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Review

Recent advances in photosynthetic energy conversion

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ABSTRACT

Photosynthesis is one of the first natural processes evolved by cyanobacteria, algae and green plants to trap light and CO_2 in the form of reduced carbon compounds while simultaneously oxidizing water to oxygen. The photosynthetic energy conversion forms the basis for all the existing life today. The photosynthetic energy is being harnessed in many ways using modern technologies for the production of fuels using photosynthetic organisms, generation of direct electricity using photosystems/photosynthetic organisms in photo-bioelectrochemical cells or through photovoltaic systems. While the production of energy rich carbon fuels (ethanol, propanol) from photosynthetic organisms has already been accomplished due to advancement in understanding microbial physiology and metabolism, the photosynthetic hydrogen production as well as direct electricity generation from light is still at its infancy. Recent advances include combining photosystem complexes with hydrogenases for hydrogen production, using isolated thylakoids, photosystems on nanostructured electrodes such as gold nanoparticles, carbon nanotubes, ZnO nanoparticles for electricity generation. Many challenging optimizations on the immobilization methods, catalyst stability and isolation procedures, electron transfer strategies have acquired momentum leading to the production of more stable and higher current densities and power densities in photosynthetic devices. Further, the use of whole cell microorganisms (cyanobacteria, microalgae) rather than their isolated counterparts has produced promising results. The photosynthetic energy conversion has an enormous potential for renewable energy generation in a sustainable and environment friendly manner.

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1. Introduction

Energy crisis is one of the most important issues that mankind facing in the 21st century. A great deal of ongoing research is focused on developing renewable, self-sustainable and environment friendly sources of energy. The currently available renewable resources include sunlight, wind, rain, tides and geothermal heat, accounting for around 16% of the global energy usage. Among these renewable sources, sunlight is the most abundant, ubiquitous and reliable energy source. Earth receives about 120,000 TW of solar energy each year, which far exceeds our current global annual demand of ~16 TW [1]. However, due to dilution effect of the Earth's atmosphere, the average solar power that comes into contact with the earth's surface is only 170 W m^{-2}, which also varies greatly with geographical location. The major routes for solar energy conversion are through photosynthesis and photovoltaics (PV). Photosynthesis is an incredible aspect of nature's ability to convert solar energy into chemical energy that has an evolutionary significance on existence of today's life. Photosynthesis is a process used by most plants, algae and cyanobacteria to convert water and carbon dioxide to carbohydrates using sunlight with the release of oxygen as byproduct. This is the only natural process known on earth to form oxygen from water. On the other hand, photovoltaic devices such as solar panels generate electrical power by converting solar radiation into direct current electricity using semiconductors. The energy conversion efficiency of PV based devices is around $18 \pm 2\%$ for the direct electricity generations [2]. Further, the materials and components of the PV system must come from limited global resources and are not 100% recyclable. Since photosynthetic organisms operate at near 100% quantum efficiency [3], an opportunity exists to tap into this natural process for energy conversion applications. Recently, a review by experts in the field of artificial photosynthesis critically analyzed both the photosynthetic and photovoltaic energy conversion mechanisms and clearly emphasized that comparing the energy conversion efficiency of current photovoltaic cells vs. living photosynthetic cells is difficult because both systems work very differently [4]. The efficiency of PVs can be measured based on power output divided by solar irradiance over the solar spectrum. However, this does not take into account the storage and transmission. Photovoltaic energy is usually stored in batteries, which increases the cost and maintenance of such systems. In contrast, photosynthesis results in stored energy within chemical bonds like biofuels or biomass. The process of photosynthesis can be effectively utilized for energy conversion applications in a variety of ways as shown in Fig. 1.

This article is aimed at reviewing the photosynthetic energy conversion in terms of both direct electricity generation in electrochemical cells as well as production of photo-biofuels (hydrogen). The review starts with description of natural photosynthesis process followed by the implications of photosynthetic machinery for hydrogen production and electricity generation. Recent advancements and challenges in development of photosynthesis-driven energy devices as well as the biomimetic approaches toward photosynthetic energy conversion have also been critically reviewed.

2. Photosynthetic electron transport chain in higher plants

2.1. Linear electron transport pathway

Photosynthesis consists of two sequences of reactions: (1) light reactions (light dependent) and (2) dark reactions (light independent). With the help of light harvesting complexes and redox enzymes present in the thylakoid membranes, plants produce reducing equivalents (NADPH) and energy currencies (ATP) through light-induced splitting of water into protons and oxygen. The set of reactions that occur during this process are called light reactions. The sequences of reactions that take place during the light reaction transferring the excited electron from water to $NADP^+$ are called photosynthetic electron transfer chain (P-ETC). During dark reactions, plants utilize the ATP and NADPH that are produced during the light reactions to synthesize carbohydrates using CO_2 captured from the atmosphere (CO_2 fixation). The net reaction of photosynthesis is the synthesis of carbohydrates using sunlight, water and CO_2 while oxygen is released as byproduct. The P-ETC consists of several multi-enzyme complexes in the thylakoid membrane such as photosystem II (PSII), cytochrome b_6f (Cyt b_6f), plastocyanin (PC), photosystem I (PSI), ferredoxin (Fd), ferredoxin-$NADP^+$ reductase (FNR) and ATP synthase which are located in the thylakoid membrane of the chloroplast. The PSII and the PSI are the major energy transducing photosystems. When a photon of light reaches the P_{680} reaction center of PSII