WHY STUDY PHOTOSYNTHESIS?

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What is photosynthesis?

Photosynthesis is arguably the most important biological process on earth. By liberating oxygen and consuming carbon dioxide, it has transformed the world into the hospitable environment we know today. Directly or indirectly, photosynthesis fills all of our food requirements and many of our needs for fiber and building materials. The energy stored in petroleum, natural gas and coal all came from the sun via photosynthesis, as does the energy in firewood, which is a major fuel in many parts of the world. This being the case, scientific research into photosynthesis is vitally important. If we can understand and control the intricacies of the photosynthetic process, we can learn how to increase crop yields of food, fiber, wood, and fuel, and how to better use our lands. The energy-harvesting secrets of plants can be adapted to man-made systems which provide new, efficient ways to collect and use solar energy. These same natural "technologies" can help point the way to the design of new, faster, and more compact computers, and even to new medical breakthroughs. Because photosynthesis helps control the makeup of our atmosphere, understanding photosynthesis is crucial to understanding how carbon dioxide and other "greenhouse gases" affect the global climate. In this document, we will briefly explore each of the areas mentioned above, and illustrate how photosynthesis research is critical to maintaining and improving our quality of life.

Photosynthesis and food. All of our biological energy needs are met by the plant kingdom, either directly or through herbivorous animals. Plants in turn obtain the energy to synthesize foodstuffs via photosynthesis. Although plants draw necessary materials from the soil and water and carbon dioxide from the air, the energy needs of the plant are filled by sunlight. Sunlight is pure energy. However, sunlight itself is not a very useful form of energy; it cannot be eaten, it cannot turn dynamos, and it cannot be stored. To be beneficial, the energy in sunlight must be converted to other forms. This is what photosynthesis is all about. It is the process by which plants change the energy in sunlight to kinds of energy that can be stored for later use. Plants carry out this process in photosynthetic reaction centers. These tiny units are found in leaves, and convert light energy to chemical energy, which is the form used by all living organisms. One of the major energy-harvesting processes in plants involves using the energy of sunlight to convert carbon dioxide from the air into sugars, starches, and other high-energy carbohydrates. Oxygen is released in the process. Later, when the plant needs food, it draws upon the energy stored in these carbohydrates. We do the same. When we eat a plate of spaghetti, our bodies oxidize or "burn" the starch by allowing it to combine with oxygen from the air. This produces carbon dioxide, which we exhale, and the energy we need to survive. Thus, if there is no photosynthesis, there is no food. Indeed, one widely accepted theory explaining the extinction of the dinosaurs suggests that a comet, meteor, or volcano ejected so much material into the atmosphere that the amount of sunlight reaching the earth was severely reduced. This in turn caused the death of many plants and the creatures that depended upon them for energy.

Photosynthesis and energy. One of the carbohydrates resulting from photosynthesis is cellulose, which makes up the bulk of dry wood and other plant material. When we burn wood, we convert the cellulose back to carbon dioxide and release the stored energy as heat. Burning fuel is basically the same oxidation process that occurs in our bodies; it liberates the energy of "stored sunlight" in a useful form, and returns carbon dioxide to the atmosphere. Energy from burning "biomass" is important in many parts of the world. In developing countries, firewood continues to be critical to survival. Ethanol (grain alcohol) produced from sugars and starches by fermentation is a major automobile fuel in Brazil, and is added to gasoline in some parts of the United States to help reduce emissions of harmful pollutants. Ethanol is also readily converted to ethylene, which serves as a feedstock to a large part of the petrochemical industry. It is possible to convert cellulose to sugar, and then into ethanol; various microorganisms carry out this process. It could be commercially important one day.

Our major sources of energy, of course, are coal, oil and natural gas. These materials are all derived from ancient plants and animals, and the energy stored within them is chemical energy that originally came from sunlight through photosynthesis. Thus, most of the energy we use today was originally solar energy!

Photosynthesis, fiber, and materials. Wood, of course, is not only burned, but is an important material for building and many other purposes. Paper, for example, is nearly pure photosynthetically produced cellulose, as is cotton and many other natural fibers. Even wool production depends on photosynthetically-derived energy. In fact, all plant and animal products including many medicines and drugs require energy to produce, and that energy comes ultimately from sunlight via photosynthesis. Many of our other materials needs are filled by plastics and synthetic fibers which are produced from petroleum, and are thus also photosynthetic in origin. Even much of our metal refining depends ultimately on coal or other photosynthetic products. Indeed, it is difficult to name an economically important material or substance whose existence and usefulness is not in some way tied to photosynthesis.

Photosynthesis and the environment. Currently, there is a lot of discussion concerning the possible effects of carbon dioxide and other "greenhouse gases" on the environment. As mentioned above, photosynthesis converts carbon dioxide from the air to carbohydrates and other kinds of "fixed" carbon and releases oxygen to the atmosphere. When we burn firewood, ethanol, or coal, oil and other fossil fuels, oxygen is consumed, and carbon dioxide is released back to the atmosphere. Thus, carbon dioxide which was removed from the atmosphere over millions of years is being replaced very quickly through our consumption of these fuels. The increase in carbon dioxide and related gases is bound to affect our atmosphere. Will this change be large or small, and will it be harmful or beneficial? These questions are being actively studied by many scientists today. The answers will depend strongly on the effect of photosynthesis carried out by land and sea organisms. As photosynthesis consumes carbon dioxide and releases oxygen, it helps counteract the effect of combustion of fossil fuels. The burning of fossil fuels releases not only carbon dioxide, but also hydrocarbons, nitrogen oxides, and other trace materials that pollute the atmosphere and contribute to long-term health and environmental problems. These problems are a consequence of the fact that nature has chosen to implement photosynthesis through conversion of carbon dioxide to energy-rich materials such as carbohydrates. Can the principles of photosynthetic solar energy harvesting be used in some way to produce non-polluting fuels or energy sources? The answer, as we shall see, is yes.

Why study photosynthesis?

Because our quality of life, and indeed our very existence, depends on photosynthesis, it is essential that we understand it. Through understanding, we can avoid adversely affecting the process and precipitating environmental or ecological disasters. Through understanding, we can also learn to control photosynthesis, and thus enhance production of food, fiber and energy. Understanding the natural process, which has been developed by plants over several billion years, will also allow us to use the basic chemistry and physics of photosynthesis for other purposes, such as solar energy conversion, the design of electronic circuits, and the development of medicines and drugs. Some examples follow.

Photosynthesis and agriculture. Although photosynthesis has interested mankind for eons, rapid progress in understanding the process has come in the last few years. One of the things we have learned is that overall, photosynthesis is relatively inefficient. For example, based on the amount of carbon fixed by a field of corn during a typical growing season, only about 1 - 2% of the solar energy falling on the field is recovered as new photosynthetic products. The efficiency of uncultivated plant life is only about 0.2%. In sugar cane, which is one of the most efficient plants, about 8% of the light absorbed by the plant is preserved as chemical energy. Many plants, especially those that originate in the temperate zones such as most of the United States, undergo a process called photorespiration. This is a kind of "short circuit" of photosynthesis that wastes much of the plants' photosynthetic energy. The phenomenon of photorespiration including its function, if any, is only one of many riddles facing the photosynthesis researcher.

If we can fully understand processes like photorespiration, we will have the ability to alter them. Thus, more efficient plants can be designed. Although new varieties of plants have been developed for centuries through selective breeding, the techniques of modern molecular biology have speeded up the process tremendously. Photosynthesis research can show us how to produce new crop strains that will make much better use of the sunlight they absorb. Research along these lines is critical, as recent studies show that agricultural production is leveling off at a time when demand for food and other agricultural products is increasing rapidly.

Because plants depend upon photosynthesis for their survival, interfering with photosynthesis can kill the plant. This is the basis of several important herbicides, which act by preventing certain important steps of photosynthesis. Understanding the details of photosynthesis can lead to the design of new, extremely selective herbicides and plant growth regulators that have the potential of being environmentally safe (especially to animal life, which does not carry out photosynthesis). Indeed, it is possible to develop new crop plants that are immune to specific herbicides, and to thus achieve weed control specific to one crop species.

Photosynthesis and energy production. As described above, most of our current energy needs are met by photosynthesis, ancient or modern. Increasing the efficiency of natural photosynthesis can also increase production of ethanol and other fuels derived from agriculture. However, knowledge gained from photosynthesis research can also be used to enhance energy production in a much more direct way. Although the overall photosynthesis process is relatively wasteful, the early steps in the conversion of sunlight to chemical energy are quite efficient. Why not learn to understand the basic chemistry and physics of photosynthesis, and use these same principles to build man-made solar energy harvesting devices? This has been a dream of chemists for years, but is now close to becoming a reality. In the laboratory, scientists can now synthesize artificial photosynthetic reaction centers which rival the natural ones in terms of the amount of sunlight stored as chemical or electrical energy. More research will lead to the development of new, efficient solar energy harvesting technologies based on the natural process.

The role of photosynthesis in control of the environment. How does photosynthesis in temperate and tropical forests and in the sea affect the quantity of greenhouse gases in the atmosphere? This is an important and controversial issue today. As mentioned above, photosynthesis by plants removes carbon dioxide from the atmosphere and replaces it with oxygen. Thus, it would tend to ameliorate the effects of carbon dioxide released by the burning of fossil fuels. However, the question is complicated by the fact that plants themselves react to the amount of carbon dioxide in the atmosphere. Some plants, appear to grow more rapidly in an atmosphere rich in carbon dioxide, but this may not be true of all species. Understanding the effect of greenhouse gases requires a much better knowledge of the interaction of the plant kingdom with carbon dioxide than we have today. Burning plants and plant products such as petroleum releases carbon dioxide and other byproducts such as hydrocarbons and nitrogen oxides. However, the pollution caused by such materials is not a necessary product of solar energy utilization. The artificial photosynthetic reaction centers discussed above produce energy without releasing any byproducts other than heat. They hold the promise of producing clean energy in the form of electricity or hydrogen fuel without pollution. Implementation of such solar energy harvesting devices would prevent pollution at the source, which is certainly the most efficient approach to control.

Photosynthesis and electronics. At first glance, photosynthesis would seem to have no association with the design of computers and other electronic devices. However, there is potentially a very strong connection. A goal of modern electronics research is to make transistors and other circuit components as small as possible. Small devices and short connections between them make computers faster and more compact. The smallest possible unit of a material is a molecule (made up of atoms of various types). Thus, the smallest conceivable transistor is a single molecule (or atom). Many researchers today are investigating the intriguing possibility of making electronic components from single molecules or small groups of molecules. Another very active area of research is computers that use light, rather than electrons, as the medium for carrying information. In principle, light-based computers have several advantages over traditional designs, and indeed many of our telephone transmission and switching networks already operate through fiber optics. What does this have to do with photosynthesis? It turns out that photosynthetic reaction centers are natural photochemical switches of molecular dimensions. Learning how plants absorb light, control the movement of the resulting energy to reaction centers, and convert the light energy to electrical, and finally chemical energy can help us understand how to make molecular-scale computers. In fact, several molecular electronic logic elements based on artificial photosynthetic reaction centers have already been reported in the scientific literature.

Photosynthesis and medicine. Light has a very high energy content, and when it is absorbed by a substance this energy is converted to other forms. When the energy ends up in the wrong place, it can cause serious damage to living organisms. Aging of the skin and skin cancer are only two of many deleterious effects of light on humans and animals. Because plants and other photosynthetic species have been dealing with light for eons, they have had to develop photoprotective mechanisms to limit light damage. Learning about the causes of light- induced tissue damage and the details of the natural photoprotective mechanisms can help us can find ways to adapt these processes for the benefit of humanity in areas far removed from photosynthesis itself. For example, the mechanism by which sunlight absorbed by photosynthetic chlorophyll causes tissue damage in plants has been harnessed for medical purposes. Substances related to chlorophyll localize naturally in cancerous tumor tissue. Illumination of the tumors with light then leads to photochemical damage which can kill the tumor while leaving surrounding tissue unharmed. Another medical application involves using similar chlorophyll relatives to localize in tumor tissue, and thus act as dyes which clearly delineate the boundary between cancerous and healthy tissue. This diagnostic aid does not cause photochemical damage to normal tissue because the principles of photosynthesis have been used to endow it with protective agents that harmlessly convert the absorbed light to heat.

Conclusions

The above examples illustrate the importance of photosynthesis as a natural process and the impact that it has on all of our lives. Research into the nature of photosynthesis is crucial because only by understanding photosynthesis can we control it, and harness its principles for the betterment of mankind. Science has only recently developed the basic tools and techniques needed to investigate the intricate details of photosynthesis. It is now time to apply these tools and techniques to the problem, and to begin to reap the benefits of this research.

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revised Friday, August 14, 1998