CHAPTER 7

Photosynthesis: Using Light to Make Food

Objectives

Introduction Describe the ways that plants use and react to light.

An Overview of Photosynthesis

7.1 Define the terms autotroph and producer.
7.2 Describe the structure and location of chloroplasts in a leaf.
7.3 Explain how plants produce oxygen.
7.4 Explain how photosynthesis is based upon redox reactions.
7.5 Compare the reactants and products of the light reactions and the Calvin cycle. Explain how the term photosynthesis relates to these reactions.

The Light Reactions: Converting Solar Energy to Chemical Energy

7.6 Describe the properties and functions of the different photosynthetic pigments.
7.7 Explain how photosystems capture solar energy.
7.8–7.9 Explain how the electron transport chain and chemiosmosis generate ATP, NADPH, and oxygen in the light reactions.

The Calvin Cycle: Converting CO_2 to Sugars

7.10 Describe the reactants and products of the Calvin cycle. Explain why this cycle is dependent upon the light reactions.

Photosynthesis Reviewed and Extended

7.11 Review the overall process of the light reactions and the Calvin cycle, noting the products, reactants, and locations of each major step.
7.12 Compare the mechanisms that C_3, C_4, and CAM plants use to obtain carbon dioxide. Note examples of plants that use these systems.

Photosynthesis, Solar Radiation, and Earth's Atmosphere

7.13 Describe the greenhouse effect and explain how deforestation and the use of fossil fuels affect this phenomenon.
7.14 Explain how the ozone layer forms, how human activities have damaged it, and the consequences of the destruction of the ozone layer.

Key Terms

autotroph	stoma	granum
producer	stroma	light reactions
mesophyll	thylakoid	Calvin cycle

- carbon fixation
- electromagnetic energy
- wavelength
- photon
- reaction center
- photosystem
- photophosphorylation
- C_3 plant
- photorespiration
- C_4 plant
- CAM plant
- greenhouse effect
- global warming

Word Roots

auto- = self; **-troph** = food (*autotroph:* an organism that obtains organic food molecules without eating other organisms)

meso- = middle (*mesophyll:* the green tissue in the middle, inside of a leaf)

photo- = light (*photosystem:* cluster of pigment molecules)

Lecture Outline

Introduction *Life in the Sun*

A. Light is central to life on Earth. Plants (and other autotrophs) capture energy from the sun to synthesize energy-rich organic molecules by the process of **photosynthesis.** Virtually all other species on Earth (that are not autotrophs) use the energy-rich molecules produced by plants directly or indirectly as a source of food.

B. Review the overall equation for photosynthesis, and note that it is the reverse of cellular respiration (Figure A).

C. Light from the sun has other roles for plants besides photosynthesis. Increased sunlight during spring and summer triggers the production of flowers. Variations in the amount of sunlight can alter the structure and appearance of a plant (Figure B).

I. An Overview of Photosynthesis

Module 7.1 Autotrophs are the producers of the biosphere.

A. **Autotroph** means "self-feeder" and the term is applied to any organism that makes its own food without eating, decomposing, or absorbing other organisms or organic molecules.

B. Autotrophs produce the biosphere's food supply (Module 36.8).

C. **Producers** include plants, some bacteria, some archaea, and some protists. (Figure 7.1A–D). Producers that utilize light energy are referred to as photosynthetic producers. *NOTE:* We will return to the term *producer* in our discussion of community ecology and the flow of energy among different kinds of organisms (Chapter 36).

Module 7.2 Photosynthesis occurs in chloroplasts (review Figures 2.1 and 4.15).

A. This is true for all photosynthetic organisms except prokaryotes, and it is true for all green parts of plants.
NOTE: It is also true for the not-quite-so-green parts of other photosynthetic eukaryotes.

B. In most plants, the leaves and, specifically, mesophyll cells are the dominant photosynthetic locations (Figure 7.2).

C. Other structures in leaves provide entries and exits for the reactants and products of the process: CO_2 and O_2 diffuse through stomata; H_2O moves through veins from the roots.

D. Within the **stroma** of chloroplasts, carbon dioxide is built up into sugars.

E. The green pigment that absorbs light energy is chlorophyll, which is located in **thylakoid** membranes (stacks of thylakoids are called grana) within the chloroplasts.

NOTE: Ask students to note the parallels between photosynthesis and cellular respiration, particularly in the types of underlying processes and the locations in which these processes occur, but be careful not to confuse the two sequences.

Module 7.3 Plants produce O_2 gas by splitting water.

A. Experiments in the 1950s tested the early hypothesis of Ingenhousz that the oxygen given off in photosynthesis came from the reactant CO_2 (Figure 7.3A). Two experiments used ^{18}O-labeled reactants as tracers (see Module 2.5; Figure 7.3B).
NOTE: The splitting of water in photosynthesis is the major source of O_2 in the atmosphere.

B. A plant given $C^{18}O_2$ did not give off $^{18}O_2$.

C. A plant given $H_2{}^{18}O$ did give off $^{18}O_2$.

D. Additional experiments have confirmed where other atoms in the products come from (Figure 7.3C).
NOTE: In Figure 7.3B and C, the overall equation for photosynthesis is written a bit differently, showing that water is both a reactant and a product. It takes 2 water molecules to get enough oxygen atoms to make 1 oxygen molecule. Since 6 molecules of oxygen are generated for each molecule of glucose formed, 12 water molecules are needed and some new water is formed at the end, with oxygen coming from the CO_2 and hydrogens from the original water molecules.

Module 7.4 Photosynthesis is a redox process, as is cellular respiration.

A. When H_2O molecules are split, yielding O_2, the water molecules are oxidized, giving up their electrons (and H^+ ions) (Figure 7.4A).

B. At the same time, CO_2 molecules are reduced to glucose as electrons and H^+ ions are added to them.

C. Compare this to the reverse overall reaction in cellular respiration (Module 6.4), where glucose is oxidized and oxygen is reduced (Figure 7.4B).

D. In photosynthesis, the electrons travel "uphill" from the water to the glucose, adding the light energy captured by chlorophyll (endergonic reactions).

E. In cellular respiration, the electrons travel "downhill" from the glucose to the water, giving up their energy to ATP (exergonic reactions).

Module 7.5 Overview: Photosynthesis occurs in two stages linked by ATP and NADPH.

A. **Light reactions:** steps that convert light energy to chemical energy and produce O_2 gas as a waste product. These reactions occur in the thylakoid membranes and produce chemical energy shuttles in the form of ATP and energized electron shuttles in the form of NADPH. Light is required for these steps (Figure 7.5).
NOTE: O_2 is produced as a waste product. When aerobic photosynthesis evolved, for many organisms oxygen was (as it still is for certain organisms) a toxin, something to be avoided.

B. **Calvin cycle:** a cyclic series of steps that assemble glucose from CO_2 molecules. These reactions occur in the stroma (the fluid outside the thylakoids but inside the inner chloroplast membrane) and use the energy and electrons from ATP and NADPH in **"carbon fixation."** Light is not directly required, but because production of the shuttles (ATP and NADPH) requires light, the Calvin cycle steps usually occur during daytime (Figure 7.5).

II. The Light Reactions: Converting Solar Energy to Chemical Energy

Module 7.6 Visible radiation drives the light reactions.

A. Light is a type of energy called radiation, or **electromagnetic energy,** which travels in rhythmic waves (Figure 7.6A).

B. Only a small fraction of electromagnetic radiation can be perceived by organisms. Humans perceive visible light of different **wavelengths** as different colors.

C. During the light reactions, a leaf absorbs some light wavelengths (blue-violet and red-orange) and not others (what we see is reflected as green light) (Figure 7.6B).

D. A variety of pigments are involved in absorbing light of different wavelengths (in plants, chlorophyll *a,* chlorophyll *b,* and carotenoids).

E. In plants, only chlorophyll *a* participates directly in the light reactions. The other pigments function to broaden the range of energy absorbed and convey this additional trapped energy to the chlorophyll *a.*

F. While some carotenoids absorb light energy that will be used in photosynthesis, other carotenoids protect chlorophyll from the damaging effects of excessive light energy.
NOTE: Carotenoids are vitamin A precursors (Modules 21.17 and 2.17).

Module 7.7 Photosystems capture solar power.

A. In addition to behaving as waves, light also behaves as discrete packets of energy called **photons.**

B. When a pigment absorbs a photon, the energy of one of the pigment's electrons is raised to an excited, unstable state.
NOTE: The molecular structure of chlorophyll *a* is perfectly suited as a light trapper, containing many double bonds that expose many electron clouds to the passing radiation.

C. In some cases, if the pigment is isolated from its surrounding molecular environment, the excited electron will lose its energy, return to the normal level, and emit heat or light (fluorescence). For instance, chlorophyll *a* fluoresces red (Figure 7.7A).

D. In contrast, in intact chloroplasts, the excited electrons are passed (the chlorophyll at the reaction center is oxidized) to a neighboring molecule, the primary electron acceptor (reduction) (Figure 7.7B).

E. Within the thylakoid membranes, many pigment molecules (200–300) are grouped with associated proteins into an antenna assembly, but only a single chlorophyll *a* molecule acts as the reaction center (Figure 7.7C).

F. Two **photosystems** (antenna assembly + **reaction center** + primary electron acceptor) have been identified, which differ in the wavelengths of peak light absorption: photosystem I (P700) and photosystem II (P680).
NOTE: If you look at Figures 4.15 and 7.2 you will see that the thylakoid membrane is continuous. The different grana are connected by thylakoid membranes called stroma lamellae. The stroma lamellae mainly bear PS I, the grana mainly PS II.

Module 7.8 In the light reactions, electron transport chains generate ATP, NADPH, and O_2.

A. The kinetic energy of light is absorbed.

B. The absorbed energy excites electrons.

C. The excited electrons are passed along an electron transport chain in a series of redox reactions.

D. The energy released by these redox reactions is used to generate ATP, NADPH, and O_2.

E. The production of NADPH requires 2 electrons. Photosystem I gets these electrons from photosystem II. Photosystem II gets its electrons from the splitting of water, a process that also produces 2 H^+ and ½ O_2 (Figure 7.8).
NOTE: There is evidence that manganese cations are directly involved in the splitting of H_2O.

Module 7.9 Chemiosmosis powers ATP synthesis in the light reactions.

A. The energy released from the electron transport chain is used to pump H^+ ions (formed when water was split) from the stroma across the thylakoid membrane to the interior of the thylakoids. This creates a concentration gradient across the thylakoid membrane (Figure 7.9).
Review: (Modules 5.1 and 5.14) Concentration gradients are a form of kinetic energy.

B. ATP synthase provides a port through which the H^+ ions can diffuse (potential energy) back into the stroma, releasing energy that is used to phosphorylate ADP to ATP.

C. This process, by which light provides energy for the chemiosmotic production of ATP, is known as **photophosphorylation.**

D. This process is very similar to chemiosmosis in mitochondria (Module 6.12).

III. The Calvin Cycle: Converting CO_2 to Sugars

Module 7.10 ATP and NADPH power sugar synthesis in the Calvin cycle.

A. The net result of the Calvin cycle is the synthesis of a phosphorylated, three-carbon molecule, glyceraldehyde-3-phosphate (G3P) from three carbon dioxide molecules. The energy and electrons are provided by ATP and NADPH from the light reactions (Figure 7.10A).

B. Each CO_2 molecule is added to a five-carbon intermediate (RuBP, for ribulose bisphosphate) catalyzed by the enzyme RuBP carboxylase (rubisco) (Figure 7.10B).

C. A number of rearrangements of molecules occur in many steps, some involving the use of energy from ATP, some oxidizing the NADPH (the reactants in these being reduced at the same time).

D. The last step of the cycle is the regeneration of the RuBP. The reactions involve considerable rearrangements of structure; all are proceeding at once, and since the steps ultimately regenerate one of the starting reactants, they can be regarded as occurring in a cycle.

E. It takes three molecules of CO_2 entering into the cycle for every G3P produced.

F. G3P can be used to make glucose or other organic compounds.

G. The Calvin cycle takes place in the chloroplast stroma.

IV. Photosynthesis Reviewed and Extended

Module 7.11 Review: Photosynthesis uses light energy to make food molecules.

A. Photosynthesis is a two-part process—the trapping of energy and then using that energy to produce sugar molecules (Figure 7.11).

B. Sugar molecules a plant produces are the plant's own food supply, expended during cellular respiration.

C. Plants use sugars as building blocks for other organic compounds, including cellulose.

D. Plants, and other photosynthesizers, are the ultimate source of food for all other organisms.

Module 7.12 C_4 and CAM plants have special adaptations that save water.

A. Plants that use only the Calvin cycle to fix carbon are known as **C_3 plants** (Figure 7.12A).

B. When normal C_3 plants try to conserve water by closing their leaf pores, oxygen is fixed to RuBP by rubisco rather than CO_2, since new CO_2 is not able to enter the plant. This is called **photorespiration,** and it yields no sugar molecules and produces no ATP.

C. **C_4 plants** have special adaptations that conserve water and prevent photorespiration (Figure 7.12B). These adaptations involve producing four-carbon compounds with a special enzyme in separate cells during hot, dry weather when the stomata are closed and the CO_2 concentration is much lower than the O_2 concentration. In other cells where the Calvin cycle is still operating, the four-carbon compounds are broken down to release CO_2 to complete the cycle. C_4 metabolism is found in corn, sorghum, and sugarcane.

D. **CAM (crassulacean acid metabolism) plants** form CO_2 into four-carbon compounds with another special enzyme at night, when temperatures are lower, humidity higher, and CO_2 more available (Figure 7.12C). During the day, the four-carbon compounds are released to the Calvin cycle. CAM is found in several different types of succulent plants, such as cacti, pineapples, and jade plants.

V. Photosynthesis, Solar Radiation, and the Earth's Atmosphere

Module 7.13 Human activity is causing global warming; photosynthesis moderates it.

A. Radiant energy from the sun is trapped in a greenhouse that can then be used to grow plants when the weather is too cold to grow them outside (Figure 7.13A).

B. In the atmosphere, CO_2 retains heat from the sun that would otherwise radiate back into space. This is the basis for the **greenhouse effect** (Figure 7.13B).

C. Burning fossil fuels (oil, coal, and gas) and wood releases excess CO_2, which may be causing **global warming.** There has been a 30% increase in atmospheric CO_2 content since the start of the industrial revolution.
Preview: The greenhouse effect is revisited in Chapter 38 (Module 38.4).

D. Photosynthesizers are a natural CO_2 sink and can moderate the effect of fossil fuels burning. However, a decrease in the world's forest has paralleled the increase in global warming.

Module 7.14 Talking About Science: Mario Molina talks about the Earth's protective ozone layer.

Preview: Module 38.3.

A. In the atmosphere O_2 is converted into O_3 (ozone) by high-energy solar radiation. Atmospheric ozone is also destroyed by compounds that are natural components of the atmosphere.

B. The ozone layer shields the surface of the Earth from UV radiation. UV radiation is damaging to life. For example, it can cause cancer in humans and damage crops.

C. Chlorofluorocarbons (CFCs) are human-made chemicals that were used as refrigerants, as propellants, and in other industrial processes. CFCs deplete ozone and this results in increased UV radiation reaching the Earth's surface.

D. CFC production has been banned in developed countries and will be phased out of use in developing countries. However, CFCs are very stable and are expected to remain in the atmosphere, damaging the ozone layer. Dr. Molina predicts that the ozone layer will not recover until the middle of the next century. Since the ban on CFC usage began in 1996, there has been a steady decline in CFC production.

E. Molina points out that the long-term environmental and economic costs of *not* dealing with environmental issues are greater than the short-term costs of dealing with these issues.

Class Activities

1. With a prism, demonstrate the spectrum of wavelengths in visible light.
2. Set up a demonstration using paper or thin-layer chromatography to separate the pigments in a leaf. The visual spread of pigments supports the multipigment makeup of photosystems, a fact that is not immediately apparent.
3. If the facilities are available, demonstrate some of the controlling factors in photosynthesis, using *Elodea* (or other aquatic plants available from aquarium supply stores). Set this up several hours before lecture. Trap the *Elodea* and its emitted oxygen bubbles in inverted, water-filled test tubes. One experimental setup could contain boiled water (to remove the CO_2). Use an unfiltered bright light, several different cellophane filters, and aluminum foil around different test tubes to show the efficiency of photosynthesis at different wavelengths. A glowing splint thrust into the gas will demonstrate its chemical makeup. In introducing these experiments, be sure to discuss experimental procedure, including the use of controls.
4. Ask students to describe the parallels between photosynthesis and cellular respiration, particularly in the types of underlying processes and the locations in which these processes occur.
5. Other than the obvious, a greenhouse, ask your class if they can think of any situations that are analogous to the greenhouse effect. The one that always comes to mind is how the interior of a car can get hot on a sunny day even if it is not particularly hot outside.
6. How might a full-blown greenhouse effect affect the particular location of your school? Will your location end up under water? become a desert? Perhaps the greenhouse effect will improve the climate of your region. Which countries would suffer the most/least from greenhouse conditions? Have your students contrast the United States with low-lying nations such as Bangladesh and island nations such as Great Britain.

Transparency Acetates

Chapter 7 Introduction: The chemical equation for photosynthesis

Figure 7.2	The location and structure of chloroplasts
Figure 7.3B	Experiments tracking the oxygen atoms in photosynthesis
Figure 7.3C	Fates of all the atoms in photosynthesis
Figure 7.4A	Photosynthesis (uses light energy)
Figure 7.4B	Cellular respiration (releases chemical energy)
Figure 7.5	An overview of photosynthesis (Layer 1)
Figure 7.5	An overview of photosynthesis (Layer 2)
Figure 7.5	An overview of photosynthesis (Layer 3)
Figure 7.6A	The electromagnetic spectrum

Figure 7.6B	The interaction of light with a chloroplast
Figure 7.7A	Fluorescence of isolated chlorophyll in solution
Figure 7.7B	Excitation of chlorophyll in a chloroplast
Figure 7.7C	Components of a photosystem
Figure 7.8	Photon and electron flow in the light reactions of photosynthesis
Figure 7.9	The production of ATP by chemiosmosis in photosynthesis
Figure 7.10A	An overview of the Calvin cycle
Figure 7.10B	Details of the Calvin cycle (Layer 1)
Figure 7.10B	Details of the Calvin cycle (Layer 2)
Figure 7.10B	Details of the Calvin cycle (Layer 3)
Figure 7.11	A summary of the chemical processes of photosynthesis
Figure 7.12A	Photorespiration in a C_3 plant
Figure 7.12B	Carbon fixation in a C_4 plant
Figure 7.12C	Carbon fixation in a CAM plant
Figure 7.13B	The greenhouse effect of CO_2 in the atmosphere
Figure 7.14B	The ozone hole in the Southern Hemisphere, Spring 2000

Thinking as a Scientist Question 2: Graph measuring the effect of light intensity on photosynthesis

Media

See the beginning of this book for a complete description of all media available for instructors and students. Animations and videos are available in the Campbell Image Presentation Library. Media Activities and Thinking as a Scientist investigations are available on the student CD-ROM and web site.

Animations and Videos	File Name
Light Reactions Animation	07-09-LightReactionsAnim.mov
Calvin Cycle Animation	07-10B-CalvinCycleAnim.mov

Activities and Thinking as a Scientist	Module Number
Web/CD Activity 7A: *The Sites of Photosynthesis*	7.2
Web/CD Activity 7B: *Overview of Photosynthesis*	7.5
Web/CD Activity 7C: *Light Energy and Pigments*	7.6
Web/CD Thinking as a Scientist: *How Does Paper Chromatography Separate Plant Pigments?*	7.6
Web/CD Activity 7D: *The Light Reactions*	7.9
Web/CD Activity 7E: *The Calvin Cycle*	7.10
Web/CD Thinking as a Scientist: *How Is the Rate of Photosynthesis Measured?*	7.11
Biology Labs On-Line: *LeafLab*	7.11
Web/CD Activity 7F: *Photosynthesis in Dry Climates*	7.12