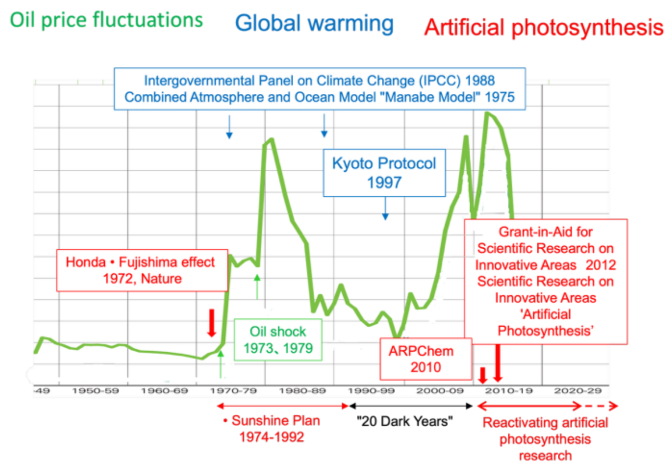

Figure 1. Relationship among artificial photosynthesis–related projects in Japan (red), crude oil prices (green; relative values adjusted for deflation), and "global warming" (blue).

Current Status and Frontiers

In Japan, the NEDO/ARPChem project ("Development of Production Technologies for Chemicals from CO_2") began in 2012, led by Setoyama, Domen, and colleagues. The goal of this project was to produce green hydrogen using photocatalysts, and subsequently use the hydrogen to reduce carbon dioxide via thermocatalysis to synthesize olefins. Within this project, Domen and co-workers successfully demonstrated green hydrogen production via water splitting on a 100 m^2 scale using the powdered photocatalyst $SrTiO_3$:Al.[1] A joint team composed of the Domen group and INPEX later won the Horizon Prize on Artificial Photosynthesis: Prototype of an Artificial Photosynthetic Fuel Production System in a competition organized by the European Innovation Council in 2022.[2] The mission of the competition was to synthesize green fuel from water and carbon dioxide and use it to power a small engine. Technologies based on "solar cell + water electrolysis" systems were excluded from consideration. After document screening, three teams remained, and each competed in performance demonstrations in Italy. The Japanese team performed water splitting using sunlight and photocatalysts and separated hydrogen from the resulting hydrogen–oxygen mixture. The green hydrogen was then used for CO_2 hydrogenation over a Ni/ZrO_2 thermocatalyst to synthesize methane. This green fuel successfully powered a small engine. This demonstration clearly established Japan as a world-leading country in green hydrogen production using photocatalysts.

In parallel, fundamental research progressed through academic projects such as the Grant-in-Aid for Scientific Research on Innovative Areas "AnApple" (Artificial Photosynthesis Project for Living Earth), launched in 2012 by Inoue and colleagues,[3] and the subsequent "I4LEC" (Innovations for Light-Energy Conversion), launched in 2017 by Shen and colleagues.[4] These KAKENHI projects brought together researchers in molecular and semiconductor photocatalysts, electrocatalysts, natural photosynthesis, and advanced measurement techniques, fostering active collaboration. Many participants continue to develop a wide range of artificial photosynthesis research today.

Based on these foundations, the **Consortium of All Nippon Artificial Photosynthesis Project for Living Earth (CanApple)**[5] was established as an artificial photosynthesis consortium in Japan. Overseas, major projects include JCAP (2010–2020), RISA (from 2020), and CHASE (from 2020) in the United States, the Horizon program in Europe, and KCAP (launched 2010) in Korea.

References

1. H. Nishiyama, K. Domen, et al., *Nature*, **598**, 304–307 (2021).
2. T. Yamada, H. Nishiyama, K. Domen, et al., *ACS Engineering Au*, **3**, 352–363 (2023).
3. https://kaken.nii.ac.jp/ja/grant/KAKENHI-ORGANIZER-24107001/
4. https://kaken.nii.ac.jp/ja/grant/KAKENHI-AREA-4906/
5. https://www.canapple.com/

Future Perspectives and Directions

For green hydrogen production using photocatalysts, achieving higher efficiency aimed at practical deployment—not merely basic research—remains a crucial challenge. Therefore, the development of highly efficient visible-light-responsive photocatalysts to replace $SrTiO_3$:Al is underway.

Green hydrogen production is often compared with systems combining solar cells and water electrolysis. Each approach has strengths and weaknesses, so pursuing diverse technological pathways—rather than narrowing down to a single method based solely on efficiency—is essential.

In CO_2 reduction, highly efficient homogeneous photocatalysts using organic electron donors have been developed, and systems using water as the electron source have also been constructed. Achieving further efficiency improvements remains an important challenge. Additionally, attention is growing toward understanding the mechanisms and developing photocatalysts capable of producing multi-electron reduction products such as alcohols and hydrocarbons, beyond two-electron products like carbon monoxide and formic acid.

Although many fundamental research challenges remain before artificial photosynthesis can become a practical technology, significant progress is also needed in process engineering and chemical engineering to integrate and implement artificial photosynthesis systems in society.

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