Chapter 7 Photosynthesis: Using Light to Make Food

Introduction

- Plants, algae, and certain prokaryotes
  - convert light energy to chemical energy and
  - store the chemical energy in sugar, made from
    - carbon dioxide and
    - water.

- Algae farms can be used to produce
  - oils for biodiesel or
  - carbohydrates to generate ethanol.
7.1 Autotrophs are the producers of the biosphere

**Autotrophs**
- make their own food through the process of **photosynthesis**, 
- sustain themselves, and 
- do not usually consume organic molecules derived from other organisms.

**Photoautotrophs** use the energy of light to produce organic molecules.

**Chemoautotrophs** are prokaryotes that use inorganic chemicals as their energy source.

**Heterotrophs** are consumers that feed on
- plants or
- animals, or
- decompose organic material.

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**Photosynthesis in plants**
- takes place in chloroplasts, 
- converts carbon dioxide and water into organic molecules, and 
- releases oxygen.
7.2 Photosynthesis occurs in chloroplasts in plant cells

- Chloroplasts are the major sites of photosynthesis in green plants.

- **Chlorophyll**
  - is an important light-absorbing pigment in chloroplasts,
  - is responsible for the green color of plants, and
  - plays a central role in converting solar energy to chemical energy.

- Chloroplasts are concentrated in the cells of the **mesophyll**, the green tissue in the interior of the leaf.

- **Stomata** are tiny pores in the leaf that allow
  - carbon dioxide to enter and
  - oxygen to exit.

- Veins in the leaf deliver water absorbed by roots.
7.2 Photosynthesis occurs in chloroplasts in plant cells

- Chloroplasts consist of an envelope of two membranes, which
  - enclose an inner compartment filled with a thick fluid called stroma and
  - contain a system of interconnected membranous sacs called thylakoids.

- Thylakoids
  - are often concentrated in stacks called grana and
  - have an internal compartment called the thylakoid space, which has functions analogous to the intermembrane space of a mitochondrion.
  - Thylakoid membranes also house much of the machinery that converts light energy to chemical energy.

- Chlorophyll molecules
  - are built into the thylakoid membrane and
  - capture light energy.

7.3 SCIENTIFIC DISCOVERY: Scientists traced the process of photosynthesis using isotopes

- Scientists have known since the 1800s that plants produce O₂. But does this oxygen come from carbon dioxide or water?
  - For many years, it was assumed that oxygen was extracted from CO₂ taken into the plant.
  - However, later research using a heavy isotope of oxygen, \(^{18}O\), confirmed that oxygen produced by photosynthesis comes from H₂O.
7.3 SCIENTIFIC DISCOVERY: Scientists traced the process of photosynthesis using isotopes

- Experiment 1: $6 \text{CO}_2 + 12 \text{H}_2\text{O} \rightarrow \text{C}_6\text{H}_{12}\text{O}_6 + 6 \text{H}_2\text{O} + 6 \text{O}_2$
- Experiment 2: $6 \text{CO}_2 + 12 \text{H}_2\text{O} \rightarrow \text{C}_6\text{H}_{12}\text{O}_6 + 6 \text{H}_2\text{O} + 6 \text{O}_2$

7.4 Photosynthesis is a redox process, as is cellular respiration

- Photosynthesis, like respiration, is a redox (oxidation-reduction) process.
  - CO$_2$ becomes reduced to sugar as electrons along with hydrogen ions from water are added to it.
  - Water molecules are oxidized when they lose electrons along with hydrogen ions.

- Cellular respiration uses redox reactions to harvest the chemical energy stored in a glucose molecule.
  - This is accomplished by oxidizing the sugar and reducing O$_2$ to H$_2$O.
  - The electrons lose potential as they travel down the electron transport chain to O$_2$.
  - In contrast, the food-producing redox reactions of photosynthesis require energy.
7.4 Photosynthesis is a redox process, as is cellular respiration

- In photosynthesis,
  - light energy is captured by chlorophyll molecules to boost the energy of electrons,
  - light energy is converted to chemical energy, and
  - chemical energy is stored in the chemical bonds of sugars.

7.5 Overview: The two stages of photosynthesis are linked by ATP and NADPH

- Photosynthesis occurs in two metabolic stages.
  1. The light reactions occur in the thylakoid membranes. In these reactions
     - water is split, providing a source of electrons and giving off oxygen as a by-product,
     - ATP is generated from ADP and a phosphate group, and
     - light energy is absorbed by the chlorophyll molecules to drive the transfer of electrons and H⁺ from water to the electron acceptor NADP⁺ reducing it to NADPH.
     - NADPH produced by the light reactions provides the electrons for reducing carbon in the Calvin cycle.
  2. The second stage is the Calvin cycle, which occurs in the stroma of the chloroplast.
     - The Calvin cycle is a cyclic series of reactions that assembles sugar molecules using CO₂ and the energy-rich products of the light reactions.
     - During the Calvin cycle, CO₂ is incorporated into organic compounds in a process called carbon fixation.
     - After carbon fixation, enzymes of the cycle make sugars by further reducing the carbon compounds.
     - The Calvin cycle is often called the dark reactions or light-independent reactions, because none of the steps requires light directly.
The Light Reactions: Converting Solar Energy to Chemical Energy

7.6 Visible radiation absorbed by pigments drives the light reactions

- Sunlight contains energy called electromagnetic energy or electromagnetic radiation.
  - Visible light is only a small part of the electromagnetic spectrum, the full range of electromagnetic wavelengths.
  - Electromagnetic energy travels in waves, and the wavelength is the distance between the crests of two adjacent waves.

- Light behaves as discrete packets of energy called photons.
  - A photon is a fixed quantity of light energy.
  - The shorter the wavelength, the greater the energy.

- Pigments—absorb light and are built into the thylakoid membrane.
- Plant pigments—absorb some wavelengths of light and reflect or transmit other wavelengths.
- We see the color of the wavelengths that are transmitted. For example, chlorophyll transmits green wavelengths.
7.6 Visible radiation absorbed by pigments drives the light reactions

- Chloroplasts contain several different pigments, which absorb light of different wavelengths.
  - Chlorophyll a absorbs blue-violet and red light and reflects green.
  - Chlorophyll b absorbs blue and orange and reflects yellow-green.
  - Carotenoids
    - broaden the spectrum of colors that can drive photosynthesis and
    - provide photoprotection, absorbing and dissipating excessive light energy that would otherwise damage chlorophyll or interact with oxygen to form reactive oxidative molecules.

7.7 Photosystems capture solar energy

- Pigments in chloroplasts absorb photons (capturing solar power), which
  - increases the potential energy of the pigment’s electrons and
  - sends the electrons into an unstable state.
  - These unstable electrons
    - drop back down to their "ground state," and as they do,
    - release their excess energy as heat.
7.7 Photosystems capture solar energy

- A photosystem consists of a number of light-harvesting complexes surrounding a reaction-center complex.
- A light-harvesting complex contains various pigment molecules bound to proteins.
- Collectively, the light-harvesting complexes function as a light-gathering antenna.

The light energy is passed from molecule to molecule within the photosystem.
- Finally it reaches the reaction center where a primary electron acceptor accepts these electrons and consequently becomes reduced.
- This solar-powered transfer of an electron from the reaction-center pigment to the primary electron acceptor is the first step in the transformation of light energy to chemical energy in the light reactions.

- Within a thylakoid membrane, chlorophyll and other pigment molecules
  - absorb photons and
  - transfer the energy to other pigment molecules.
- In the thylakoid membrane, chlorophyll molecules are organized along with other pigments and proteins into photosystems.

Two types of photosystems (photosystem I and photosystem II) cooperate in the light reactions.
- Each type of photosystem has a characteristic reaction center.
  - Photosystem II, which functions first, is called P680 because its pigment absorbs light with a wavelength of 680 nm.
  - Photosystem I, which functions second, is called P700 because it absorbs light with a wavelength of 700 nm.
In the light reactions, light energy is transformed into the chemical energy of ATP and NADPH. To accomplish this, electrons are
- removed from water,
- passed from photosystem II to photosystem I, and
- accepted by NADP⁺, reducing it to NADPH.
Between the two photosystems, the electrons
- move down an electron transport chain and
- provide energy for the synthesis of ATP.

The products of the light reactions are
- NADPH,
- ATP, and
- oxygen.
7.9 Chemiosmosis powers ATP synthesis in the light reactions

- Interestingly, chemiosmosis is the mechanism that
  - is involved in oxidative phosphorylation in mitochondria and
  - generates ATP in chloroplasts.

- ATP is generated because the electron transport chain produces a concentration gradient of hydrogen ions across a membrane.

In photophosphorylation, using the initial energy input from light,
- the electron transport chain pumps H⁺ into the thylakoid space, and
- the resulting concentration gradient drives H⁺ back through ATP synthase, producing ATP.

How does photophosphorylation compare with oxidative phosphorylation?
- Mitochondria use oxidative phosphorylation to transfer chemical energy from food into the chemical energy of ATP.
- Chloroplasts use photophosphorylation to transfer light energy into the chemical energy of ATP.

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7.10 ATP and NADPH power sugar synthesis in the Calvin cycle

- The Calvin cycle makes sugar within a chloroplast.
- To produce sugar, the necessary ingredients are
  - atmospheric CO₂ and
  - ATP and NADPH generated by the light reactions.
- The Calvin cycle uses these three ingredients to produce an energy-rich, three-carbon sugar called glyceraldehyde-3-phosphate (G3P).
- A plant cell may then use G3P to make glucose and other organic molecules.

7.10 ATP and NADPH power sugar synthesis in the Calvin cycle

- The steps of the Calvin cycle include
  - carbon fixation,
  - reduction,
  - release of G3P, and
  - regeneration of the starting molecule ribulose bisphosphate (RuBP).
7.11 EVOLUTION CONNECTION: Other methods of carbon fixation have evolved in hot, dry climates

- In hot and dry weather, C₃ plants
  - close their stomata to reduce water loss but
  - prevent CO₂ from entering the leaf and O₂ from leaving.
  - As O₂ builds up in a leaf, rubisco adds O₂ instead of CO₂ to RuBP, and a two-carbon product of this reaction is then broken down in the cell.
  - This process is called photorespiration because it occurs in the light, consumes O₂, and releases CO₂.
  - But unlike cellular respiration, it uses ATP instead of producing it.

- C₄ plants have evolved a means of
  - carbon fixation that saves water during photosynthesis while
  - optimizing the Calvin cycle.

- C₄ plants are so named because they first fix CO₂ into a four-carbon compound.
- When the weather is hot and dry, C₄ plants keep their stomata mostly closed, thus conserving water.

Another adaptation to hot and dry environments has evolved in the CAM plants, such as pineapples and cacti:

- CAM plants conserve water by opening their stomata and admitting CO₂ only at night.
- CO₂ is fixed into a four-carbon compound,
  - which banks CO₂ at night and
  - releases it to the Calvin cycle during the day.
PHOTOSYNTHESIS REVIEWED AND EXTENDED

7.12 Review: Photosynthesis uses light energy, carbon dioxide, and water to make organic molecules

- Most of the living world depends on the food-making machinery of photosynthesis.
- The chloroplast
  - integrates the two stages of photosynthesis and
  - makes sugar from CO₂.
- About half of the carbohydrates made by photosynthesis are consumed as fuel for cellular respiration in the mitochondria of plant cells.
- Sugars also serve as the starting material for making other organic molecules, such as proteins, lipids, and cellulose.
- Excess food made by plants is stockpiled as starch in roots, tubers, seeds, and fruits.
7.13 CONNECTION: Photosynthesis may moderate global climate change

- The greenhouse effect operates on a global scale.
  - Solar radiation includes visible light that penetrates the Earth’s atmosphere and warms the planet's surface.
  - Heat radiating from the warmed planet is absorbed by gases in the atmosphere, which then reflects some of the heat back to Earth.
  - Without the warming of the greenhouse effect, the Earth would be much colder and most life as we know it could not exist.

- The gases in the atmosphere that absorb heat radiation are called greenhouse gases. These include
  - water vapor,
  - carbon dioxide, and
  - methane.

- Increasing concentrations of greenhouse gases have been linked to global climate change (also called global warming), a slow but steady rise in Earth’s surface temperature.
  - Since 1850, the atmospheric concentration of CO₂ has increased by about 40%, mostly due to the combustion of fossil fuels including
    - coal,
    - oil, and
    - gasoline.
7.13 CONNECTION: Photosynthesis may moderate global climate change

- The predicted consequences of continued warming include
  - melting of polar ice,
  - rising sea levels,
  - extreme weather patterns,
  - droughts,
  - increased extinction rates, and
  - the spread of tropical diseases.

7.13 CONNECTION: Photosynthesis may moderate global climate change

- Widespread deforestation has aggravated the global warming problem by reducing an effective CO₂ sink.
- Global warming caused by increasing CO₂ levels may be reduced by
  - limiting deforestation,
  - reducing fossil fuel consumption, and
  - growing biofuel crops that remove CO₂ from the atmosphere.

7.14 SCIENTIFIC DISCOVERY: Scientific study of Earth’s ozone layer has global significance

- Solar radiation converts O₂ high in the atmosphere to ozone (O₃), which shields organisms from damaging UV radiation.
- Industrial chemicals called CFCs have caused dangerous thinning of the ozone layer, but international restrictions on CFC use are allowing a slow recovery.

You should now be able to

1. Define autotrophs, heterotrophs, producers, and photoautotrophs.
2. Describe the structure of chloroplasts and their location in a leaf.
3. Explain how plants produce oxygen.
4. Describe the role of redox reactions in photosynthesis and cellular respiration.
5. Compare the reactants and products of the light reactions and the Calvin cycle.
You should now be able to

6. Describe the properties and functions of the different photosynthetic pigments.
7. Explain how photosystems capture solar energy.
8. Explain how the electron transport chain and chemiosmosis generate ATP, NADPH, and oxygen in the light reactions.
9. Compare photophosphorylation and oxidative phosphorylation.
10. Describe the reactants and products of the Calvin cycle.

You should now be able to

11. Compare the mechanisms that C3, C4, and CAM plants use to obtain and use carbon dioxide.
12. Review the overall process of the light reactions and the Calvin cycle, noting the products, reactants, and locations of every major step.
13. Describe the greenhouse effect.
14. Explain how the ozone layer forms, how human activities have damaged it, and the consequences of the destruction of the ozone layer.