CURRENT CHALLENGES IN PHOTOSYNTHESIS: FROM NATURAL TO ARTIFICIAL

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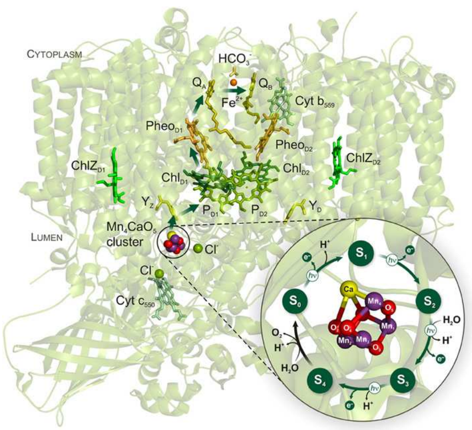

Principles of artificial photosynthesis.
Figure taken from: Shevela D and Messinger J (2013) Studying the oxidation of water to molecular oxygen in photosynthetic and artificial systems by time-resolved membrane-inlet mass spectrometry. *Front. Plant* Sci. 4:473.
doi: 10.3389/fpls.2013.00473

Jules Verne (1828-1905), author of Around the World in Eighty Days (1873) and Journey to the Center of the Earth (1864), wrote in 1875

"I believe that water will one day be used as a fuel, because the hydrogen and oxygen which constitute it, used separately or together, will furnish an inexhaustible source of heat and light. I therefore believe that, when coal (oil) deposits are oxidised, we will heat ourselves by means of water. Water is the fuel of the future"

Solar energy is the only renewable energy source that has sufficient capacity for the global energy need; it is the only one that can address the issues of energy crisis and global climate change. A vast amount of solar energy is harvested and stored via photosynthesis in plants, algae, and cyanobacteria since over 3 billion years. Today, it is estimated that photosynthesis produces more than 100 billion tons of dry biomass annually, which would be equivalent to a hundred times the weight of the total human population on our planet at the present time, and equal to a global energy storage rate of about 100 TW.

The solar power is the most abundant source of renewable energy, and oxygenic photosynthesis uses this energy to power the planet using the amazing reaction of water splitting. During water splitting, driven ultimately by sunlight, oxygen is released into the atmosphere, and this, along with food production by photosynthesis, supports life on our earth. The other product of water oxidation is “hydrogen” (proton and electron). This ‘hydrogen’ is not normally released into the atmosphere as hydrogen gas but combined with carbon dioxide to make high energy containing organic molecules. When we burn fuels we combine these organic molecules with oxygen. The design of new solar energy systems must adhere to the same principle as that of natural photosynthesis. For us to manipulate it to our benefit, it is imperative that we completely understand the basic processes of natural photosynthesis, and chemical conversion, such as light harvesting, excitation energy transfer, electron transfer, ion transport, and carbon fixation. Equally important, we must exploit application of this knowledge to the development of fully synthetic and/or hybrid devices. Understanding of photosynthetic reactions is not only a satisfying intellectual pursuit, but it is important for improving agricultural yields and for developing new solar technologies. Today, we have considerable knowledge of the working of photosynthesis and its photosystems, including the water oxidation reaction. Recent advances towards the understanding of the structure and the mechanism of the natural photosynthetic systems are being made at the molecular level. To mimic natural photosynthesis, inorganic chemists, organic chemists, electrochemists, material scientists, biochemists, biophysicists, and plant biologists must work together and only then significant progress in harnessing energy via “artificial photosynthesis” will be possible.

This Research Topic provides recent advances of our understanding of photosynthesis, gives to our readers recent information on photosynthesis research, and summarizes the characteristics of the natural system from the standpoint of what we could learn from it to produce an efficient artificial system, i.e., from the natural to the artificial. This topic is intended to include exciting breakthroughs, possible limitations, and open questions in the frontiers in photosynthesis research.

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frontiers in
PLANT SCIENCE

EDITORIAL
published: 28 May 2014
doi: 10.3389/fpls.2014.00232

Current challenges in photosynthesis: from natural to artificial

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Keywords: photosynthesis, artificial photosynthesis, water oxidation, thylakoid, chlorophyll *f*

Photosynthesis is a process by which plants, algae, cyanobacteria, and anoxygenic photosynthetic bacteria capture and store solar energy on a massive scale, in particular via the water-splitting chemistry (Hoganson and Babcock, 1997; Blankenship, 2002; Ferreira et al., 2004; Loll et al., 2005; Yano et al., 2006; Umena et al., 2011). It is the most important reaction on Earth, estimated to produce more than 100 billion tons of dry biomass annually; this means that photosynthesis is producing biomass equal to two Egyptian pyramids per hour. But, this will not be enough to sustain life on Earth by the year 2050. The global fossil fuels on which we currently depend are derived from millions of years of past photosynthetic activity. The fossil energy fuels are limited and must be replaced by renewable and environment-friendly energy source to support and sustain life on Earth (Lewis and Nocera, 2006; Blankenship et al., 2011). To address this immediate energy crisis, worldwide efforts are being made on artificial photosynthesis using the principles and mechanisms observed in nature (Brimblecombe et al., 2009; McConnell et al., 2010; Kanady et al., 2011; Wiechen et al., 2012; Najafpour et al., 2013). It is not a matter of mimicking natural photosynthesis, but to use its current knowledge to improve photosynthesis itself, as well as to produce biofuels, including hydrogen evolution by artificial means (Barber, 2009; Hou, 2010; Nocera, 2012; He et al., 2013).

This book contains 10 chapters and presents recent advances in photosynthesis and artificial photosynthesis. It starts with two opinion articles on possible strategies to improve photosynthesis in plants and fascinating mechanisms of unidirectional photodamage of pheophytin in photosynthesis. The idea that plant photosynthesis is maximized due to the perfect evolution might be faulty. Leister evaluated and argued the issue openly and proposed that improvement of photosynthesis can be made by synthetic biology including genetic engineering, redesign or de novo creation of entire photosystems as well as conventional breeding (Leister, 2012). Unidirectional photodamage of a pheophytin molecule in photosystem II and purple bacterial reaction centers was observed. The mysterious phenomena were analyzed and discussed in terms of different possible functions of the pheophytin in photosynthesis (Hou, 2014).

The book is followed by four review articles that discuss the current state of research on: photosynthetic water oxidation in natural and artificial photosynthesis, as obtained by mass spectrometry (MS) and Fourier transform infrared spectroscopy (FTIR); functional models of thylakoid lumen; and horizontal gene transfer in photosynthetic eukaryotes. The time-resolved isotope-ratio membrane-inlet mass spectrometry (TR-IR-MIMS) is able to determine the isotopic composition of gaseous products. Shevela et al briefly introduced the key aspects of the methodology, summarized the recent results on the mechanisms and pathways of oxygen formation in PS II using this unique technique and outlined the future perspectives of the application in water splitting chemistry (Shevela and Messinger, 2013) Another unique technique in probing the mechanism of water oxidation in PS II is the light-induced FTIR difference spectroscopy. Chu reviewed the recent fruitful structural data, and believed that the FTIR will continue to provide vital structural and mechanistic insights into the water-splitting process in PS II together with isotopic labeling, site-directed mutagenesis, model compound studies, and computational calculation (Chu, 2013). The thylakoid lumen offers the environment for oxygen evolution, electron transfer, and photoprotection in photosynthesis. Jarvi et al evaluated the recent studies of many lumen proteins and highlighted the importance of the thiol-disulfide modulation in controlling the functions of the thylakoid lumen proteins and their pathways of photosynthesis (Järvi et al., 2013). Qiu et al discussed that importance of the horizontal gene transfer (HGT) in enriching the algal genomes and proposed that the alga endosymbionts may be the HGT vectors in photosynthetic eukaryotes (Qiu et al., 2013).

Finally, the book offers four research articles, which focus on FTIR studies on photosynthetic reaction centers, functions of thylakoid protein kinases STN7 and STN8, photosynthesis acclimation of maize seedlings, and characterization of the newly discovered chlorophyll *f*-containing cyanobacterium *Halomicronema hongdechloris*. The computational calculation (ONIOM) is increasingly critical in interpreting the FTIR data in elucidating the structural and functional relationship in photosynthesis. Zhao et al using ONIOM type calculation to simulate isotope edited FTIR difference spectra for reaction centers with a variety of foreign quinones in the Q_A site and allows a direct assessment of the appropriateness of previous IR assignments and suggestions (Zhao et al., 2013). The protein kinases STN7 and STN8 are predominately responsible for the thylakoid phosphorylation in PS II. Wunder et al reported the effects of the STN8 expression levels on the formation and modulation of thylakoid proteins and kinases (Wunder et al., 2013). Hirth et al assessed the photosynthetic acclimation responses of the C3 and C4 plants under simulated field light conditions (Hirth et al., 2013). Recently a chlorophyll *f* (Chl *f*) in cyanobacterium *Halomincronema hongdechloris* was identified and has the most red-shifted absorption peak of 707 nm in oxygenic photosynthesis (Chen et al., 2010), which may enhance the potential photosynthesis efficiency for solar fuel production. The *Halomincronema hongdechloris* was characterized upon the exposure to the different light, pH, salinity, temperature, and nutrition to achieve the optimizing growth culture conditions (Li et al., 2014).

Due to the extremely limited time frame for collecting manuscripts and the strict deadline for publishing this book, several planned manuscripts by world leaders, who had agreed to contribute, are unfortunately not included in this book. Thus, the current book provides a snapshot of the latest work in photosynthesis research. To obtain complete information on the current progress in the field of photosynthesis, we highly recommend reviews and research articles, published in 2013, in two volumes of *Photosynthesis Research* (Allakhverdiev et al., 2013a,b)

In conclusion, the book provides readers with some of the most recent and exciting breakthroughs from natural to artificial photosynthesis, discusses the potential limitations of the results, and addresses open questions in photosynthesis and energy research. It is written by 31 young active scientists and established leading experts from Australia, Finland, Germany, Sweden, Taiwan, and the United States. We hope that this book is able to provide novel and insightful information to readers and stimulate the future research endeavors in the photosynthesis community.

ACKNOWLEDGMENTS

We take this opportunity to acknowledge and thank all the authors for writing excellent book chapters, and for being supportive and cooperative when their manuscripts were being reviewed and revised. We also thank the external reviewers for their timely contribution and effort in judging the value of the manuscript and delivering constructive comments, which have undoubtedly improved the quality and readability of the book. We thank the Specialty Chief Editor of *Frontiers in Plant Science*, Steve Huber, for his valuable advice and insightful discussions. We also thank Kennedy Wekesa and Audrey Napier for critical reading of the manuscript. We are very grateful to Amanda Baker, Graeme Moffat, Despoina Evangelakou, and Adriana Timperi of the Frontiers Production Office for their insightful advice and meaningful assistance during the entire book project.

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

Received: 26 March 2014; accepted: 09 May 2014; published online: 28 May 2014.
Citation: Hou HJM, Allakhverdiev SI, Najafpour MM and Govindjee (2014) Current challenges in photosynthesis: from natural to artificial. Front. Plant Sci. ***5****:232. doi: 10.3389/fpls.2014.00232*
This article was submitted to Plant Physiology, a section of the journal Frontiers in Plant Science.