Chapter Outline

7.1 Photosynthetic Organisms
A. Photosynthesis Transforms Solar Energy
   1. Photosynthetic organisms (algae, plants, and cyanobacteria) transform solar energy into carbohydrates.
   2. If all carbohydrates produced were converted to coal, it would fill 100 cars per second.
   3. Except for the rare life based on chemosynthetic organisms, all food chains can be traced back to photosynthesizers.
   4. Organic molecules built by photosynthesis provide both the building blocks and energy for cells.
B. Flowering Plants as Photosynthesizers
   1. Raw materials for photosynthesis are carbon dioxide and water.
   2. Roots absorb the water and move it up vascular tissue in the stem until it reaches the leaf veins.
   3. Carbon dioxide enters a leaf through small openings called stomata.
   4. Carbon dioxide and water then diffuse into the chloroplasts, organelles that carry on photosynthesis.
   5. In chloroplasts, a double membrane encloses a fluid-filled space called the stroma.
   6. Even more internal membranes within stroma form flattened sacs called thylakoids, which are sometimes organized into stacks called grana.
   7. Spaces within all thylakoids are connected and form an inner compartment or thylakoid space.
   4. Chlorophylls and other pigments involved in absorption of solar energy reside within thylakoid membranes; these pigments absorb solar energy, energize electrons prior to reduction of CO₂ to a carbohydrate.

7.2 Plants as Solar Energy Converters
A. Solar Radiation
   1. Only 42% of solar radiation that hits the earth’s atmosphere reaches surface; most is visible light.
   2. Higher energy wavelengths are screened out by ozone layer in upper atmosphere.
   3. Lower energy wavelengths are screened out by water vapor and CO₂.
   4. Both the organic molecules within organisms and processes such as vision and photosynthesis are adapted to the radiation that is most prevalent in the environment.
B. Photosynthetic Pigments
   1. Photosynthetic pigments use primarily the visible light portion of the electromagnetic spectrum.
   2. Pigments found in chlorophyll absorb various portions of visible light; this is their absorption spectrum.
   3. Two major photosynthetic pigments are chlorophyll \textit{a} and chlorophyll \textit{b}.
   4. Both chlorophylls absorb violet, blue, and red wavelengths best.
   5. Very little green light is absorbed; most is reflected back; this is why leaves appear green.
   6. Carotenoids are yellow-orange pigments which absorb light in violet, blue, and green regions.
   7. When chlorophyll breaks down in fall, the yellow-orange pigments in leaves show through.
   8. Absorption and action spectrum
      a. A \textit{spectrophotometer} measures the amount of light that passes through a sample of pigments.
         1) As different wavelengths are passed through, some are absorbed.
         2) Graph of percent of light absorbed at each wavelength is \textit{absorption spectrum}.
      b. Action spectrum
         1) Photosynthesis produces oxygen; production of oxygen is used to measure the rate of photosynthesis.
         2) Oxygen production and, therefore, photosynthetic activity is measured for plants under each specific wavelength; plotted on a graph, this produces an \textit{action spectrum}.
         3) Since the action spectrum resembles absorption spectrum, this indicates that chlorophylls contribute to photosynthesis.
C. Photosynthetic Reaction
   1. In 1930 C. B. van Niel showed that O₂ given off by photosynthesis comes from water and not from CO₂.
2. The net equation reads: \(6\text{CO}_2 + 6\text{H}_2\text{O} \rightarrow C_6\text{H}_{12}\text{O}_6 + 6\text{O}_2\).
3. This is better generalized as: \(\text{CO}_2 + \text{H}_2\text{O} \rightarrow \text{CH}_2\text{O} + \text{O}_2\) where \(\text{CH}_2\text{O}\) is a generalized carbohydrate.

D. Two Sets of Reactions
1. In 1905, F. F. Blackman proposed two sets of reactions for photosynthesis.
2. **Light reactions** cannot take place unless light is present.
   a. Light reactions are the energy-capturing reactions.
   b. Chlorophyll within thylakoid membranes absorbs solar energy and energizes electrons.
   c. Energized electrons move down the electron transport system; energy is captures and used for ATP production.
   d. Energized electrons are also taken up by \(\text{NADP}^+\), becoming \(\text{NADPH}\).
3. **Calvin Cycle Reactions**
   a. These reactions take place in the stroma; can occur in either the light or the dark.
   b. These are synthesis reactions that use \(\text{NADPH}\) and ATP to reduce \(\text{CO}_2\).

7.3 Light Reactions
A. Two Pathways
1. Two electron pathways operate in the thylakoid membrane: the noncyclic pathway and the cyclic pathway.
2. Both pathways produce ATP but only the noncyclic pathway also produces \(\text{NADPH}\).
3. ATP production during photosynthesis is sometimes called photophosphorylation; therefore these pathways are also known as cyclic and noncyclic photophosphorylation.

B. Noncyclic Electron Pathway
1. This pathway occurs in the thylakoid membranes and requires participation of two light-gathering units: **photosystem I (PS I)** and **photosystem II (PS II)**.
2. A photosystem is a photosynthetic unit comprised of a pigment complex and electron acceptor; solar energy is absorbed and high-energy electrons are generated.
3. Each photosystem has a pigment complex composed of green chlorophyll \(a\) and chlorophyll \(b\) molecules and orange and yellow accessory pigments (e.g., carotenoid pigments).
4. Absorbed energy is passed from one pigment molecule to another until concentrated in reaction-center chlorophyll \(a\).
5. Electrons in reaction-center chlorophyll \(a\) become excited; they escape to electron-acceptor molecule.
6. The noncyclic pathway begins with PSII; electrons move from \(\text{H}_2\text{O}\) through PS II to PS I and then on to \(\text{NADP}^+\).
7. The PS II pigment complex absorbs solar energy; high-energy electrons (\(e^-\)) leave the reaction-center chlorophyll \(a\) molecule.
8. PS II takes replacement electrons from \(\text{H}_2\text{O}\), which splits, releasing \(\text{O}_2\) and \(\text{H}^+\) ions:
   \[
   \text{H}_2\text{O} \rightarrow 2 \text{H}^+ + 2 e^- + \frac{1}{2} \text{O}_2.
   \]
9. Oxygen is released as oxygen gas (\(\text{O}_2\)).
10. The \(\text{H}^+\) ions temporarily stay within the thylakoid space and contribute to a \(\text{H}^+\) ion gradient.
11. As \(\text{H}^+\) flow down electrochemical gradient through ATP synthase complexes, chemiosmosis occurs.
12. Low-energy electrons leaving the electron transport system enter PS I.
13. When the PS I pigment complex absorbs solar energy, high-energy electrons leave reaction-center chlorophyll \(a\) and are captured by an electron acceptor.
14. The electron acceptor passes them on to \(\text{NADP}^+\).
15. \(\text{NADP}^+\) takes on an \(\text{H}^+\) to become \(\text{NADPH}\): \(\text{NADP}^+ + 2 e^- + \text{H}^+ \rightarrow \text{NADPH}\).
16. \(\text{NADPH}\) and ATP produced by noncyclic flow electrons in thylakoid membrane are used by enzymes in stroma during light-independent reactions.

C. Cyclic Electron Pathway
1. The cyclic electron pathway begins when the PS I antenna complex absorbs solar energy.
2. High-energy electrons leave PS I reaction-center chlorophyll \(a\) molecule.
3. Before they return, the electrons enter and travel down an **electron transport system**.
   a. Electrons pass from a higher to a lower energy level.
   b. Energy released is stored in form of a hydrogen (H+) gradient.
   c. When hydrogen ions flow down their electrochemical gradient through ATP synthase complexes, ATP production occurs.
   d. Because the electrons return to PSI rather than move on to NADP⁺, this is why it is called cyclic and also why no NADPH is produced.
4. It is possible that in plants, the cyclic flow of electrons is utilized only when CO₂ is in such limited supply that carbohydrate is not being produced.
5. There is now no need for additional NADPH, which is produced only by the noncyclic electron pathway.

D. **The Organization of the Thylakoid Membrane**
1. PS II has a light-gathering antenna on an acceptor molecule for electron; it oxidizes H₂O and produces O₂.
2. The electron transport system consists of cytochrome complexes and transports electrons and pumps H⁺ ions into the thylakoid space.
3. PS I has a light-gathering antenna and an acceptor molecule; it is associated with an enzyme that reduces NADP⁺ to NADPH.
4. ATP synthase complex has an H⁺ channel and ATP synthase; it produces ATP.

E. **ATP Production**
1. The thylakoid space acts as a reservoir for H⁺ ions; each time H₂O is split, two H⁺ remain.
2. Electrons move carrier-to-carrier, giving up energy used to pump H⁺ from the stroma into the thylakoid space.
3. Flow of H⁺ from high to low concentration across thylakoid membrane provides energy to produce ATP from ADP + P by using an ATP synthase enzyme
4. This is called **chemiosmosis** because ATP production is tied to an electrochemical gradient.

7.4 **The Calvin Cycle Reactions**

A. **Overview**
1. The Calvin Cycle is a series of reactions producing carbohydrates.
2. The cycle is named for Melvin Calvin who used a radioactive isotope of carbon to trace the reactions.
3. The Calvin Cycle includes: carbon dioxide fixation, carbon dioxide reduction, and regeneration of RuBP.

B. **Fixation of Carbon Dioxide**
1. CO₂ fixation is the attachment of CO₂ to an organic compound called RuBP.
2. RuBP (ribulose bisphosphate) is a five-carbon molecule that combines with carbon dioxide.
3. The enzyme RuBP carboxylase (rubisco) speeds this reaction; this enzyme comprises 20–50% of the protein content of chloroplasts, probably since it is a slow enzyme.

C. **Reduction of Carbon Dioxide**
1. With reduction of carbon dioxide, a PGA (3-phosphoglycerate[C₃] ) molecule forms.
2. Each of two PGA molecules undergoes reduction to PGAL in two steps.
3. Light-dependent reactions provide NADPH (electrons) and ATP (energy) to reduce PGA to PGAL.

D. **Regeneration of RuBP**
1. Every three turns of Calvin cycle, five molecules of PGAL are used to re-form three molecules of RuBP.
2. Every three turns of Calvin cycle, there is net gain of one PGAL molecule; five PGAL regenerate three molecules of RuBP.

E. **The Importance of the Calvin Cycle**
1. PGAL, the product of the Calvin Cycle can be converted into all sorts of other molecules.
2. Glucose phosphate is one result of PGAL metabolism; it is a common energy molecule.
3. Glucose phosphate is combined with fructose to form sucrose used by plants.
4. Glucose phosphate is the starting pint for synthesis of starch and cellulose.
5. The hydrocarbon skeleton of PGAL is used to form fatty acids and glycerol; the addition of nitrogen forms various amino acids.
7.5 Other Types of Photosynthesis

A. Photorespiration
   1. In C₃ plants, the Calvin cycle fixes CO₂ directly; first molecule following CO₂ fixation is PGA, a C₃ molecule.
   2. In hot weather, stomates close to save water; CO₂ concentration decreases in leaves; O₂ increases.
   3. This is called “photorespiration” since oxygen is taken up and CO₂ is produced; this produces only one PGA.

B. C₄ Photosynthesis
   1. In a C₃ plant, mesophyll cells contain well-formed chloroplasts, arranged in parallel layers.
   2. In C₄ plants, bundle sheath cells as well as the mesophyll cells contain chloroplasts.
   3. In C₄ leaf, mesophyll cells are arranged concentrically around the bundle sheath cells.
   4. C₃ plants use RuBP carboxylase to fix CO₂ to RuBP in mesophyll; the first detected molecule is PGA.
   5. C₄ plants use the enzyme PEP carboxylase (PEPCase) to fix CO₂ to PEP (phosphoenolpyruvate); the end product is oxaloacetate (a C₄ molecule).
   6. In C₄ plants, CO₂ is taken up in mesophyll cells and malate, a reduced form of oxaloacetate, is pumped into the bundle-sheath cells; here CO₂ enters Calvin cycle.
   7. In hot, dry climates, net photosynthetic rate of C₄ plants (e.g., corn) is 2–3 times that of C₃ plants.
   8. Photorespiration does not occur in C₄ leaves because PEPCase does not combine with O₂; even when stomates are closed, CO₂ is delivered to Calvin cycle in bundle sheath cells.
   9. C₄ plants have advantage over C₃ plants because in hot and dry weather, photorespiration does not occur (e.g., bluegrass [C₃] dominates lawns in early summer, crabgrass [C₄] takes over in hot midsummer).

C. CAM Photosynthesis
   1. CAM (crassulacean-acid metabolism) plants form a C₄ molecule at night when stomates can open without loss of water; found in many succulent desert plants including the family Crassulaceae.
   2. At night, CAM plants use PEPCase to fix CO₂ by forming C₄ molecule stored in large vacuoles in mesophyll.
   3. C₄ formed at night is broken down to CO₂ during the day and enters the Calvin cycle within the same cell, which now has NADPH and ATP available to it from the light-dependent reactions.
   4. CAM plants open stomates only at night, allowing CO₂ to enter photosynthesizing tissues; during the day, stomates are closed to conserve water but CO₂ cannot enter photosynthesizing tissues.
   5. Photosynthesis in a CAM plant is minimal, due to limited amount of CO₂ fixed at night; but this does allow CAM plants to live under stressful conditions.