Wisdom from plants: artificial photosynthesis as a key for a carbon-neutral society?

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Since the Industrial Revolution, the world has enjoyed the fruit of the advancement of science and technology. However, its rapid industrialization has been quietly but steadily eroding our precious nature. Industrialization which relied upon the burning of fossil fuel has caused an increase in the emission of carbon dioxide (CO_2) into the atmosphere. This increase in CO_2 concentration in the atmosphere greatly contributes to global warming, as CO_2 is responsible for about 60% of the increase in heat capacity of the atmosphere.[1] The increase in global temperature could bring the destruction of ecosystems and extreme weather events.[2] Also, an increase in the atmospheric CO_2 can lead to more acidity in oceans, which could alter the marine life cycle. Because of these risks, certain measures against carbon emission are indispensable for our brighter future.

To combat this crisis, the world is shifting its way to deal with carbon-dependent production. One of the strategies is to absorb CO_2 emitted from factories so the net carbon emission will be zero. This idea is called carbon neutrality. In a carbon-neutral society, artificial photosynthesis should play a promising role because CO_2 will be recycled into commercially valuable substances with this technology.

So, what is artificial photosynthesis? Before explaining what that is, let's go through what photosynthesis is. As you may already know, photosynthesis is a process that transforms sunlight energy into chemical energy. The overall process is driven by the movements of electrons. When the light is absorbed by the matter called sensitizer (i.e., a photocatalyst), an electron excites up to a high energy state and initiates the transitions of other electrons as well.[3] As a result, the overall electrons' energy increases. This increased energy is then used for the reaction that produces oxygen (O_2) and carbohydrates from water (H_2O) and CO_2. Plants use their chloroplasts to perform this process to store energy in form of chemical energy.

Artificial photosynthesis fundamentally follows the same mechanism as photosynthesis but uses an artificial system instead of a chloroplast. This technology started to gain attention after the discovery of the Honda-Fujishima effect.[3] This effect turns sunlight energy into chemical energy by flowing electric current when UV light is irradiated to the titanium dioxide anode of the electrolyte aqueous solution. As a result, it splits H_2O and produces hydrogen (H_2) and O_2. Then, the discoveries of molecular catalysts for artificial photosynthesis followed. These discoveries built a foundation for artificial photosynthesis technology that is still being researched today.

With these discoveries, artificial photosynthesis has been intensively studied for past decades. There are several approaches to realize artificial photosynthesis. One is to use a photocatalyst, in which the photocatalyst drives the Honda-Fujishima effect for artificial photosynthesis.[3] Another approach is to combine semiconductor photovoltaic (PV) cells and molecular catalysts to drive artificial photosynthesis.

One way to evaluate these approaches is to look at their solar-to-chemical energy conversion efficiency η_{STC}. This indicator is very important for the wide use of artificial photosynthesis technologies because the efficient energy conversion from sunlight energy to chemical energy is critical for mass consumption of CO_2. Currently, the approach that combines semiconductor PV cells and molecular catalysts has reached the highest solar-to-chemical energy conversion efficiency.[4] Let's take a deeper look into this approach.

The combination of semiconductor PV cells and molecular catalysts has already reached a higher efficiency than that of chloroplasts, but there remains a lot of challenges before it is practically realized.[4] The first thing is its cost. If the manufacturing process of a system or a material for artificial photosynthesis emits more CO_2 than consumed, it would be meaningless. Another thing to care about is its size. To apply this technology to a large factory, the electrodes used for artificial photosynthesis must be large enough to handle large amount of CO_2 emitted from the factory. Also, factors like the durability of the device need to be considered.[3]

Although there are many difficulties, let's focus on the conversion efficiency and the scale-up for now. In general, raising the sizes of the PV cells lowers the conversion efficiencies. [4] This is because some of the energy will be lost as electric resistance rises with an increase in the size of the electrode. Also, the inhomogeneous flow of CO_2 dissolved water leads to an insufficient supply of CO_2 for large electrochemical reactors.

To solve this problem, researchers in Toyota Central R&D Lab created a large-sized cell with a new structure that sustains high conversion efficiency.[4] One major change from the previous cell is that instead of sandwiching a PV cell between electrodes, a PV cell was placed outside the reactor. By doing so, electrodes no longer needed to use highly resistive light-transparent material for the light to reach the sandwiched PV cells. Also, instead of just making a large monolithic cell, they designed the device that consists of 5 stacked pairs of electrode catalysts all connected parallel with the PV cell. This structure and newly developed electrodes succeed to realize the enlarged reaction area while suppressing an increase in the electrical resistivity. Moreover, the newly designed cell incorporates an electrolyte circulating pump for a sufficient supply of CO_2 and quick extraction of produced formate (HCOOH).

This new device has an irradiation area of around 1000 cm^2 and recorded the highest η_{STC} of 7.2% for such a size.[4] This design was very innovative because it is applicable for even larger sizes. Along with scaling up, the researchers also target η_{STC} of 10% for the future realization.

In conclusion, artificial photosynthesis is expected to play an essential role in the reduction of CO_2 emission to the atmosphere from factories by recycling CO_2 into commercially valuable substances. Although there are many difficulties regarding the energy conversion efficiency, costs, and scaling up of the reaction, recent research has overcome some of the challenges, probably more in the future.

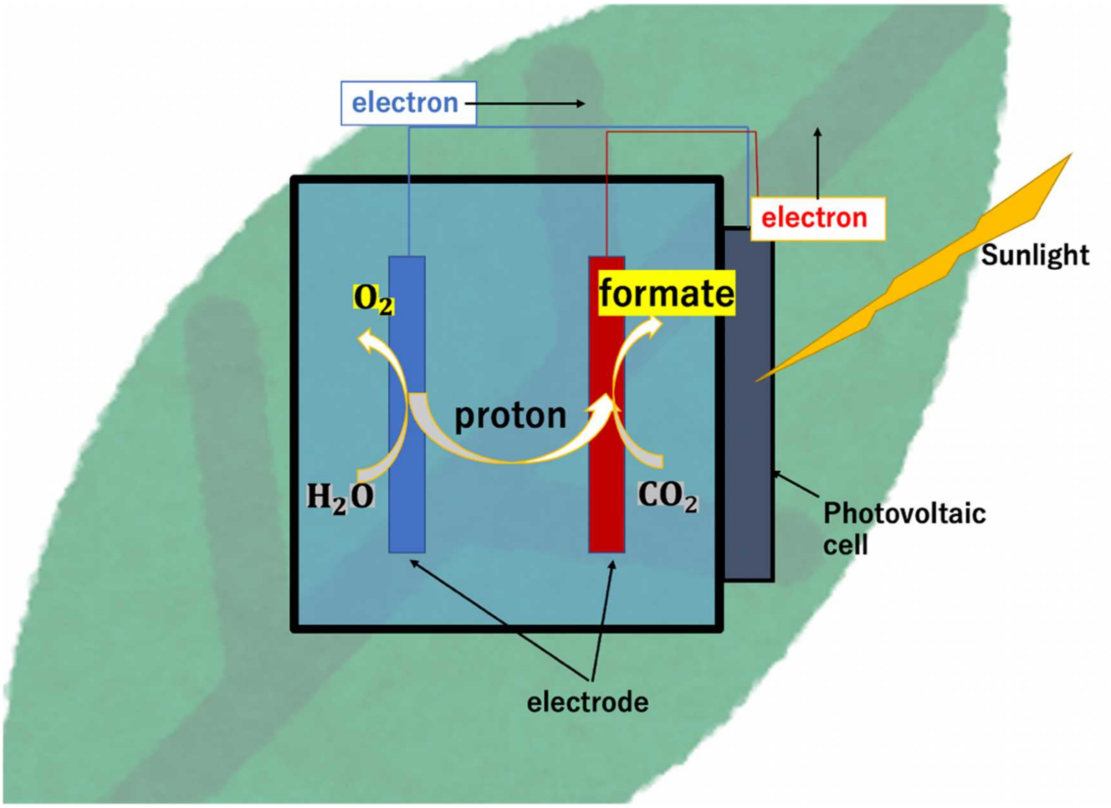

Figure 1：A simple diagram of artificial photosynthesis using a photovoltaic (PV) cell.

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