Chapter Outline

9.1 PHOTOSYNTHESIS: AN OVERVIEW
- Electrons play a primary role in photosynthesis
- In eukaryotes, photosynthesis takes place in chloroplasts

9.2 THE LIGHT-DEPENDENT REACTIONS OF PHOTOSYNTHESIS
- Electrons in pigment molecules absorb light energy in photosynthesis
- Chlorophylls and carotenoids cooperate in light absorption
- The photosynthetic pigments are organized into photosystems in chloroplasts
- Electrons flow from water to photosystem II to photosystem I to NADP⁺ leading to the synthesis of NADPH and ATP
- Electrons can also drive ATP synthesis by flowing cyclically around photosystem I
- Experiments with chloroplasts helped confirm the synthesis of ATP by chemiosmosis

9.3 THE LIGHT-INDEPENDENT REACTIONS OF PHOTOSYNTHESIS
- The Calvin cycle uses NADPH, ATP, and CO₂ to generate carbohydrates
- Three turns of the Calvin cycle are needed to make one net G3P molecule
- Rubisco is the key enzyme of the world’s food economy
- G3P is the starting point for synthesis of many other organic molecules

9.4 PHOTORESPiration AND THE C₄ CYCLE
- The oxygenase activity of rubisco leads to the formation of a toxic molecule
- Elevated temperatures increase the level of photorespiration in many plants
- The C₄ cycle circumvents photorespiration by using a carboxylase that has no oxygenase activity
- Some plants circumvent photorespiration by running C₄ and Calvin cycles in different locations
- Other plants control photorespiration by running the C₄ and Calvin cycles at different times

Unanswered Questions

Learning Objectives

After reading the chapter, you should be able to:

1. Understand the basic properties of light and how sunlight specifically affects pigments in plants.
2. Define where photosynthesis takes place and the two stages of photosynthesis.
3. Explain the importance of the proton gradient and why a final electron acceptor is necessary to maintain the gradient.
4. Analyze the difference between the cyclic and noncyclic reactions of photosynthesis.
5. Understand the importance of the generation of NADPH and the utilization of ATP in the reactions of photosynthesis.
6. Know the steps of the light-dependent and light-independent reactions. Know the raw materials (reactants) needed to start each step, the products made by each step, and where in the plant cell each step occurs.
7. Explain the difference between cyclic and noncyclic pathways in photosynthesis.
8. Explain how autotrophs use the intermediates as well as the products of photosynthesis in their own metabolism.
9. Apply their knowledge of photosynthesis to the impact autotrophs living in the oceans and on land have on global processes such as carbon cycling. Understand how this activity influences the global climate and discuss the role humans play in these events.

10. Explain the role of Rubisco to the world’s food economy.

**Key Terms**

- photosynthesis
- autotroph
- photoautotrophs
- heterotrophs
- light-dependent reactions
- light-independent reactions (Calvin Cycle)
- CO$_2$ fixation
- electromagnetic spectrum
- chlorophylls
- carotenoids
- absorption spectrum
- action spectrum
- photosystems
- photosystems I and II
- antenna complex
- reaction center
- plastoquinone
- cytochrome complex
- plastocyanin
- ferredoxin
- photophosphorylation
- cyclic electron flow
- Calvin cycle
- rubisco (RuBP carboxylase, oxygenase)
- photorespiration
- C$_4$ cycle
- phosphoenolpyruvate (PEP)
- PEP carboxylase
- mesophyll cells
- bundle sheath
- CAM plants (crassulacean acid metabolism)

**Lecture Outline**

A. Plants and algae use light energy to produce organic molecules like sugar.
B. Englemann’s experiment demonstrates light color that is needed.
C. Violet, blue, and red light release the most oxygen.
D. We now know that archaea and some bacteria can photosynthesize.

9.1 Photosynthesis: An Overview

A. Primary producers (autotrophs) produce organic molecules and serve to provide food to consumers (heterotrophs).
B. Decomposers finally break down the organic material.
C. Electrons play a primary role in photosynthesis.
   1. Light reaction and light-independent reactions (a.k.a. Calvin cycle)
      a. Light energy is converted into chemical energy: ATP and NADPH.
      b. This energy is used for CO$_2$ fixation.
      c. Added electrons and protons convert this into a sugar.
      d. Oxygen is released by the water-dependent reaction.
      e. Oxygen comes from the water not the CO$_2$ as shown by radioactive oxygen experiments.
   2. In eukaryotes, photosynthesis takes place in chloroplasts.
   3. An outer membrane covers the entire surface of the organelle.
   4. An inner membrane lies just inside the outer membrane.
   5. Between these is an intermembrane compartment.
   6. Fluid in the middle is called the stroma.
   7. Thylakoids, a third membrane system, are found in the stroma.
   8. Stacks of thylakoids are called grana.
   9. The grana are interconnected into stromal lamellae.
   10. The thylakoid membranes and stromal lamellae house the molecules that carry out the light-dependent reactions, including the light reaction pigments, electron transfer carriers, and ATP synthase enzymes.
   11. Stomata bring CO$_2$ into cells containing chloroplasts.
   12. Water and minerals are transported through the roots.
9.2 The Light-Dependent Reactions of Photosynthesis

A. These involve two main processes: light absorption and synthesis of NADPH and ATP.

B. Electrons in pigments absorb light energy.
   1. Electromagnetic spectrum
   2. Shorter wavelengths have greater energy.
   3. Humans see from 700–400 nm.
   4. Chlorophylls (yellow-green) and carotenoids (yellow-orange) absorb energy.
   5. Light is absorbed by the pigments.
   6. Energy is then either released, fluoresces, or goes to a primary acceptor.

C. Chlorophylls and carotenoids cooperate in light absorption.
   1. Carotenoids act as accessory pigments; they absorb light energy and pass it on to the chlorophylls.
   2. Chlorophyll has a magnesium atom at the center of the ring structure.
      a. Chlorophyll $a$ is found in plants, algae, and cyanobacteria.
      b. Chlorophyll $b$ is found only in plants and algae.
      c. The absorption spectrum is the wavelength of light used by a pigment.

D. Photosynthetic pigments are organized into photosystems.
   1. Photosystems are embedded into the thylakoids.
   2. Photosystems I and II collect different parts of the light reactions.
      a. Each photosystem has an antenna or light-harvesting complex.
      b. It also has a reaction center where chemical energy is produced.
      c. Photosystem I is called P700 due to the wavelength it absorbs.
      d. Photosystem II is called P680 for the same reason.

E. Electrons flow from water through photosystems to products.
   1. Electrons are produced by splitting of water: two per molecule of water.
   2. Electrons are sent through electron carriers in photosystem II.
   3. Then they are passed to photosystem I.
   4. Energy from this transfer is used to create a proton gradient.
   5. The proton gradient supplies energy to make ATP.
   6. Then they pass through photosystem I and make NADPH.
   7. NADPH supplies energy for CO$_2$ fixation.
   8. This is called the noncyclic reaction.

F. Cyclic electron flow system
   1. Electrons flow through the cytochrome complex to P700 of photosystem I excited by light energy then back to the cytochrome complex.
   2. Electrons are not used for NADPH production.
   3. Each cycle pumps one more proton pair across the membrane.

G. Experiments with chloroplasts confirm synthesis of ATP by chemiosmosis.
   1. Jagendorf and Uribe placed chloroplasts in darkness first, then in acidic medium, and then into a basic medium.
   2. The change in proton gradient resulted in synthesis of ATP.

9.3 The Light-Independent Reactions of Photosynthesis

A. NADPH reduces CO$_2$ into carbohydrates in the Calvin cycle.

B. Calvin uses CO$_2$, ATP, and NADPH and produces ADP, NADP, and glyceraldehyde-3-phosphate (G3P).

C. The dark reaction is separated into three phases.
   1. Carbon from CO$_2$ is added to ribulose 1,5-bisphosphate (RuBP) and produces two three-carbon 3-phosphoglycerate (3PGA) molecules.
   2. 3PGA is converted into G3P, another three-carbon molecule, which combines to form glucose.
   3. Regeneration occurs using some G3P to produce RuBP.

D. Three turns of the Calvin cycle are required for 1 surplus G3P.

E. Rubisco is the key enzyme of the world’s food economy.
   1. Rubisco is the first step of the Calvin cycle.
   2. Rubisco converts 100 billion tons of CO$_2$ into carbohydrates annually.

G. G3P is the starting point for synthesis of other molecules like sucrose, starch, and cellulose.

9.4 Photorespiration and the C$_4$ Cycle

A. Rubisco is oxygen-sensitive, and high oxygen is toxic to plants. This is known as photorespiration.

B. The C$_4$ cycle allows carbon dioxide to be fixed against a high oxygen gradient.

C. Oxygenase activity of rubisco leads to the formation of a toxic glycolate.
D. Increased temperatures can increase photorespiration rates.
E. The $C_4$ cycle uses a carboxylase with no oxygenase activity.
F. Some plants run $C_4$ and Calvin cycles in different locations.
G. Some plants run these processes at different times and are called CAM plants.