CHAPTER 7 PHOTOSYNTHESIS

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 CO_2 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 CO_2.
   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 *a*** and **chlorophyll *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 **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 **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 **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 O_2 given off by photosynthesis comes from water and not from CO_2.

2. The net equation reads: $6CO_2$ plus $6H_2O$ forms $C_6 H_{12}O_6$ plus $6O_2$.
3. This is better generalized as: CO_2 plus H_2O forms CH_2O plus O_2 where CH_2O 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. Chlorophyl 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 $NADP^+$, becoming 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 NADPH and ATP to reduce 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 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 H_2O through PS II to PS I and then on to $NADP^+$.
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 H_2O, which splits, releasing O_2 and H^+ ions:
   $H_2O \rightarrow 2\ H^+ + 2\ e^- + \frac{1}{2}\ O_2$.
9. Oxygen is released as oxygen gas (O_2).
10. The H^+ ions temporarily stay within the thylakoid space and contribute to a H^+ ion gradient.
11. As 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 $NADP^+$.
15. $NADP^+$ takes on an H^+ to become NADPH: $NADP^+ + 2\ e^- + H^+ \rightarrow NADPH$.
16. 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 CO_2 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 H_2O and produces O_2.
    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 H_2O 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. **CO_2 fixation** is the attachment of CO_2 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[C_3]) 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. Photorespiraton
  1. In C_3 plants, the Calvin cycle fixes CO_2 directly; first molecule following CO_2 fixation is PGA, a C_3 molecule.
  2. In hot weather, stomates close to save water; CO_2 concentration decreases in leaves; O_2 increases.
  3. This is called "photorespiration" since oxygen is taken up and CO_2 is produced; this produces only one PGA.

B. C_4 Photosynthesis
  1. In a C_3 plant, mesophyll cells contain well-formed chloroplasts, arranged in parallel layers.
  2. In C_4 plants, bundle sheath cells as well as the mesophyll cells contain chloroplasts.
  3. In C_4 leaf, mesophyll cells are arranged concentrically around the bundle sheath cells.
  4. C_3 plants use RuBP carboxylase to fix CO_2 to RuBP in mesophyll; the first detected molecule is PGA.
  5. C_4 plants use the enzyme PEP carboxylase (PEPCase) to fix CO_2 to PEP (phosphoenolpyruvate); the end product is oxaloacetate (a C_4 molecule).
  6. In C_4 plants, CO_2 is taken up in mesophyll cells and malate, a reduced form of oxaloacetate, is pumped into the bundle-sheath cells; here CO_2 enters Calvin cycle.
  7. In hot, dry climates, net photosynthetic rate of C_4 plants (e.g., corn) is 2–3 times that of C_4 plants.
  8. Photorespiration does not occur in C_4 leaves because PEPCase does not combine with O_2; even when stomates are closed, CO_2 is delivered to Calvin cycle in bundle sheath cells.
  9. C_4 plants have advantage over C_3 plants because in hot and dry weather, photorespiration does not occur (e.g., bluegrass [C_3] dominates lawns in early summer, crabgrass [C_4] takes over in hot midsummer).

C. CAM Photosynthesis
  1. **CAM (crassulacean-acid metabolism)** plants form a C_4 molecule at night when stomates can open without loss of water; found in many succulent desert plants including the family Crassulacaeae.
  2. At night, CAM plants use PEPCase to fix CO_2 by forming C_4 molecule stored in large vacuoles in mesophyll.
  3. C_4 formed at night is broken down to CO_2 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 CO_2 to enter photosynthesizing tissues; during the day, stomates are closed to conserve water but CO_2 cannot enter photosynthesizing tissues.
  5. Photosynthesis in a CAM plant is minimal, due to limited amount of CO_2 fixed at night; but this does allow CAM plants to live under stressful conditions.