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Artificial Photosynthesis for Renewable Energy

Mugisha Emmanuel K.

Faculty of Science and Technology Kampala International University Uganda

ABSTRACT

Artificial photosynthesis is a bio-inspired technology designed to mimic the natural photosynthetic process of converting sunlight, water, and carbon dioxide into energy-rich fuels. This technology aims to provide a sustainable and renewable source of solar fuel, potentially alleviating the reliance on fossil fuels and mitigating greenhouse gas emissions. By using photoelectrodes and catalysts to drive the necessary chemical reactions, artificial photosynthesis can produce various fuels, including hydrogen, methanol, and other hydrocarbons. Recent advancements in materials science and nanotechnology have significantly improved the efficiency and scalability of artificial photosynthesis systems. This paper reviews the key components, recent research developments, and future prospects of artificial photosynthesis as a viable solution for global energy demands and environmental sustainability.

Keywords: Artificial Photosynthesis, Renewable Energy, Solar Fuel, Photoelectrodes, Catalysts.

INTRODUCTION

Artificial photosynthesis is regarded as a technology to provide renewable solar fuel (green fuel), where a photoelectrode takes the place of natural leaves and sunlight plays a part in creating fuel molecules through carbon fixation. Artificial photosynthesis, a bio-inspired approach, is defined as the solar-light-driven CO2-to-fuel conversion that mimics the processes occurring in natural leaves. Indeed, the grand challenge posed to the scientific and engineering communities is providing sustainable solar fuel using a mixture of H2O and CO2 that is already present in the environment humans breathe [1, 2]. Artificial photosynthesis provides a means for the continuous production of biofuel. There are various fuels such as methanol, ethanol, butanol, gaseous C1 fuels, and other hydrocarbons that are present in nature based on the type and concentration of reducing agent present in the reaction medium. In 1970, electrical power was over 40,000 petawatt hours (PWh), resulting from a 1.5% decrease in the growth rate decades earlier. In 2013, it reached 22,600 PWh, a 45% growth over 1960. The huge demand for this tremendous amount of power comes mainly from fossil resources in the form of chemical energy. The proportion of global supply grid in 2013 was 64% fossil resources (oil, natural gas, coal), with 20% resulting from pollution accidents and 16% from natural disasters. It can be concluded that fossil energy is the greatest source of energy, but its share will decrease in a few decades. Furthermore, water must be electrolyzed using geothermal, nuclear, and renewable energies to mediate bio-photosynthesis' ultimate endothermic, water-consuming reducing agent [3].

DEFINITION AND CONCEPT

Artificial photosynthesis (AP) is a process that is made possible by means of reasonable and controlled cathodic and anodic reduction and oxidation processes, with the aim of using sunlight. There are three possible definitions for AP: 4

1) During AP, a dye sensitizer splits water into oxygen and hydrogen. In other words, the dye sensitizer mimics a Photosystem II counterpart of natural photosynthesis. This is one of the most successful miniaturizations of artificial photosynthesis, using only a few molecules [5].

2) Another miniaturization of artificial photosynthesis would be to design light-absorbing molecules arranged in a supramolecular structure. This is a central experiment to identify how light-harvesting of an entire photosystem is organized in living systems [6].

3) More generally, AP may represent any processes that use photocatalytic reduction and oxidation, specifically the reduction of water with sunlight [7, 8]. In natural photosynthesis, the chlorophyll molecule absorbs sunlight and the energy from the absorbed light is used to split the water molecule, releasing oxygen molecules, protons, and electrons. The oxygen, protons, and electrons are then used to form glucose, which is an energy-carrying molecule. These steps present artificial processes aimed at performing artificial photosynthesis, either to produce alternative energy carriers or artificial leaves. Artificial photosynthesis progresses either by mimicking all the components of photosynthesis or by dividing the reaction into systems specialized in one reaction. The main principle of solar energy conversion is similar to that of natural photosynthesis: charge separation followed by charge recombination. This is known as part of the physical processes, which cover energy, electron transfer, exciton, etc [9].

IMPORTANCE FOR RENEWABLE ENERGY

Artificial photosynthesis holds the potential to provide for the global solar energy demands, which are anticipated to grow by 30% annually. Sustainability for the world's energy needs remains the greatest dual-headache of making it compatible with greenhouse gas (GHG) abatement. As energy prices spur, suitable treatments for worldwide environmental quality are becoming a shadow for powerful diplomacy. The possible extent of applications for renewable energy is nearly twice the amount of energy that may be harnessed from all of the world's fossil fuel reserves. So, the potential for solar-based energy applications is obvious. As part of the ongoing quest for sustainable energy resources completely free of greenhouse gases and waste, artificial photosynthesis is beginning to attract broad attention. Water solvent using solar-based systems is an excellent candidate for developing an effective technology for hydrogen generation [10]. A solar direct approach may be exploited to attain artificial photosynthesis on an industrial scale at a significantly lower value than green energy obtained from any known renewable energy source. Artificial photosynthesis or chemical chaining of reactions/processes is driven by chemical catalysis and magnetism. Both processes are reciprocal reactions or processes having the same reaction type with a different sign of the Gibbs Free Energy of Reaction. This makes feasible the integration of the two functions. It is difficult to give the most accurate estimated area because the local and regional solar photoactive site could be a different place from where other steps are thermodynamically more favorable. The endothermic/endogenic nature of water splitting is the photo electrode desorption of oxygen and dissolved water protons join to make free H+. Subsequently, H+ ions travel to the H capturing sites. For water splitting, a catalyst would energetically downshift the electrochemical potential of the captured H+ from the oxidation of H2O at the anode. If the sum of all reactions/steps that maximized overall efficiency slightly exceeds zero, then the system is viable [9, 11].

NATURAL PHOTOSYNTHESIS: INSPIRATION FOR ARTIFICIAL SYSTEMS

Solar fuels inspired by natural photosynthesis are a major research field aiming to contribute to solving global climate challenges and renewable energy production, storage, and use. Essentially, artificial photosynthesis is the process of using an artificial system to directly convert solar energy, water, and carbon dioxide into solar fuels, with oxygen production as a byproduct. The research on natural photosynthesis and the development of effective mechanisms and biosensors in response to those processes provide a structural framework for the overall design of artificial light-reactive and dark-reactive systems. Since before 2020, the design and scaling up of these systems have focused mechanistically on their similarity with the natural triggers and processes for fuel formation. The evolution of this field has been well described in several collaborative studies across international borders [12, 13]. Here we outline the photosynthetic process of green plants, as it is the prototypical state of the art of photosynthesis in natural processes. Artificial replica technologies are increasingly emerging to co-opt other photoautotrophs and/or purple bacterial systems to produce carbon-based fuels. Additionally, this chapter has been expanded to describe the role of the development of these systems in the extraction of pollution from the atmosphere and in the monitoring of the photosynthetic apparatus in organisms through a newly emerging form of artificial photosynthesis: purified components of the photosynthesis machinery isolated in a biomimetic environment. Such a process involves the binding light to the extraction of crystallized ATP-synthase and is discussed further in the section on coupling the bleed of the photosynthetic membrane to the generation of molecularly energetic molecules [14].

KEY COMPONENTS OF ARTIFICIAL PHOTOSYNTHESIS

Artificial photosynthesis is the technique that incorporates features of natural photosynthesis in converting solar energy to produce storable renewable energy. The technique comprises a light absorber, an electronic charge donor-acceptor, and a catalyst. Progress in artificial photosynthesis has been critiqued in terms of the concept's relevance to natural photosynthesis and solar fuel production. But,

from a broader perspective, electrocatalysts for artificial photosynthesis are imperative energy materials for producing as good or better fuels than are extracted from underground. Major progress in electrocatalysts for artificial photosynthesis is imminent to be realized because of the thrust given by fuel cells' research and natural photosynthesis after the recent advent of free partnering of acceptor-donor charges without a catalyst. Artificial photosynthesis is structured with one quantum photon absorber or two (light and/or heat) absorbers appropriate for natural photosynthesis and/or fuel cell and manganese brown-cocktail catalyst [9]. The most absolute goal of artificial photosynthesis (AP) is to produce fuels using the free energy of solar radiation accumulated on Earth. Artificial photosynthesis is a process that functions in the opposing direction of natural photosynthesis (converting water and carbon dioxide into carbohydrates). In AP, light absorbers break water into hydrogen and oxygen—thus incorporating carbon dioxide into artificial photosynthesis is necessary to produce more practical fuels, such as methane or methanol. Artificial photosynthesis (AP) components expression has appeared in the title only after 1990. Given a catalyzing light source in the form of a light charging unit (LCU), which is a capacitor that upswings the energy level of input charges till their transformation at the catalyst potentials, the enzymes get activated by another light. Balzani and others have emphasized the role of light absorber and catalyst as central to artificial photosynthesis and solar fuel production. Light absorbers are known and optimized for efficient usage of solar light absorbing limitations placed at around 1.1 to 1.3 eV. Such a range of bandgap energy in semiconductors is required for independent water splitting catalyst and is around 0.6 eV more than the RedOx potential for water splitting. Thus, one can change the way the light absorber works to receive 1 to 1.1 eV light and/or concentrate the sunlight with a diffraction-limited system. The other component that is the catalyst, though available in nature, does this process in the aqueous layered interior of a biomimetic device with available multi-layer materials. Electrocatalysts have already been reported to perform several times better than the best biological enzymes. Roses iron-based, boride, and similar methane-generating catalysts have undergone sub-mic sponsorship worth over 10 million in the USA (DOE) as fuel surrogate studies. Scientists at UW have reported one or two nano catalysts using inexpensive light absorber to produce H2 and/or oxygen at the rate of 10000+ micromoles mg-1m-1 in three to four types of fuels plus oxygen. Research is in progress at UW to combine all three processes of artificial photosynthesis: H2, O2, and CO2 reduction in one solar-powered device [15, 16, 17].

LIGHT ABSORBERS

Light absorbers are essential components in the field of artificial photosynthesis. Solar fuel production in the laboratory often relies on the ability of semiconductors to capture light and efficiently deliver the corresponding charge carriers to the electrode surface. Without the capacity for light absorption and photoexciton formation, no fuel synthetase or catalyst molecules can function. In this sense, light absorbers set the standard of how much energy is wasted in harvesting solar photons, and how fast solar-produced electrons can be delivered into dedicated redox couples for subsequent storage or reaction [1]. Light absorbers in multisubunit systems, such as photosynthetic reaction centers, are often unprotected in water to create a robust redox buffer. However, water, as a solvent, prohibits the intradiffusion of redox center moieties in a more direct way and could potentially limit the overall reaction speed. Reactive and inwardly oriented light absorbers are often constructed for a protected environment that includes the direct or indirect incorporation of some of the rest of the components of a given (cofactor-less) charge carrier battery. Light absorbers and supporting charge-carrier-transfer (cCTT) setups can either consist of solid electrodes and dyes, molecular solutions, nanohybrids, or split and reclined photocatalysts. Catalytic coenzymes serve as wet or dry counter-electrodes in an electrochemical setup, and battery coenzymes one often needs to be added in the case of light absorbers embedded in a lipid membrane. Opening, occluding, or removing water enables faster charge-carrier extraction with solid-state counter-electrodes. Inside a lipid bilayer or on a solid surface, negative membranes or slightly smaller electrode gap setups indeed show an increased bimolecular charge transfer rate [18].

CATALYSTS

The large task of converting solar energy into chemical energy is accomplished largely by the use of catalysts. Because small-scale reactions often involve intermediates that are difficult to directly observe, these electrocatalysts and photocatalysts can have a substantial effect on the efficiency and selectivity of the process. Some key examples of such catalysts and co-catalysts for artificial photosynthesis and CO2RR include platinum metals, Fe, Ni, Cu, and W, oftentimes in place of, or heteroatom-copposed on Mn, Co, and Mo surfaces. As we head into a world in which we rely on energy by conversion of sunlight into chemical fuels, the group of catalysts with titanium and cerium oxides, capable of band-structure demonstrated high quantum efficiency needed for the future but shown early on are being exploited to synt 100%, were also discovered. This list is, in no way, complete, but is meant to show the potential of

using photoelectrochemical cells, where liquid, gaseous, or solid fuels are produced [19]. In the future of artificial photosynthesis, while it is likely that key advances will come from initially studying very efficient natural systems, this knowledge will then be used to produce a series of stable catalysts for fuels production, which for simple are the "redox" equivalents of the creation of O2. Metallic catalysts will be required as a bridge from when the light shines down the light harvesting dendrimes. But the other constituents will not be homogeneous, except for the substrate. This is because as soon as the electron is placed on the electrode, i.e., at the surface, the small chemical compounds that evolutionary pressures bring about, while being probably quite stable in the short term, are almost certainly subject to chemical damage in the long term. The vast quantity of potentially stable small molecules in groups is thus much greater than those systems where the gathered small carbohydrates are so far been the goal for those using ("natural") plants for energy. Furthermore, since solid metallic catalysts last longer than the CO2RR products, metals and/or metal-metal oxide catalysts enable us to increase the amount of "fuels" produced by more or fewer, more stable, catalysts [20].

RECENT ADVANCES IN ARTIFICIAL PHOTOSYNTHESIS RESEARCH

Research is a dynamic field, and this constant motion contributes to the steady advance of many key processes and technologies. As a result, this section focuses on the latest breakthroughs in artificial photosynthesis research, putting the focus on the most recent progress in the field and highlighting up-to-date, innovative research into artificial photosynthesis. The work considered here includes a variety of potential methodologies that could contribute to the development of efficient artificial photosynthesis [21]. Research into artificial photosynthesis continues to advance, optimizing diverse designs and methodologies while using a wide variety of materials to advance understanding and the capability of these approaches. As both an efficient energy storage medium and a good substitute for natural gas or conventional fuels, methane production from aqueous carbon dioxide reduction via artificial photosynthesis is attractive. In this study, we report the application of a microporous amorphous boron oxide film as a photocathode for ethylene production via gas diffusion electrode configuration. Based on first-principles calculations, the scientific and energetically examinations and the structure-property relationship interpretations solidly demonstrate that the electrochemical hydrogen binding free energy could be conveniently modulated without additional metal species [22].

APPLICATIONS AND FUTURE PROSPECTS

Due to the high efficiency achieved during the splitting of water, the apportioned world is diverse as follows: (i) fuel production, especially the synthesis of ammonia and alcohols; (ii) environmental applications; (iii) stand-alone devices for renewable energy production or energy storage in the form of H2; and (iv) application as oxygen evolution reaction (OER) catalyst. Apart from the main application of absorbing sunlight toward hydrogen production, the direct fixation of carbon dioxide for the production of fuels and chemicals that have very high energy density is another interesting field. Also, chemical industries to produce chemicals through carbon dioxide value-added and CO can be absorbed, so it has a positive impact on the environmental aspect, as it can reduce the effect of greenhouse gases. One of the most important applications of CO production is that the Fischer-Tropsch process can be used for the production of various types of fuels (e.g., gasoline, diesel, and kerosene), methanol, and olefins [23]. Artificial photosynthesis offers a potentially elegant combination of energy and environmental remedy all at the same time. Prospects will be many and wide for artificial photosynthesis, with opportunities ranging across energy, the environment, and storage. The most obvious application is, of course, solar energy conversion via splitting water into hydrogen as a means of addressing our energy demands and as a store of solar energy for a daylight-independent fuel supply. It is predicted that it can meet the energy demand up to 2045, especially in the fields of electricity, heating, and transportation. Simultaneously, turning carbon dioxide to carbon monoxide poses a potential immediate solution to mitigate the impacts of climate change and provide important feedstock for chemical industries. Artificial photosynthesis technologies can play a pivotal role in the vast transition that approaches us inexorably, a transition enabling a world without net carbon emissions [24].

CONCLUSION

Artificial photosynthesis holds immense potential as a sustainable and renewable energy solution that can meet the growing global demand for clean energy while addressing environmental concerns. By mimicking the natural process of photosynthesis, this technology can convert solar energy into storable and transportable fuels such as hydrogen and methanol. The development of efficient light absorbers, catalysts, and integrated systems has brought us closer to realizing the industrial-scale application of artificial photosynthesis. Future research should focus on enhancing the efficiency, durability, and cost-effectiveness of these systems to make them commercially viable. As the world transitions towards a

carbon-neutral future, artificial photosynthesis offers a promising pathway to harness solar energy and reduce our dependence on fossil fuels, contributing to a more sustainable and eco-friendly energy landscape.

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